CAMBORNE SCHOOL OF MINES, UNIVERSITY OF EXETER

The Use of Laser Scanning and 3D Modelling in Accident Investigations

PhD Thesis

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2015

The Use of Laser Scanning and 3D Modelling in Accident Investigations

Submitted by

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To the University of Exeter as a thesis for the degree of Doctor of Philosophy

March 2015

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Abstract

In order to prevent accidents we need to understand them, this is achieved through effective accident investigation. Accident investigation is a complex process of gathering and evaluating information to determine factors that may have implications on the final event. One of the fundamental aspects in the investigation process is to capture geospatial data of the incident, to document the scene in its current condition, providing the investigation team with a record for future reference. The production of plans have conventionally remained the same, with a surveyor tasked to illustrate a 3D scene with 2D representations.

Recent developments in instrumentation have provided the geospatial industry with the means to capture vast amounts of 3D data directly using laser scanning. In addition, there have been considerable advancements in software applications which can be used to process the surveyed datasets. This research evaluates the use of the latest technology in respect of accident investigation applying the methodology to fire related incidents, industrial accidents and mining incidents. This is achieved by using a number of case studies that have been undertaken throughout the timeline of the project and whilst working with industry professionals in the field.

Acknowledgements

This project would not have been possible without the help of many people who have sacrificed their time and energy in order to help me fulfil my objectives required in this PhD study.

Firstly, I would like to thank the staff at Camborne School of Mines and 3D Mine Surveying International who have been instrumental in the conception, development and creation of this study, while providing me with access to a wealth of knowledge and expertise. Special thanks must go to James Jobling-Purser, for providing me with exposure to this exciting industry and for his ongoing support throughout this project,

Secondly, I would like to thank academic staff at Camborne School of Mines with special reference to Patrick Foster and John Coggan for their help throughout this project.

I would like to give my sincere thanks to UK Health and Safety Executive, namely Georgina Speake who has been of considerable help throughout the course of the project sharing her extensive knowledge in respect to accident investigation processes, while also allowing me to work alongside HSE in a number of "live" incidents. This help was invaluable providing direction and support during this research study.

Finally I would like to thank my mother Laura Eyre and father John Eyre for their help and continual support, while providing diligent proof reading.

Many thanks,

Matthew Eyre

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1.0. Chapter 1: Introduction

This chapter will describe the reasons for the research and its related aims and objectives, with discussion of the research methodology and the time frame of the work undertaken.

1.1. Reasons for research

Although there has been an improved focus on safety worldwide, accidents continue to occur year on year. With this in mind, understanding why an accident occurred is essential in order to prevent recurrence of similar events. This can be achieved through an effective accident investigation, which is then used to highlight both the immediate and underlying failures that contributed to the incident occurring. Once the failures have been identified, the investigation team can determine controls that need to be introduced to prevent a recurrence.

In the accident investigation process, the production of a plan of the accident scene is a core element of the procedure, with the scale and the detail of the plan, being largely dependent on the consequence of the accident. Whilst, a crude drawing may be deemed acceptable for a low consequence accident, a high consequence event, such as a fatality will require a detailed plan. The plan should give the investigator and any other interested party, an accurate representation of the event, detailing the scene and including the locations of personnel and related equipment.

Typically, accident surveys have been undertaken using conventional surveying methodology utilising tape measures and discrete point mapping (for example by means of a total station), complemented with digital photography and video. However, there are limitations in adopting this approach, such as the time taken to gather the data and the limited detail of the information collected.

Over recent years there have been considerable developments in survey instrumentation and related software, used to process data obtained. One of these major advancements within the geospatial industry is laser scanning technology. Laser scanning describes a process where a surface is sampled or scanned using electromagnetic distance measurement and electronic angle measurement. The result is a dense collection of points referred collectively as a point cloud with each singular point having its own unique 3D co-ordinate, the distance between the points often being less than a millimetre apart. This point cloud data can be collected in a relatively short period of time, far surpassing the amount of data captured by conventional means.

1.2. Aims and objectives

This project aims to:

- Identify suitable industrial applications of this technology in relation to the management of incident scenes.
- To review and develop skills in a wide range of software applications used to process point cloud data, produce mesh models and subsequent visualisation of findings, critical for this project's development.
- Investigate the integration of laser scanning and the subsequent presentation of geospatial data, to the widest range of stakeholders associated with;
    - The development of commercial applications
    - The display of evidence in legal proceedings
    - The improvement of survey methodology employed in accident investigations
- Evaluate the use of laser scanning technology to capture geospatial data of a scene and to investigate the benefits and limitations associated with its deployment, in terms of accident reconstruction and data gathering.
- Develop accident reconstructions of a number of case studies throughout the project timeline.

1.3 Methodology

With regard to methodology, firstly a structured literature review was conducted to review research of the following topics: why accidents occur, the accident investigation process, developments in surveying technology, the history of accident surveying and current uses for digital data in the legal process. This literature review will help define the current status of accident investigation, the advancements in geospatial data gathering and the interpretation of this data by legal profession, in relation to the surveying of accident scenes.

In order to develop this work a number of software applications will have to be understood and the possible processes that have to be undertaken in order to produce final deliverable data required within the selected fields.

Following a structured literature review and ongoing software training, a number of public and private institutions will be contacted in order to develop contacts within the various industries in which they hold responsibility. This will aid in the development of commercial applications of the technology and provide access to the various cases studies that are required throughout the course of the work undertaken.

A number of case studies will be evaluated from real or staged incidents in order to consider the use of the technology with regard to the selected fields. The case studies will then form the basis for further evaluation into the benefits and limitations of the employment of the technology. Following this, conclusions will be made drawing the research findings together.

1.4. Thesis overview

In summary, this thesis explores the use of laser scanning and its application to accident investigation and other uses to which the technology could be applied. An outline of each chapter is given below:

Chapter 1

This chapter contains details of reasons for research, aims, objectives and methodology and outlines of each chapter.

Chapter 2

This chapter presents the literature review of the project, firstly discussing accident causation models, the importance of accident investigations and of developing an effective accident methodology. The literature review will then focus on the surveying of accidents and on the surveying technology that have been incorporated into the documentation of accident scenes.

Chapter 3

The Fire and Rescue Service (FRS) are responsible with regard to extinguishing fires and the overall management of fire incident scenes. In addition, the FRS service perform the extrication of trapped persons from accidents involving vehicles, with Road Traffic Collisions (RTCs) being the highest cause of accidental death worldwide. Given the volume of the FRS responsibility, it is appropriate to investigate how laser scanning and 3D modelling methodologies could be applied to the processes undertaken by FRS, with the aim of helping to improve the management and investigation of events.

This is achieved by presenting three case studies, resulting from collaborative research with Cornwall Fire and Rescue Service (CFRS), Fire Investigations UK and the Building Research Establishment:

3.1. The Use of Laser Scanning and 3D Modelling in Fire Investigations

This section will consider the incorporation of laser scanning and 3D modelling within the scientific approach to fire investigation. Using a case study of a staged fire undertaken with the Building Research Establishment (BRE) and Fire Investigations UK (FIUK) will be discussed, where a mock staff room was constructed and laser scanned prior to ignition, and again following combustion. This information was then evaluated, in order to assess the benefits and the limitations of the technology with reference to the origin and cause of a fire.

3.2. The Potential Use of Augmented Reality in the Extrication Process of Road Traffic Collisions (RTCs)

This section explores the current methodology for the extrication of trapped persons as employed by the UK Fire and Rescue Service (FRS) and the potential problems that can be encountered regarding vehicle safety systems. Following this, the author introduces the concept using of augmented reality to aid FRS crews in the extrication process, by visually displaying the locations of safety systems on a crashed vehicle. Discussion, will focus on how this may be integrated into the extrication process and the possible benefits that could be obtained in adopting this procedure.

3.3. The Application of Deformation Monitoring as a Risk Assessment Tool in Fire Incident Management

This section will highlight the current problems that are encountered by Fire and Rescue Personnel when managing the suppression of a fire safely, while remaining effective in their execution. This is of particular importance when there may be persons trapped within the structure and time is of the essence to ensure their survival. There are a number of new surveying technologies available that can provide real-time assessment of a buildings structural capacity. This section will address their use within this context exploring the possible benefits and limitations that could be drawn from their use. A case study which highlighted the problem to the author (Falmouth Beach Hotel Fire, Cornwall UK) will also be discussed.

Chapter 4

In the UK, the Health and Safety Executive (HSE) are responsible for undertaking accident investigation in workplaces and for prosecuting when necessary, if a breach in the law is established. The number of industrial accidents has been declining for several decades, owing to the focus on proactive safety measures and rigorous enforcement of the law. However, these incidents still present a significant risk to workforces in the UK. Therefore, it was appropriate to work with the HSE on developing the use of laser scanning and 3D modelling in the investigation process following fatal accidents.

This has been achieved by presenting three case studies, resulting from collaborative research with the HSE, Health and Safety Laboratory (HSL) and their legal representatives. Two of which have been accepted for publication and the third is awaiting submission:

4.1. The Integration of Laser Scanning and 3D Models in the Legal Process Following an Industrial Accident

On occasion, an accident investigation may highlight that a breach of the law has occurred. In the UK, the Health and Safety Executive (HSE) along with the British legal system, will aim to secure justice for those involved. The legal system is used to ensure a fair trial and provide a verdict. With this in mind, the judicial system is beginning to be exposed to laser scan deliverables aiding in the explanation of the circumstances of the incident to people unconnected to the event.

This section highlights the place in which laser scanning can be introduced as a tool, within a court room through a case study of a fatal accident, exploring the possible benefits and limitations of incorporating the technology, with discussion of both physical and virtual models.

4.2. The Use of Laser Scanning as a Method for Measuring Stairways Following an Accident

This work was undertaken in collaboration with the UK Health and Safety Laboratory (HSL) to examine the suitability of laser scanning for stair fall investigations, following an accident. Evaluation will be made of the use of a laser scanner to provide a precise and accurate survey of a stairwell, focusing on the classification of errors generated from incorporating a laser scan survey, and comparing it to conventional approved methodologies currently employed by HSL. In addition, the section will also assess other possible benefits that can be obtained and how it may complement an accident investigation involving a fall on stairs.

4.3. The Integration of Laser Scanning and 3D Modelling in the Industrial **Accident Investigation Process**

This section will evaluate the use of laser scanning and 3D modelling within the accident investigation process after a fatal incident and will focus on the importance of an accident survey and the incorporation of laser scanning technology in the process. A case study undertaken in conjunction with Health and Safety Executive (HSE) and the Police will be evaluated, with discussion into the methodology undertaken with regard to the survey process and data processing. Following this, benefits specific to the case study will be highlighted and examined.

Chapter 5

The mining industry is essential in order to supply the world with the raw materials that are required for its development. However, hazards in operations are recognised and mining companies are tasked to control them in order to ensure the safety of the workplace. Due to the significant numbers of incidents that occur in the industry and the extensive complex geometry found in excavations, there is considerable scope to develop the processes in accident investigation and surveying methods in this sector.

This chapter will present the use of laser scanning and 3D modelling within the investigation process following a mining incident. This has resulted from collaborative research with the mining Health and Safety Executive (HSE) and their legal representatives, which has been accepted for publication.

5.1. The Benefits of Laser Scanning and 3D Modelling in Accident Investigation: In a Mining Context

Over a number of years, there have been considerable innovations in accident survey instrumentation and software. This section explores the benefits that can be obtained by using laser scanning data (3D data) with regard to the accident investigation process, with discussion on accuracy, time, witness verification, and reduction in human error. A staged electrocution in a working underground mine will be explored, with the benefits and drawbacks specific to mine accident investigations being evaluated.

Chapter 6: Conclusions

This chapter draws together all the key findings of this research, discusses the results in respect of the main aims of the study and identifies areas for future research.

1.5. Timescale of the Research

In order to complete the research and maintain a consistent timeframe objectives had to be set:

- In the first year, a number of software applications were learnt in order to process the data obtained. In addition, a full literature review was undertaken exploring published work in the fields of laser scanning and accident investigation.

- In the second year, a number of staged case studies were undertaken exploring the use of laser scanning in accident investigation, while continuing to hone skills in the computer software required.
- In the third year, more case studies were explored and writing up of the project commenced, while attending and presenting at a number of conferences in order to promote greater impact of the research undertaken.

1.6. Contribution of Thesis

This thesis sets out to demonstrate the use of laser scanning and 3D modelling in the investigation process whilst exploring the magnitude of different possibilities in which the technology can be applied. There has been significant work within the sector of Computer Generated Visualisation (CGV) in the legal process following accidents and in crime scene reconstruction, providing a powerful mechanism for the evaluation of scenes to people unconnected to the event.

Laser scanning as a technology is still relatively new and applications for its use are continually being developed, particularly in a commercial setting. It is widely accepted that the technology offers significant benefits over conventional surveying techniques, in relation to the speed of data capture and the density of the datasets that the equipment can provide. These benefits have led to laser scanning beginning to gain acceptance in the legal system, where its application has mainly focused on crime and RTCs, particularly in the United States. Also in the UK, due to the numerous benefits that have been found through implementing the technology, police and legal teams now have access to information that was previously unattainable. This has resulted in considerable investments that have been made by police forces across the country to purchase laser scanning equipment. This was undertaken following a number of successful trials by the Metropolitan Police, relating to RTCs and the cost savings associated with prolonged road closures, when using conventional surveying methods.

Nevertheless, there is little published work worldwide in the use of laser scanning as a method to capture geospatial data of a scene following RTCs and other incidents. It is not known why this is the case, although it could be due to the fact that when this technology has been used, much of the data and subsequent work could be legally restricted or protected by commercial confidentiality, resulting in a lack of academic publications.

This project aims to explore the use of laser scanning and state of the art software applications and the extent to which they can aid investigation teams and emergency services when undertaking their duties. This research will be undertaken working with a number of agencies both in the UK and abroad in order to establish if there are common themes developing across various illustrative case studies and incidents. In addition, academic assessment will be provided of the benefits and limitations of employing this instrumentation in the specific case studies undertaken. This will add clarity to the use of this emerging technology in the investigation process, providing information to prospective users regarding the management and analysis of incidents, which have largely been previously unexplored in an academic setting,

This will be achieved by applying the technology to a number of "live" incidents and if the information becomes legally restricted, staged incidents will be created where possible to mimic the incident in order to express some of the findings of the investigation in relation to geospatial capture techniques and subsequent processing methods. After applying the technology to live incidents the data will be analysed and conclusions will be drawn.

2.0. Literature Review

In this chapter a literature review has been undertaken investigating accidents and the current research being undertaken in the subject area.

2.1. Accident Causation

Accidents are a major cause of injury and death. An accident can be defined as "an unforeseen event or one without an apparent cause" (Collins 2014). Expansion of this definition implies that, "every accident has a cause", although sometimes it is not immediately clear and an investigation into the event is required in order to help define it.

For many years accident causation models have been developed in order to assist people investigating accidents and to ensure an effective investigation procedure is followed (HSE 2011a). Proactive accident investigation is essential when identifying failures and errors that generally cause accidents. Taking action through risk management (establishing and implementing controls) will aid in the prevention of future events (HSE 2011a). There has been considerable research undertaken into the factors surrounding accidents. Considering these factors, a number of causation models have been produced, some of which will be discussed in this chapter.

2.1.1. Heinrich: Domino Theory

H.W.Heinrich was a safety engineer who produced what has been credited as the first scientific method of injury prevention and the effects of accidental injury causation (Lee 2010). Heinrich presented a set of theorems "the axioms of industrial safety", in which the first axiom stated "the occurrence of an injury invariably results from a complicated sequence of factors, the last of which being the accident itself" (HSE 2011a).

Heinrich compared the accident sequence to a row of dominoes, collision causes the next to fall in sequence ultimately resulting in the accident itself. Heinrich gave each domino a "factor" with each dependent on the one previously. If any domino was removed from the sequence the following domino will not fall, as it is dependent on the one previous to trigger it. Therefore in the context of accident causation Heinrich discovered if any single "factor" was removed from the sequence the accident won't occur. Heinrich's accident sequence is shown below in Figure 1.

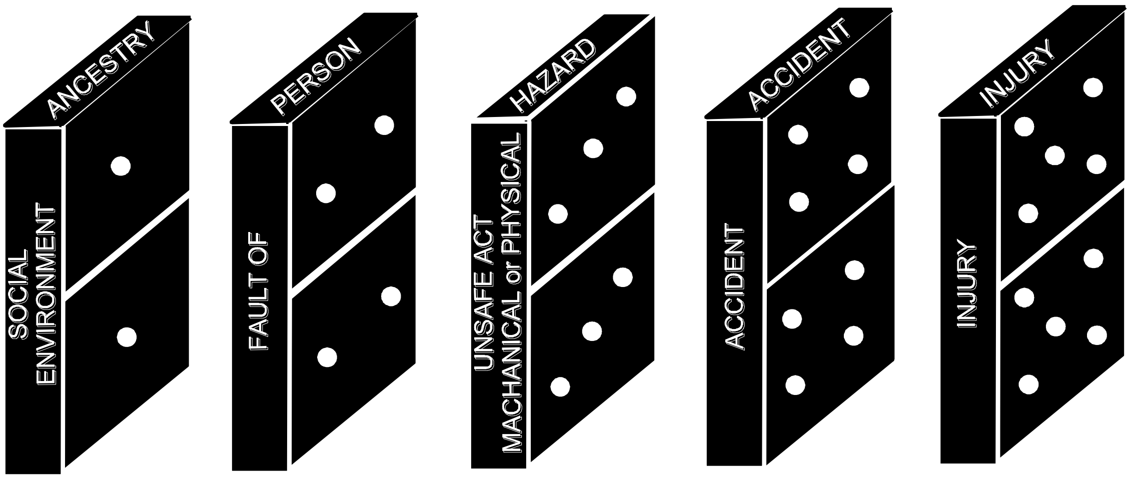


Figure 1 Heinrich Domino Theory (HSE 2011a)

This can be explained as:

- Injury, caused by an;
- Accident, due to an;
- Unsafe act and/or mechanical or physical hazard, due to the;
- Fault of the Person, caused by their;
- Ancestry and Social Environment.

Heinrich stated, by removing one of the above, the accident would be prevented. However, particular attention should be paid to the unsafe act, as this is the easiest to control (HSE 2011a). Heinrich's studies involved 75,000 insurance accident report cases in the 1930s. His studies highlighted that 88% of investigated accidents were caused by unsafe acts (Hazards) with 10% due to unsafe conditions and 2% being unpreventable. Heinrich stated that an individual's characteristics and behaviour were the root cause of most accidents, suggesting these traits were inherited or acquired while in the workplace (Lee 2010).

Heinrich believed that management have to judge an employee's skill level and assign appropriate tasks to suit, while providing the employee with the appropriate training and information on the risks which could be encountered. Understanding the risk and consequences of a person's actions will reduce the probability of an accident. This will have a direct effect on the "Social Environment" and/ or the "Fault of the Person" domino's and removing these will stop the accident from occurring (breaking the chain of domino's). Heinrich theorised that by changing safety behaviour through appropriate training, work systems and procedures the management can reduce human error and thus prevent incidents.

The domino theory has been updated several times, the first of which was by Bird & Loftus in 1986 (HSE 2011a). This resulted in two new concepts that:

- management and managerial error contribute to accidents
- losses from accidents need not be restricted to injury and can include production loses, damage to property and or other assets

The updated by Bird & Loftus causation theory (known as the International Loss Control Institute (ILCI) model) is shown below in Figure 2.

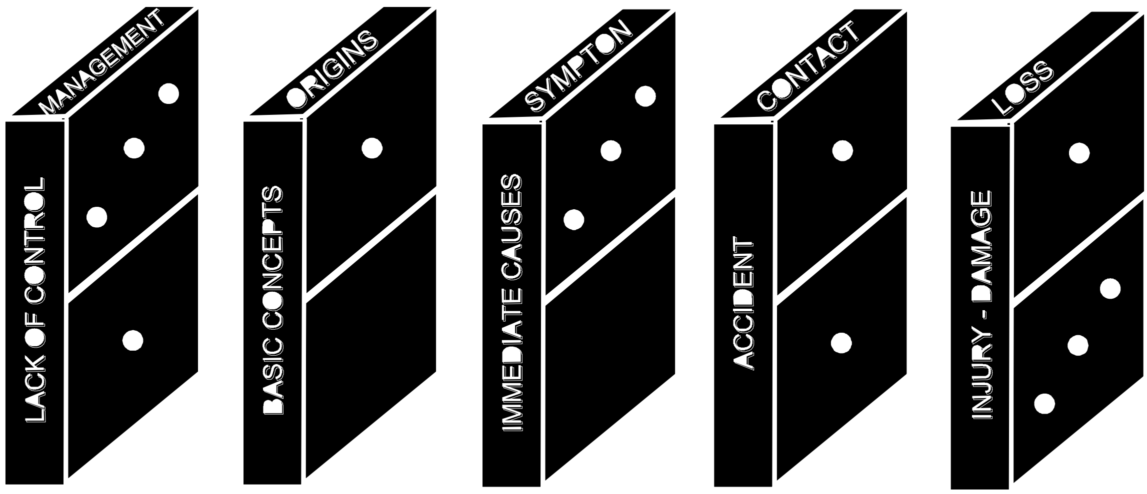


Figure 2 ILCI Model (HSE 2011a)

It can be seen that the ILCI model is of similar structure to Heinrich's original and is considered as a one dimensional sequence of events to a incident be it injury or damage. However through additional research, it was discovered that many accidents have multiple causes and there are many contributing factors involved (HSE 2011a).

This was noted by Peterson (1978), that while performing an investigation, the investigator must identify as many causes as possible for each "domino" rather than focus on one (HSE 2011a). Below in Figure 3 is an example of a multi cause accident model.

Root Cause(s) (Lack of Control)		Obvious Cause		Incident		LOSS
• Management's Safety Program • Personal Factors • Job Factors	⇒ ⇒	• Unsafe Acts • Unsafe Conditions	⇒ ⇒	• Contact with Energy or Substance	⇒ ⇒	• Personnel Harm • Property Damage • Production Loss

Figure 3: Example of a Multi Cause Accident Model (Staley & Foster 1996)

<u>Root Cause</u>

The root causes are the reasons why the unsafe acts and conditions exist. The root causes of accidents are usually found within the poor management of a safety management system. These failures are sometimes hard to spot but are very cost effective to remove as poor management could be contributing to multiple factors and possibly future incidents (Staley & Foster 1996).

<u>Obvious Cause</u>

The obvious cause of an accident is the combined effect of unsafe acts or conditions which have a direct influence on the incident. An unsafe act is the conduct of the employee that increase the likelihood of an incident occurring. An unsafe condition is the environment in the vicinity of the operator that has an effect on the incident. Thus, unsafe conditions may not always be a result of operator error (Staley & Foster 1996).

Below are some examples to help distinguish an unsafe act from an unsafe condition, using a mining example (Staley & Foster 1996).

Unsafe Act	Unsafe Conditions
• Operating equipment without authorisation • Using equipment Incorrectly • Using defective equipment • Defeating safety devices • Failure to warn workmates or to secure a load • Failure to use PPE • Improper loading of supplies • Poor personal positioning • Incorrect manual handling • Working on moving machinery • Horseplay • Under the influence of alcohol/drugs	• Inadequate supports • Inadequate guards • Defective tools, equipment or supplies • Congestion of work place • Inadequate warning system • Fire and explosion hazards • Disorderly workplace • Excessive noise • Poor illumination • Poor ventilation • Poor geology

Table 1: Examples of Unsafe Acts and Conditions

<u>Incident</u>

The incident is an undesired event in which the individual comes into contact with a form of energy that can or could cause damage or harm (Staley & Foster 1996).

<u>Loss</u>

The result of an accident is some form of loss and can be wide ranging from an injury to financial implications. Accidents cost money and are only partially covered by insurance policies. Other costs associated with accidents are hidden and are considerably more than insured costs. This is illustrated in Figure 4.

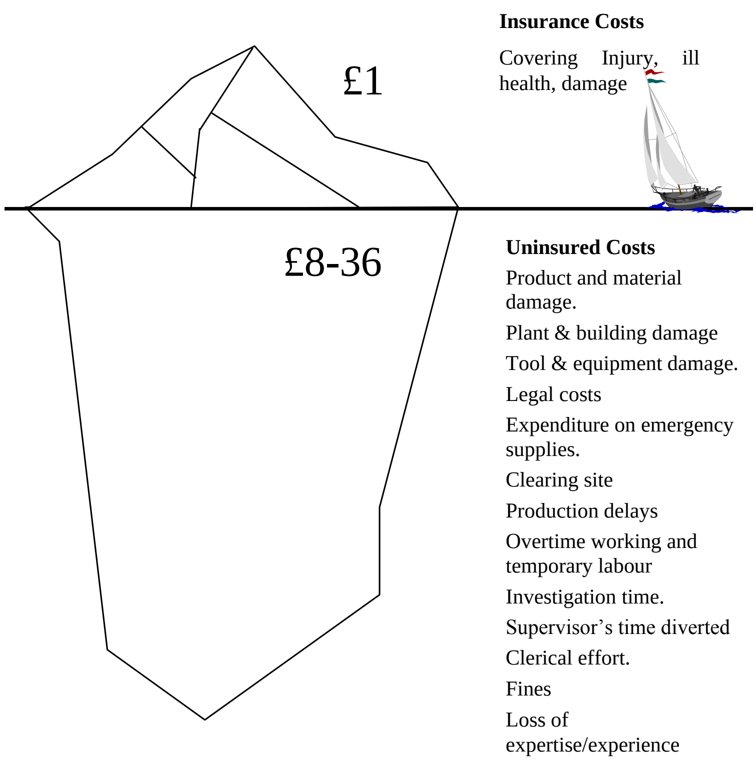


Figure 4 The Iceberg Concept (HSE 2011a)

2.1.2. Viner: Accident Analysis and Risk Control

Viner analysed a series of accident causation models and found that three basic principles arose common in all (Borys 2000) that:

1. energy is required to produce injury and damage
2. the process develops sequentially in time
3. the process involves uncertainty

Viner used the above principles to form the basis of three separate models shown in Figure 5.

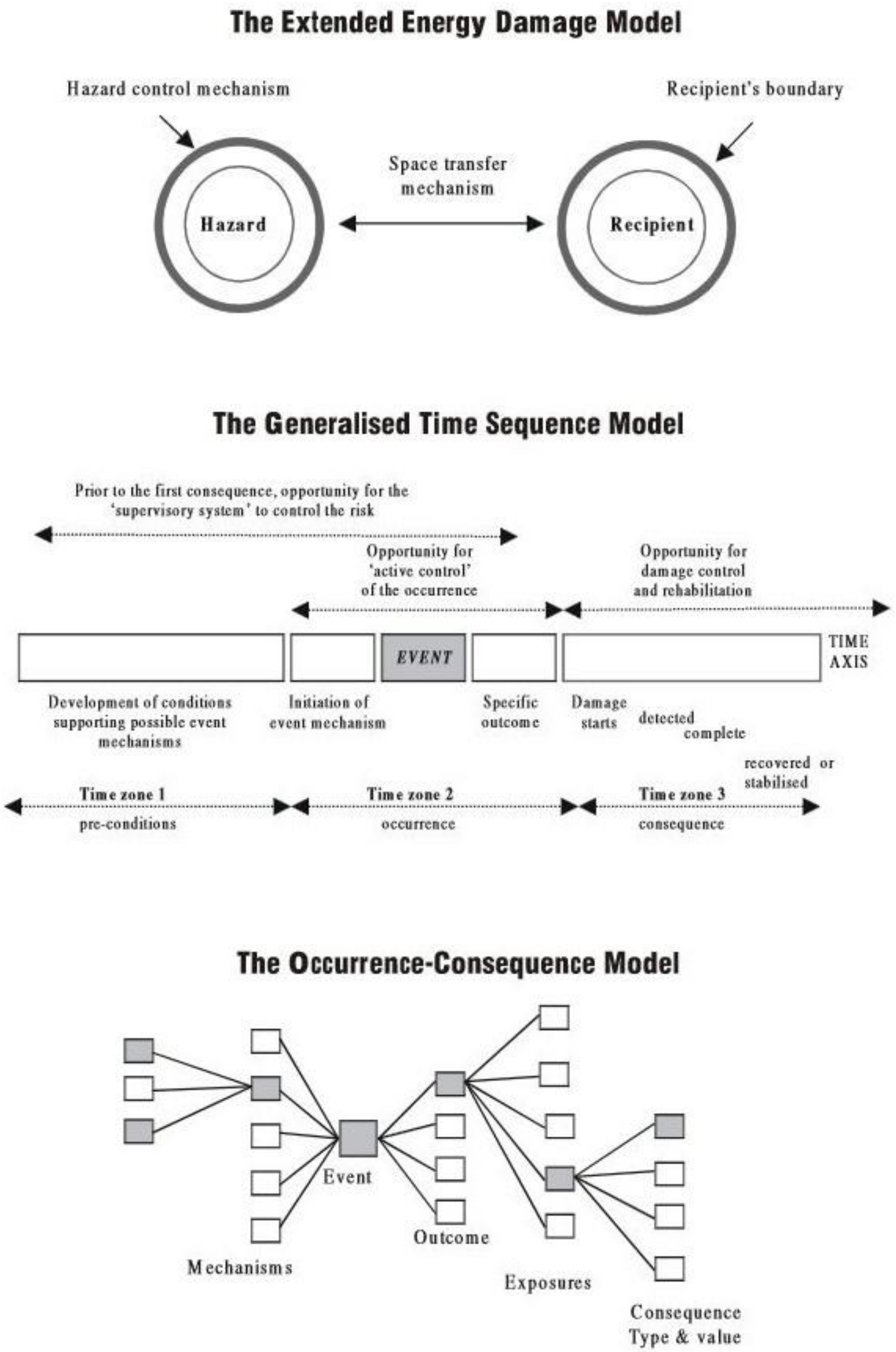


Figure 5 Accident Analysis and Risk Control (Borys 2000)

2.1.2.1. The Extended Energy Damage Model

This model looks at the relationship between the effect of an energy source on the recipient and if an exchange of energy occurred, with reference to Figure 5.

The model requires the user to identify all the types of harmful energy sources within the workplace and the controls in place to manage them. With this information, the user then has to determine the transfer pathway in which the energy will travel. Finally, the user must determine how the energy will be received by the individual. Once these components have been defined, controls have to be developed for each component to prevent an incident occurring. Much like the model developed by Heinrich the focus is on the control of the unsafe act that will release the energy (Lee 2010).

For example (Taylor et al. 2004)

Define the three components

Energy Source: Vibration

Transfer Pathway: Air

Individuals Reception: Damage to hearing

Define the control measures required to be implemented for all components

Prevent, contain or limit the energy source: Dampen the vibration

Remove the mechanism for the pathway travel: Use acoustic insulating material in pathway

Protect the individual from exposure: Hearing protection devices

2.1.2.2. The Generalised Time Sequence Model

This model defines an incident in three specific time zones in order to gain clarity on the controls that can be applied to prevent and recover from accidents (with reference to Figure 5).

<u>Time zone one</u>

This time zone one ("pre-conditions") allows the user to classify potentially damaging energies and helps identify control conditions in place in order to prevent a hazard being released.

<u>Time zone two</u>

This is the time zone in which the "event" occurs and it can be seen from the model in Figure 5 that time is subdivided further, into three additional subsections. The first subsection is short and is the time in which an active control (i.e the means employed to immediately contain the release of a hazard) has to react to the hazard and regain charge of it, thus preventing its release (Brooke et al. 2010). The second subsection is the incident event itself. The third is again short in nature and is the time in which "activities" (i.e. passive safety systems used to limit damage) can be deployed.

Time zone three

It can be seen in Figure 5, that this is the time zone associated with the recovery from the incident and is undertaken to minimise loss suffered. This time zone, much like time zone one, is longer in nature.

An important point to stress relating to the model is that only time zones one and two allow the user to implement a control to prevent the event. Again, this model can be referred back to Heinrich's model of removing the unsafe act and/or condition, social environment or fault of person.

2.1.2.3. The Occurrence-Consequence Model

Viner considered that there are many factors that have to be taken into account when assessing the cause of an incident. Some of these factors can be classified into categories and others are found to be uncertain and thus hard to control. However, all events can be linked into a chain and with the result being the incident occurring. This model can be presented as a spider diagram (as shown in Figure 5), that allows the user to define and link all actions and events that may have contributed to the incident, and to observe their relationship with each other.

2.1.3. Rasmussen: SRK Model

The Rasmussen SRK model assists the user to classify an operator's behaviour into three levels:

Skill Based Behaviour

This is a type of behaviour classification, where the individual performs a task with little or no conscious attention during its execution. This means that performance of the operation is smooth, automated and consists of highly integrated patterns of behaviour (Rasmussen 1990). This means that the individual has enough mental capacity to perform another task in parallel to a skill based operation.

For example, an experienced driver has the ability to talk whist maintaining control of the vehicle (Taylor et al. 2004).

Rule-Based Behaviour

This type of behaviour is when an operator's action is governed by the use of rules and procedures. This type of behaviour can be obtained through training or experience in performing a particular task (Rasmussen 1990). The operator may not need to understand the concepts behind the rule or how it was produced, as long as it obeyed for example, if a car driver is obeying the "rules of the road" i.e. signposts and giving way correctly etc. However, the conventional driving operations will still be on a skill based level (changing gear, braking, etc..) (Taylor et al. 2004).

Knowledge-Based Behaviour

This is when an operator's actions are related to problem solving (Rasmussen 1990). This behaviour requires a more advanced level of reasoning (Wirstad 1988). This type of behaviour occurs when a situation is novel or unexpected. Therefore, the operator is required to have considerable knowledge of the principles and laws in the system (Rasmussen 1990).

For example, If a car driver encounters traffic lights which are out of order the person must make a decision to what would be the safest course of action (Taylor et al. 2004). However, the driver will still be governed by rule based behaviour i.e. speed limits etc. In addition, skill based behaviour will still be operating i.e. changing gear etc..

In addition, the model infers that an accident occurs as a consequence of goal setting by the individual or company followed by an incorrect human decision (Taylor et al. 2004). It requires the user to define the behaviour of an individual and once this has been completed, controls, training and procedures can be put in place in order to ensure accident prevention.

2.1.4. James Reason: Swiss Cheese Accident Model

Reason suggests that even the most advanced and well maintained controls within a workplace have failures within them (Reason 1997). When these failures "align" allowing a hazard to be released in a series of events, the result is an accident. Reasons model is shown in Figure 6.

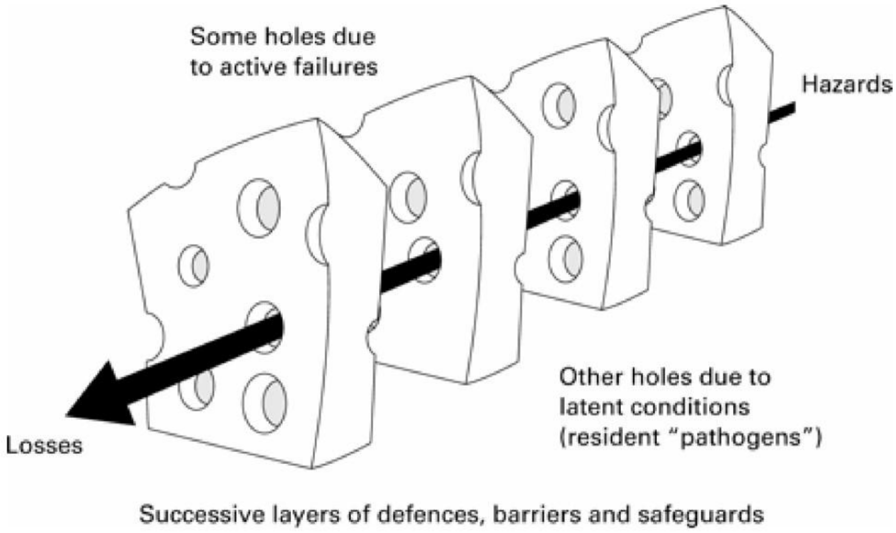


Figure 6 Reason's Accident Model (Reason 1997)

Failures which cause a "hole" in a control can be either "active" or "latent". Active failures are described as: failures which have an immediate consequence, usually made by front line individuals and immediately precede the event, being the direct cause of an accident (Foster 2011).

Latent failures can be defined as aspects of the organisation which can immediately predispose active failures such as (Foster 2011):

- Poor design of plant and equipment
- Ineffective training
- Inadequate supervision
- Ineffective communications
- Uncertainties in roles and responsibilities

Due to their nature, latent failures are harder to define as they can lay dormant in a company's organisation. However, every active failure has underlying latent ones, which must be found in order to prevent future incidents. In addition, one latent failure often influences several other factors within the organisation. Therefore removal of latent failures can be very cost effective (Foster 2011).

2.1.4.1. Classifying Human Error

Reason began to evaluate in depth failures which have been a result of human interaction. The research found that active failures can be subdivided into separate categories shown below in Figure 7.

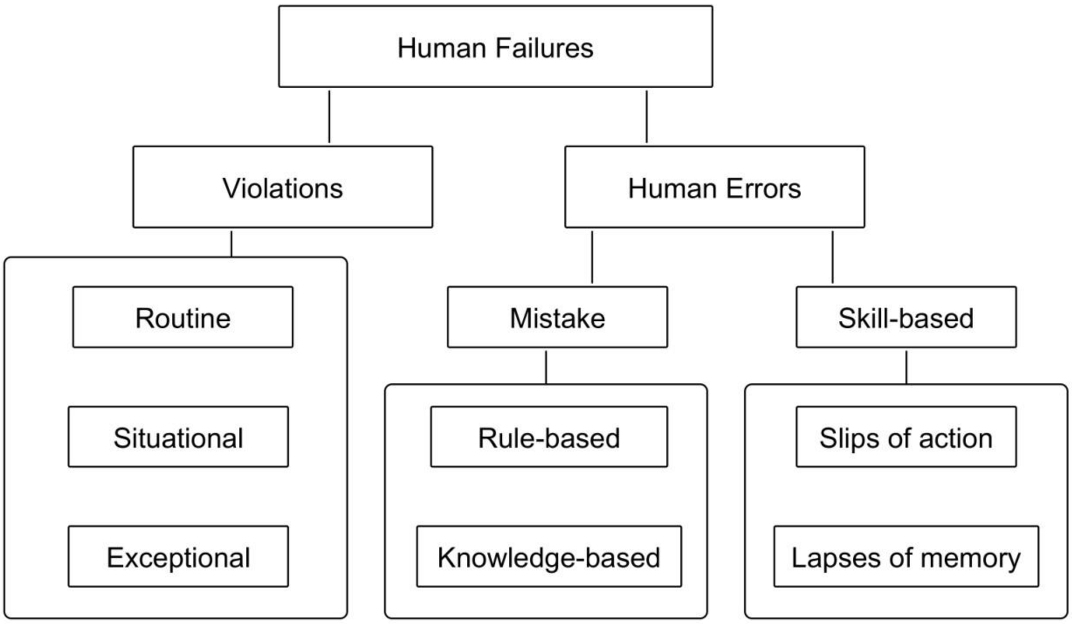


Figure 7 Classifying Active Failures (HSE 1999)

It can be seen in Figure 7 that failures can be separated into Human Errors and Violations.

Errors: These failures occur when an operator believes they are "doing the right thing" and something goes wrong. Errors are un-intentional and can be Mistakes or Skill based errors (HSE 1999).

- Mistakes are errors of judgement or decision making (HSE 1999). Mistakes are decisions that are found to be incorrect after the incident even though the operator believed them to be correct at the time. A mistake can be behaviour that is rule based or knowledge based as defined previously by Rasmussen.
- Skill based errors or slip/lapse errors occur in routine operations when the operator knows the task well and becomes complacent or "switches off" briefly (HSE 1999). These errors often occur in repetitive tasks in

which the operator has undertaken many times and a lapse in concentration results in failure.

Violations: These are failures that occur when an operator knows the right course of action but decides to "do something different". Violations can be subdivided further into routine, situational and exception violations (HSE 1999).

- Routine: These are violations that occur consistently in operations and are considered "the better way of performing a task", be it for speed or perceived safety.
- Situational: These are violations in that occur due to the operator's environment. The individual considers this is the best method for the setting, again possibly for speed or perceived safety.
- Exceptional: These are violations that are out of the ordinary and only happen in unusual or particular circumstances, often when a something goes wrong (HSE 1999).

2.1.4.2. Reason: Organisational Error Model

In order to address the latent and active failures efficiently Reason developed a model to address organisational error shown below in Figure 8.

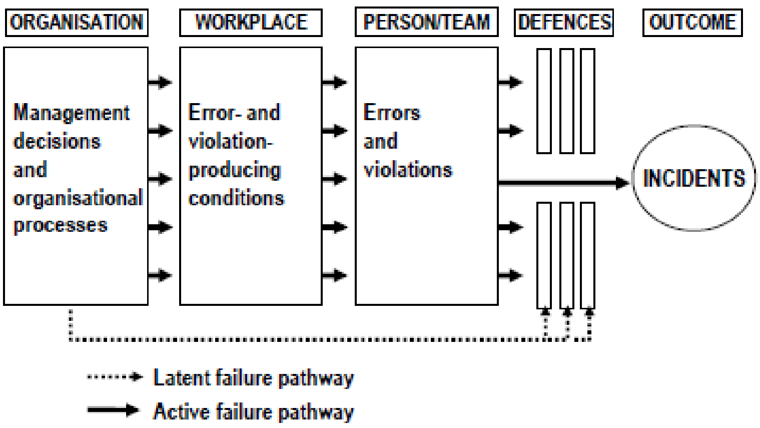


Figure 8 Organisational Error Model (Foster 2011)

It can be seen from the model above, that Reason classified the stages involved in an organisational accident. The organisation can have a direct effect on the defences of a system through a latent failure pathway, while also contributing active failures to the system. The other areas of a work environment can only influence the system by an active failure. Therefore, the organisation needs to have adequate training and procedures in place, while developing a good safety culture in order to reduce the possibility of a latent failure occurring. However, active failures can be reduced through effective equipment design and maintenance.

2.2. Why Investigate Accidents?

An accident investigation is a widely accepted method to clarify the immediate and underlying latent failures that may have contributed to an incident. In addition, an effective investigation will be used to highlight the appropriate measures that need to be adopted to prevent the reoccurrence of similar incidents (Roed-Larsen et al. 2004). In addition to the above, other reasons to conduct an accident investigation may include (Ferry 1998):

- To reduce danger to employees and the public from further incidents
- To prevent a company's resource losses
- To respond to the needs of management
- To develop information relating to the cost of accidents
- To improve a company's operating efficiency
- To help define errors within the operation in question
- To help to provide responses to public concerns
- To satisfy internal company rules
- To reduce disruption to work processes
- To provide protection against legal action
- To satisfy an insurance company's requirements
- To satisfy media pressure
- To improve quality control and reliability
- For research purposes
- To aid in the education of staff and management
- To satisfy regulatory requirements
- To comply with affected party's compensation rules

Within the UK, accident investigation forms an essential component of a formal Health and Safety Management System certification such as OHSAS 18001 or the forthcoming ISO 45001. Therefore, if an incident has occurred within an accredited company or one trying to obtain certification, the corporation must investigate the accident and demonstrate that they have addressed the issues arising, thus demonstrating continual improvement (NQA 2009).

2.2.1. Types of Accidents

Accidents can be classified into a number of types (Geigle Safety Group 2013):

Struck-by. This is when a person is struck by an object. The force of contact is provided by the object.

Struck- against. This is when a person forcefully strikes an object. The force of the impact is provided by the person.

Contact-by. This is when contact arises by a substance or material, which is by its very nature, harmful and causes an injury.

Contact-with. This is when a person comes into contact with a harmful substance or material, where the person initiates the contact.

Caught-on. This is when a person's clothing or equipment is caught on an object that is either moving or stationary. This category encompasses the additional accidents caused from the initial event of being caught, such as if a person were to lose balance and fall, and then subsequently be pulled into the machine or suffer other harm.

Caught-in. This is when a person or body part is trapped/caught in a opening or enclosure.

Caught-between. This is when a person is crushed, pinched etc by a moving or stationary object or between two moving parts.

Fall-to-surface. This is a when a person falls to the surface they are standing or walking on as a result of a trip or slip.

Fall-to-below. This is when a person falls to a level below the surface they were walking or standing on, as a result of a slip or trip.

Over-exertion. This is when a person over extends or strains their body while performing work.

Over-exposure. This is when a person is exposed to harmful energy (noise, heat), lack of energy (cold) or substances (toxic chemicals/atmospheres) over a period of time.

Bodily reaction. This is when a person suffers harm from a stress being imposed on the body via free movement or unnatural body position.

Accidents can sometimes be perceived as unplanned and freak occurrences. However, many result from hazardous conditions and unsafe working practices that have been overlooked, ignored or tolerated for a period of time. In certain cases indicators have been ignored, then it's not a question of "if" an accident will happen it is "when". A company should employ a competent person who is able to examine (through accident investigation) the workplace, highlighting behaviours, conditions and underlying systems to predict accidents that may occur. In consideration of this information, decisions should be made to the management system to prevent them (Geigle Safety Group 2013).

2.3. Undertaking an Effective Accident Investigation

The output of an employer's accident investigation should not end with identifying violations in the employer's safety rules. Instead, the investigation should indentify root causes of the accident and highlight weaknesses in the Health and Safety Management System which need to be strengthened in order to stop future occurrences. An accident investigation must not be focused on finding blame, since if this is the case the system will still be open to a recurrence and will not improve. In the most effective accident investigations, the employer should only suggest liability if no weaknesses were found in the Management System (Geigle Safety Group 2013)

"No activity in Safety and Health, Environmental and Quality management holds more potential for solving problems, reducing losses, preventing injuries and transforming an organisation from a traditional, reactive one to a progressive, proactive one, than incident investigation." (Germain & Rowan 1997).

In order to undertake an effective accident investigation a number of steps have to be followed (Geigle Safety Group 2013):

- Secure and document the scene
- Conduct interviews
- Obtain the relevant records
- Develop a sequence of events
- Conduct a cause analysis

- Determine the solutions
- Write a report

2.3.1 Secure and Document the accident scene

This is the first step in the investigation process and should be done as soon as possible. However, it is important that the emergency response is undertaken first and that it is safe to begin the investigation (Geigle Safety Group 2013). The investigation may begin as soon as the crisis has stopped, while the victim is comfortable or is receiving first aid and/or medical treatment (Nationwide Mutual Insurance Company 2013).

It is always important to secure the scene, preventing material evidence from being removed or relocated in any way. This has particular importance if there has been a serious injury which may warrant an investigation from a governing body (Geigle Safety Group 2013).

In certain cases the employer may be keen to restart production. However, it is of upmost importance to protect material evidence, as it is almost impossible to establish the root causes of an accident if related material evidence has been removed (Geigle Safety Group 2013). Therefore, focus should be placed on undertaking the investigation efficiently and not being governed by external pressures.

"One of the most critical and complex parts of the investigation is the gathering of evidence" (Rochester Insitutue of Technology 2010). Therefore, when a scene is secure, it is important to immediately start gathering evidence. One of the hardest aspects in respect of data gathering, is determining what is relevant and therefore needs to be recorded. It is important to note, that information can always be disregarded and it is better to have too much information than too little. In large scenes or serious accidents, there is a benefit of undertaking the investigation as a team, due to the amount of data to be collected and the response required. Information that may be relevant and investigated might be as follows (Geigle Safety Group 2013):

- Tools, equipment, materials etc. Do they appear to be broken or involved in the accident?

- Irregularities on surfaces. This can include skid marks, tracks, gouges, scratches, fluid spills etc. Were these factors involved?
- The time of day, location, lighting conditions, terrain etc. Additionally, any distractions, adverse conditions that may have contributed to the accident.
- The activities that were being undertaken around the accident scene.
- Who was there and who was not? This information is essential information to gather from the interview process.
- Obtain initial statements from the witnesses. In the initial statements the investigator should try to obtain the position of witnesses in relation the accident and what they saw. Also, include details of any materials which have been moved or disturbed following the incident.
- Measurements and positions of everything that the investigator feels relevant.
- Photographs of the scene. These photographs should be taken from different angles and positions (taking note of their location) in order to get a good overview of the scene.
- Sketch the accident scene.

2.3.2. Conduct Interviews

Once the scene has been secured and documented, the next stage in the investigation process, is to obtain additional information by conducting interviews. "The purpose of the interview process is to obtain a accurate and comprehensive picture of what happened". In order to do this, the investigator requires co-operation from the interviewee. The purpose of the interview is to establish information regarding hazardous conditions, unsafe working conditions and weaknesses in controls that may have contributed to the accident. Due to the sensitive nature of this information, it is very important to establish trust and a cooperative atmosphere between the interviewer and interviewee (Geigle Safety Group 2013).

Additionally, events should be as fresh as possible in the mind of persons involved (Nationwide Mutual Insurance Company 2013). Accidents can be traumatic events resulting in not only physical but psychological harm to the persons involved. With time, a person's memory will be affected and the thoughts and emotions of the individuals can alter. With this in mind, it is important to capture information before this happens (Geigle Safety Group 2013). In addition when asking a question, changing a single word in a question can systematically change a witnesses account of events (Loftus 1975).The Investigator should indentify the witnesses quickly and where possible separate them. Although, the legal system put prescience into ensure the physical traces found within a scene does not become contaminated. However, little cautions tends to be placed in the contamination of a witness memory (Wells & Loftus 2003). If witnesses are allowed to converse or compare stories the quality of the information could be compromised (Nationwide Mutual Insurance Company 2013).

Answers given by witness can often depend on the wording of question (Harris 1973), depending on the interviewee the approach by the accident investigator will be different and the questions will have to be designed specifically for each person (Geigle Safety Group 2013).

The Victim: Questions should be designed in order to gather information on the events immediately leading up to the accident.

Co-workers: Questions should be structured in order to obtain information on the "actual" procedures that are being undertaken be the employees of the organisation.

Direct supervisor: Questions should be asked in order to obtain background information on the victim. In addition, information in relation to procedures, training, workload and resources can be provided from the supervisor.

Manager: Questions should relate to obtaining information in relation to the Health and Safety Management System / Programs in place.

Training department: Questions should be designed in order to obtain information in relation to quantity\quality of training given to the victim and other related employees.

Personnel department: The investigator should obtain information on the victims and related employees work history, discipline, appraisals etc.

Maintenance personnel: Questions should relate to determining a background on the corrective and preventive maintenance of any equipment involved in the accident.

Emergency responders: The investigator should ask questions relating to the accident site and surrounding environment in terms of what they saw and did responding to the accident.

Medical personnel: Information should be obtained relating to medical issues with the victim. It must be noted that this information will be governed by law.

Coroner: The coroner can provide crucial information in relation to the type and extent of fatal injuries to the victim.

Police: Did they file a report relating to the accident ?

Other interested persons: Anyone interested in the accident may be a valuable source of information.

The victims spouse or family: People in close company to the victim may be able to provide a insight into their state of mind and any other relevant work related issues.

The key point in relation to conducting the interviews is to avoid finger-pointing and blame. This will ensure cooperation and that the information supplied will be of good quality (Geigle Safety Group 2013).

2.3.3. Obtain relevant records

The next stage in the investigation process is to obtain records that may be relevant to the incident. Records can include the maintenance record of equipment involved, permits to work, training certificates etc. The key point is to obtain "relevant" records and not be overwhelmed with paperwork (Geigle Safety Group 2013). Once obtained, the investigator should explore the information for its relevance to the particular case. This will aid the investigator to determine if there were any shortcomings having a direct effect on the event and therefore requiring further analysis.

2.3.4.Develop a Sequence of Events

The investigators challenge, at this point is to bring all the information obtained together, determining the sequence of events which led up to the incident (Geigle Safety Group 2013). Determining the sequence of events can be a painstaking task but it can greatly help in the identification of immediate, underlying and root causes of an incident (The Institution of Engineering and Technology 2012).

This can be done in the form of a diagram where the investigator can work back though the incident sequence in order to help define the contributing factors of the event. The diagram should be started as soon as the facts on the incident begin to be collected, developing as more information is brought to light by the investigation team (Livingston et al. 2001). It is essential for the investigation team to probe deeper into the accident, understanding the interaction of events through a chronological chain of activity to best identify the root cause(s) (Buys & Clark 1995). There are a number of methods that can be used in order to produce a sequence diagram such as:

- Event and Causal Factors Charting
- Multilinear Events Sequencing
- Sequentially Timed Events Plotting Procedure

2.3.4.1. Event and Causal Factors (ECF) Charting

A event and causal factors chart is used to identify and document all the events surrounding an incident from the beginning to the end, with factors, conditions, field barriers, energy flows etc discovered (Livingston et al. 2001). The centre of a ECF chart is a sequence of events that are plotted on a timeline from the initiation event to the incident itself (The Institution of Engineering and Technology 2012). In addition, joining in from the side are causal factors, barriers and changes displaying their effect on the events displayed in a graphical format. An example of a ECF chart is shown in Figure 9. While primary events are generally close in time to an unplanned outcome, secondary events are used to explain why a primary event may have occurred. A secondary event could be days, weeks or years back in time from the unplanned outcome and is generally an indication of a latent failure pathway that could become the focus of an investigation (Kingston et al. 2007).

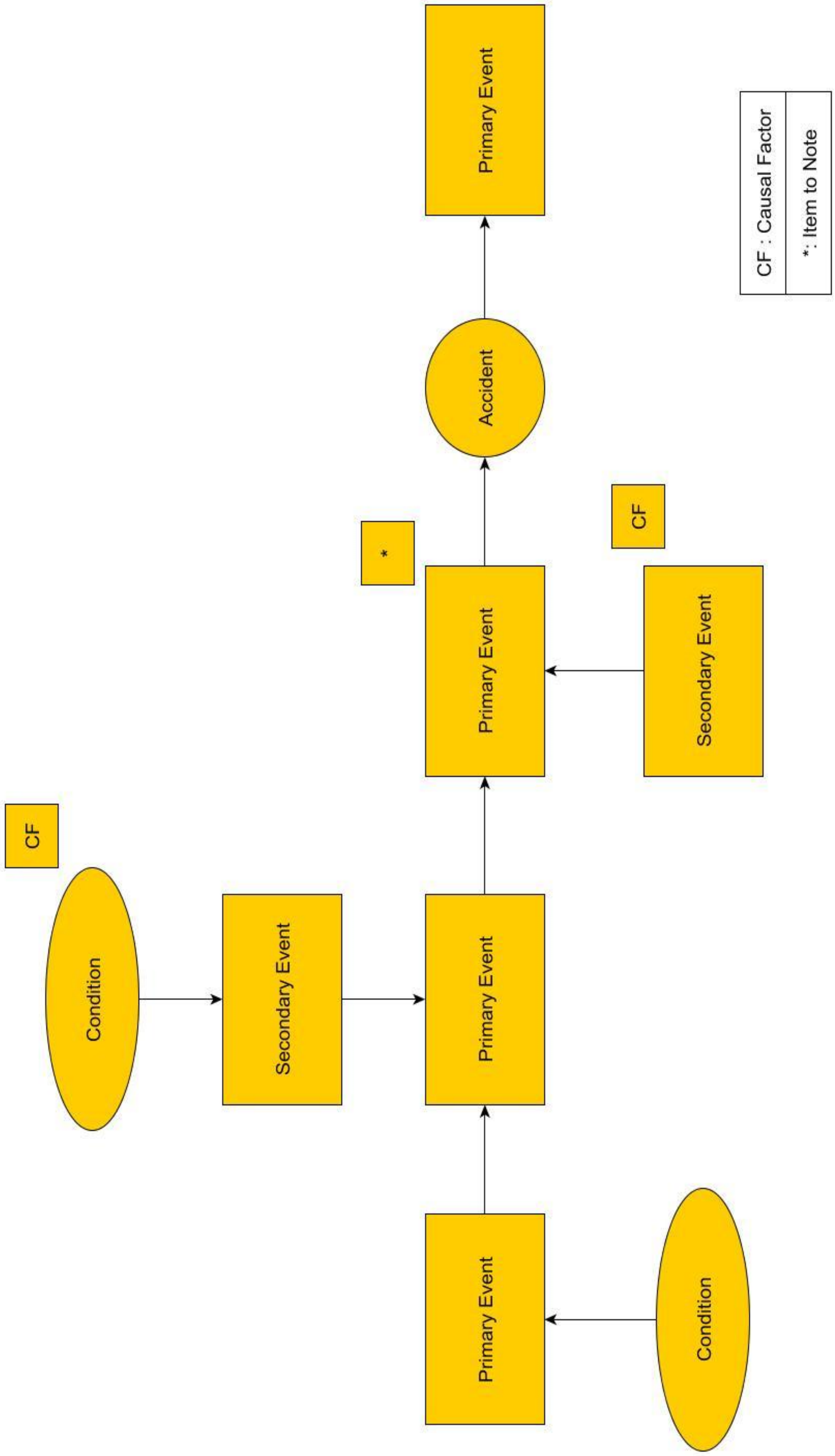


Figure 9: ECF Chart (Adapted from (OSHAcademy 2006)**)**

2.3.4.2. Multilinear Event Sequencing (MES)

In order for the investigator to use this method, firstly, actors, actions and events have to be defined. Actors can be people, equipment, substances etc, and actions are anything that is carried out by an action. An event is the result of the combination of an actor and an action. Following this, a time line is formed and the events are plotted horizontally across the page (resulting in the incident) in relation to the actors which are positioned vertically on the left hand side of the page (Livingston et al. 2001). An example of a MES diagram is shown in Figure 11. 'Conditions' are defined as passive states that contribute to an 'event' occurring, while the 'event' is the result of an 'action' performed by an 'actor' (not necessarily being a person).

2.3.4.3. Sequentially Timed Events Plotting Procedure (STEP)

STEP analysis is essentially a refinement of the MES technique (Livingston et al. 2001). Event blocks are organised into sequentially timed events with links showing causal relationships in the form of arrows (NASA 2000). A STEP analysis again utilises the same structure as MES, with the timeline shown in the middle and actors positioned to the left hand side of the document. An example of STEP procedure is shown in Figure 10.

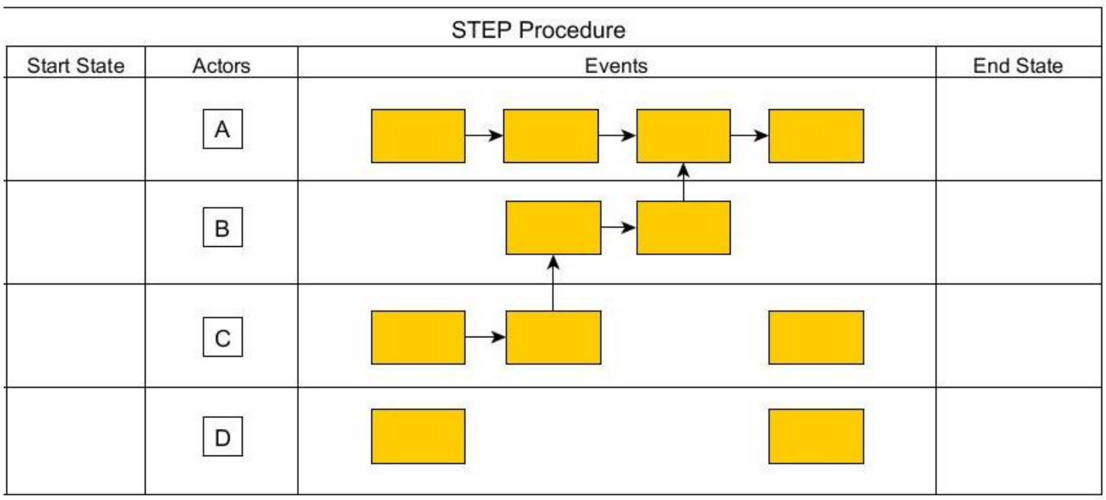


Figure 10: STEP Procedure (Adapted from (Livingston et al. 2001)**)**

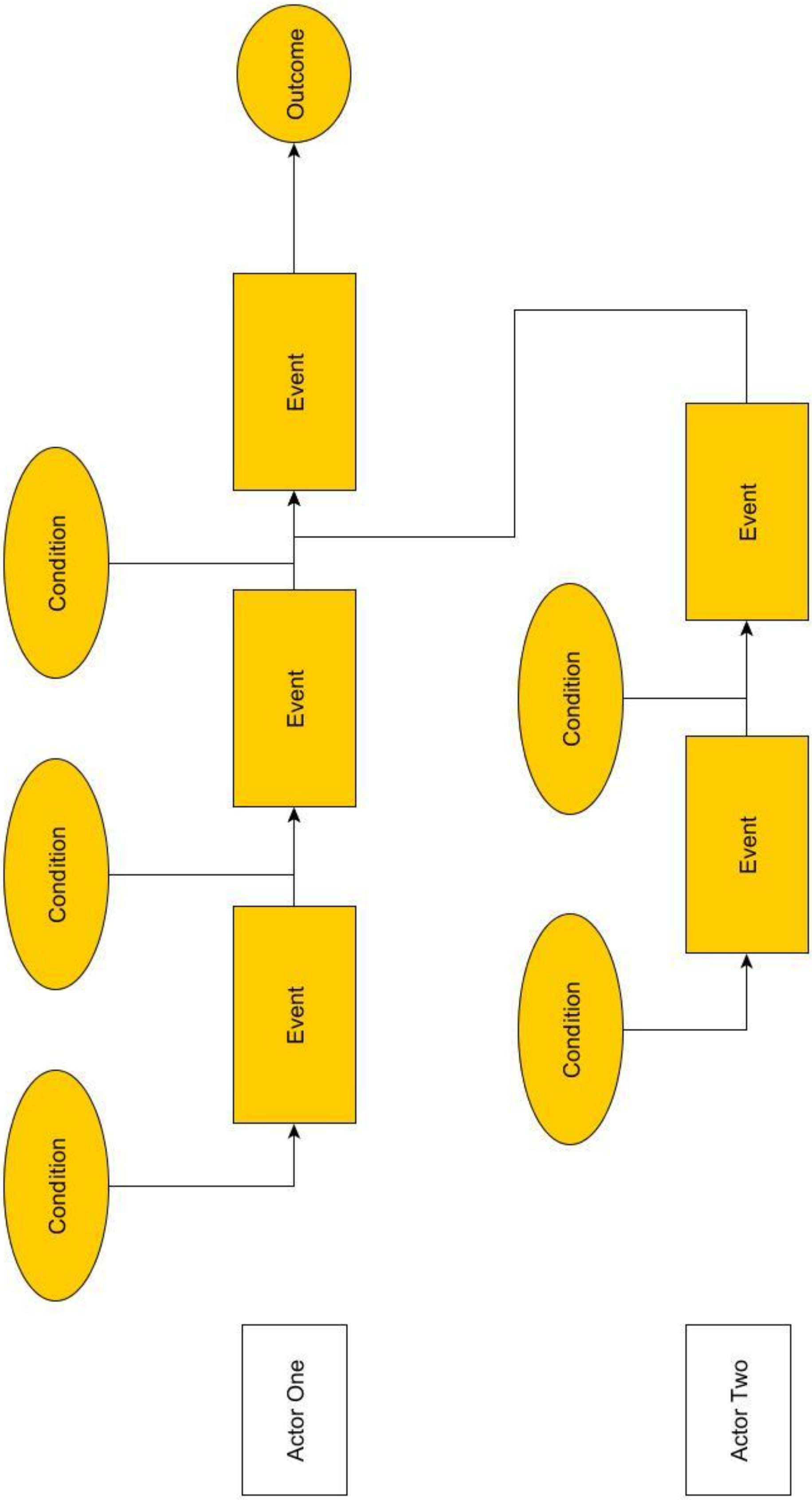


Figure 11: MES Diagram (Adapted from (Livingston et al. 2001)**)**

2.3.5. Conduct a Cause Analysis

Root Cause Analysis (RCA) is a problem solving process used by an accident investigator in order to identify the problem, concern or non conformity, which resulted in the incident. RCA requires the investigator to look beyond the solution to the immediate problem and understand the underlying, fundamental cause(s) of the situation (BRC Global Standards 2012). Identification of root causes are essential in order to ensure that there is not a recurrence of the same or similar accident. Once obtained, solutions to the failures are sought in the form of controls that are applied to the Health and Safety Management System, thus preventing future incidents.

The ultimate aim of a RCA is to answer the following question "What process or system failed so that a problem occurred resulting in an incident?" (BRC Global Standards 2012).

There is no specific one method of conducting a RCA and any structured approach which is sufficient to identifying a non-conformity could be used. Many methods have been published on RCA, the choice of methodology being a personal decision of the investigating team that best suits the non conformity and the company policy (BRC Global Standards 2012). As RCA is the fundamental purpose of an accident investigation, it requires particular attention and therefore a review of different RCA methods will be discussed later in this chapter.

Once all the data has been gathered, the investigator can draw conclusions from the information in order to determine what areas in the investigation require further focus or where more information may be required. Following this the underlying causes can be indentified and the next stage of the investigation can continue (BRC Global Standards 2012).

2.3.6. Determine the Solutions

When the immediate and underlying causes have been identified, the investigative process turns from being reactive to proactive in nature (Geigle Safety Group 2013). The proactive action will address the incident and then solutions (in the form of controls) will be applied to the safety management system in order to prevent future similar accidents.

Where risks should be reduced to a level that is As Low As Reasonably Practicable (ALARP) (HSE 2011b). Therefore, when determining solutions to prevent future incidents the hierarchy of control must be considered. This is where controls are ranked on their effectiveness in the order shown in Figure 12.

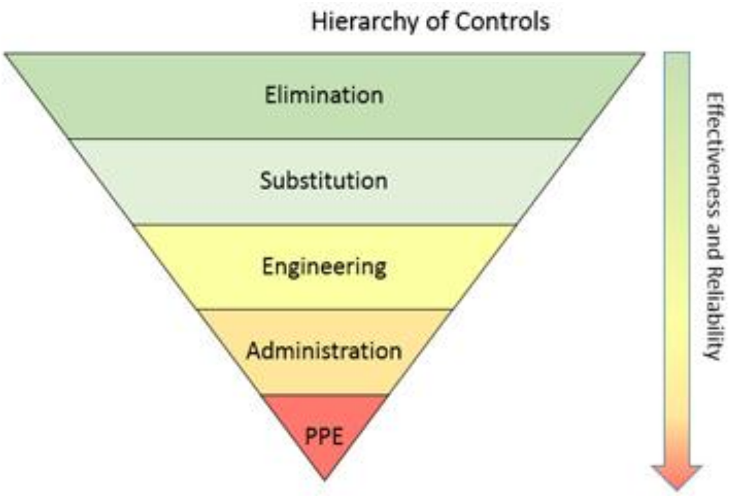


Figure 12: Hierarchy of Controls (Andrew 2013)

Elimination: This is a control that removes or eliminates the hazard through redesign of a work procedure. An example would be that the dutyholder must avoid working at height where possible (HSE 2011b). Elimination is the most effective form of control and should be used whenever possible (Canadian Centre for Occupational Health and Safety 2006).

Substitution: This is a control that replaces the process or material with a less hazardous one. An example would include using a Mobile Elevating Work Platform (MEWP) instead of using step ladders (HSE 2011b).

Engineering: This is a control that is designed to separate the hazard from the operator by using additional machinery or equipment as protection. For example, this could be guarding around dangerous equipment that prevents the operator being in contact with the hazard (HSE 2011b). However, engineering controls are only effective if they are designed, used and maintained properly (Canadian Centre for Occupational Health and Safety 2006).

Administration: These are controls that are used to identify and implement procedures that are needed to work safety and reduce the possibly of the hazard being released (HSE 2011b). Administration controls aim to change the way in which people work through training or warning an operator of the hazard using signage (Andrew 2013). An example would include risk and method statements, used to identify the hazards and specify a safe method of work.

Personal Protective Equipment PPE: This is where the person wears clothes or equipment that are designed to reduce the effect of a hazard (Andrew 2013). However, this form of control must only be used after all other higher ranked control measures have been considered and found to be ineffective (HSE 2011b). For example, a operator of a hammer drill may wear ear defenders in order to reduce the noise generated, reducing the possibility of hearing damage.

Once suitable controls have been selected an action plan should be produced in order to ensure their introduction into the system. The action plan should include a defined timescale in which the work is to be completed and the responsible person(s) to implement the changes identified. The final stage is to ensure the integrity of the process through monitoring and verification, which can include audits from internal and external sources to ensure compliance (BRC Global Standards 2012).

2.3.7. Write a Report

The final stage of the accident investigation process is to write a report of the event. This should be split up into key sections that aid in the explanation of the incident and the solutions applied to stop a reoccurrence. The sections should include the background to the incident, description of the accident, the findings of the investigation and the controls established, with details of implementation and monitoring (Geigle Safety Group 2013).

2.4. Root Cause Analysis Methods

When an accident occurs it is important for the management to understand how the incident happened. By understanding the failure, action changes can be made in order to prevent reoccurrence. Considering this, if an investigator(s) arrives at vague recommendations which are not fundamental for a company to implement effective controls, the investigation process may have been undertaken in vain (Livingston et al. 2001). Therefore, root cause analysis is essential in order to find the basic (or root) cause of the incident. There are a number of RCA techniques available some of which will be reviewed within this section, such as:

- 5 Whys Approach
- Management Oversight and Risk Tree (MORT)
- Control, Change, Cause Analysis (3CA)
- Ishikawa (Fishbone) Diagrams
- Systematic Accident Cause Analysis (SACA)

2.4.1. 5 Whys Approach

This method is a simple method in order to develop a structured root cause analysis. The investigator keeps asking the question "why?" until a meaningful conclusion is found. It is generally considered that this should be a minimum of 5 times, however certain cases require further interrogation in order to obtain the root cause (BRC Global Standards, 2012).

Figure 13 The 5 Why's Approach

<u>Example</u>

The following is an example of RCA using the 5 whys approach related to an accident investigation (Accident Investiagtion Solutions, 2011):

1. Why was the worker's finger crushed?

   His finger was caught between a moving pulley and belt.

2. Why was the finger caught between the pulley and the belt?

   The guard on the pulley was missing.

3. Why was the guard missing?

   A mechanic had overlooked replacing it.

4. Why was it overlooked?

There is no written equipment servicing checklist.

5. Why is there no checklist?

No Hazard Assessment has been completed.

The root cause of this accident is a managerial failure, resulting in a Hazard Assessment not having been completed. This needs to be rectified in order or to prevent reoccurrence of this type of accident.

The 5 why's approach has a number of benefits, such as:

- It helps identify the root causes of a problem
- It determines the relationship between different causes that may have an a larger impact on an organisation
- It is simple to undertake and complete without using complicated statistical analysis

However, there are a number of drawbacks, mainly due to the simplicity of this RCA technique and also where people unwittingly apply it wrongly. This results in problems which didn't actually cause the failure, being resolved inadvertently (Sondalini 2011). Additionally, there is no certain confirmation that the root cause has been found using this method.

2.4.2. Management Oversight and Risk Tree (MORT)

The Management Oversight and Risk Tree is an analytical procedure that allows investigators to determine the causes and contributing factors of an incident (Ferjencik & Kuracina 2008). The MORT technique is regarded by some as a checklist representation of a complex fault tree analysis (Santos-Reyes et al. 2009). The intention is to ensure that when the model is processed through the system, every level of an company's management is assessed for possible contributing causes (Santos-Reyes et al. 2009).

The MORT method is applied in three steps (Kingston et al. 2009):

Step 1 (what happened?): define the events to be analysed. In this stage the investigator evaluates a sequence diagram such as the methods which were previously explained within this chapter (Livingston et al. 2001) along with a barrier analysis. The barrier analysis is used to assess the transfer of energy from a harmful agent (such as an environmental condition or hazard) to a target and how barriers (or controls) performed to reduce the risk (Kingston et al. 2009).

Step 2 (Why?): characterise each event in relation to unwanted transfers of energy. In this stage the "energy exchanges" are evaluated further with the aim of understanding how harm, damage or danger was created from the transfer (Kingston et al. 2009).

Step 3 (How?): evaluation of unwanted energy transfers to establish if they were as a result of risk and its management (Kingston et al. 2009). In this stage the analyst determines how the accident may have occurred. This is achieved using a MORT chart, allowing the analyst to track their progress (Kingston et al. 2009).

When producing a MORT chart, the investigator must start at the top with the defined outcome of the incident, from there, working down the fault tree breaking down the incident further into more components connected via "AND" or "OR" gates. Upon discovery of basic causes (at the end of a chain), the analyst must establish whether the element is applicable to the incident. If it is determined not to be applicable, the element must be crossed out. For the remaining elements, the next question that needs to be asked is "was this item adequate ?". If not, then the element is marked in red. If more information is needed, the element is marked in blue and if the item is considered adequate, it is marked in green. The investigator must then gather more information on the blue items to establish if the item is adequate or not (Livingston et al. 2001). Following this, red items then need to be examined further to determine root cause(s). A MORT chart is highly visible, easily reviewed and updated if more material comes to light during the course of an investigation (Munson 1999). An example of a MORT chart is shown in Figure 14.

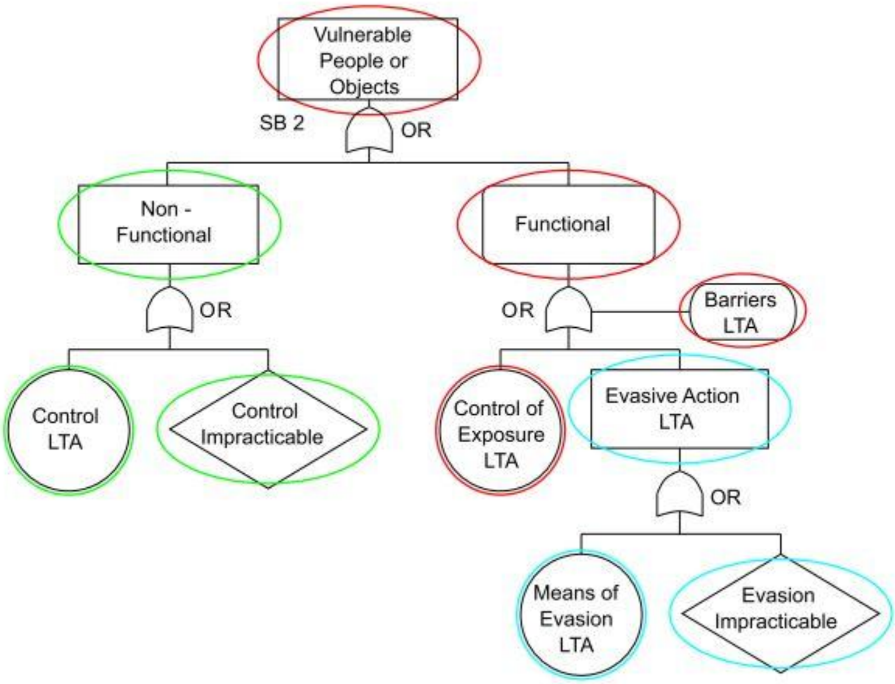


Figure 14: MORT Structure Example

2.4.3. Control, Change, Cause Analysis (3CA)

3CA is designed to help analysts structure and review their investigations (Kingston et al. 2008). In 3CA, the investigator must classify the incident as a series of events in which unwanted changes have occurred and classify which events were significant. If an event is deemed significant the investigator then must consider the preventive measures in place and assess them for adequacy (Kingston et al. 2008).

The preventative measures are then evaluated in order to establish where they were ineffective. Firstly, the investigator explores the tangible barriers and controls at an operational level. Following this, the investigator explores what was expected of the preventative measure and the actual performance. This difference in performance then forms the basis of the analysis and the investigator explores the factors influencing the barrier and the control inadequacy. Focus is placed on accounting for the differences with regard to responsible people employing the control and preventive systems in place, while considering organisational and safety culture factors that may have influenced the situation (Kingston et al. 2008). A schematic showing the sequence of analysis is shown in Figure 15.

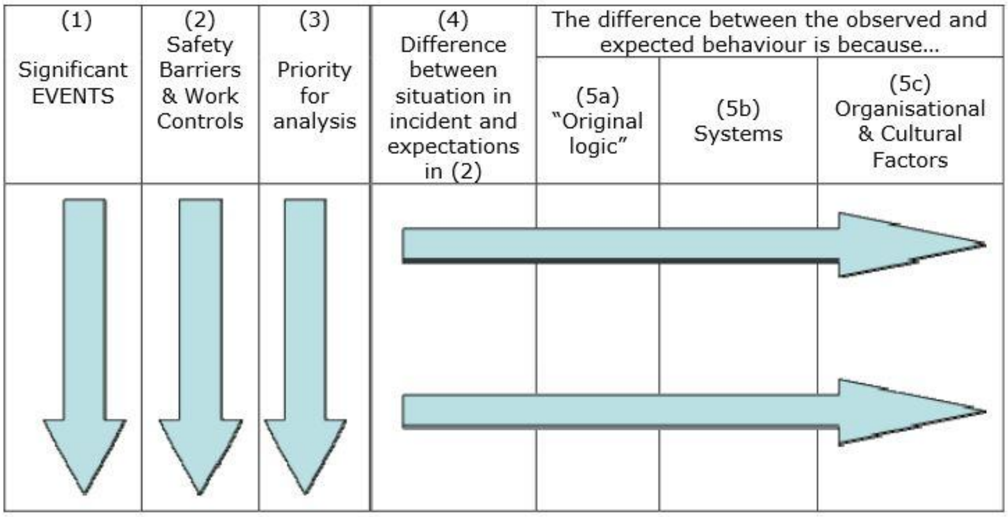


Figure 15: Schematic Showing a 3CA Timeline (Kingston et al. 2008)

2.4.4. Ishikawa (fishbone) Diagrams

A fishbone diagram can be applied to anything, allowing a situation to be broken down into an hierarchical set of factors that affected the end event (Hydro Tasmania 2010). Although, fishbone diagrams were originally developed as a quality control tool, the technique has been used in order to help identify root cause in relation to accident investigation.

In order to apply the diagram to an accident, firstly the investigator needs to write down the outcome of the event in a box on the right hand side of a page and draw a line horizontally from it across to the left hand side of the paper. A number of key categories should be identified such as materials, policies, systems, machines, people, surroundings etc. These then form the "bones of the fish" and drawn off the line from above and below illustrated in Figure 16 (Nelson 2012). The investigation team then brainstorms things that have an influence on the category breaking the diagram down further to another level. This is then repeated on the sub categories until it cannot be broken down again and therefore the root cause has been determined. These causes again like many of the other techniques have to be evaluated to determine if they are significant to the event. An example of a fishbone diagram is shown in Figure 16.

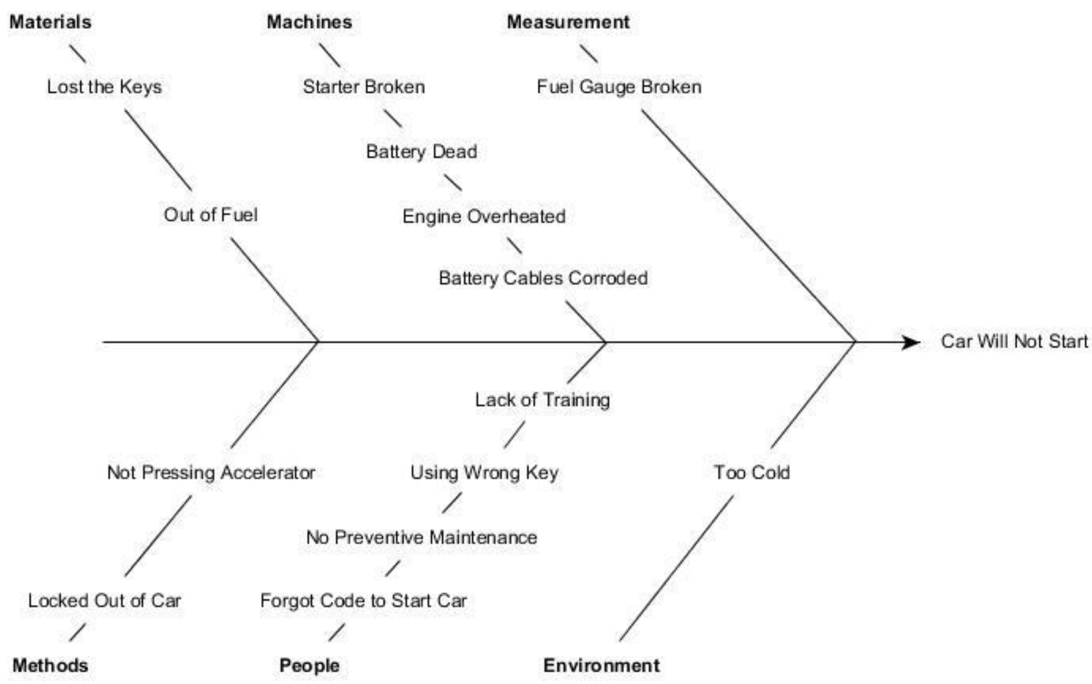


Figure 16: Ishikawa (fishbone) Diagram Example (McNeese 2005)

2.4.5. Systematic Accident Cause Analysis (SACA)

SACA is a checklist method of conducting a RCA and is undertaken in order to find multiple causes of incidents. The technique is based around a five step fault tree through a series of predefined yes\no questions (Hydro Tasmania 2010).

In order to perform a SACA, firstly the investigator needs to collect evidence and separate the information into specific categories. The five categories are as follows, people evidence, position evidence, paper evidence, parts evidence and re-enactment of the accident. Following this, the investigator must then consider the loss potential if the accident is not controlled. Then the investigator must define the group in which the hazard belongs such as equipment, machinery, explosive devices, electricity etc. SACA uses 25 predefined groups which the investigator can choose from (Hydro Tasmania 2010).

Thirdly, the investigator is then required to identify the immediate and direct causes from two defined lists; one for sub standard acts and the other for sub standard conditions. Each list contains a number of options relating to the cause, which the investigator can pick from, for example "use of unsafe/ substandard equipment" (Hydro Tasmania 2010).

The investigator then needs to answer two hundred and one questions across thirteen categories in order to identify the root causes of the incident. This step divides the root causes into three categories which are; personal factors, job factors and natural factors (Hydro Tasmania 2010).

Finally, the investigator is required to establish controls that will elevate the hazard and prevent reoccurrence, using a guided process of questions designed to ensure the control(s) are adequate to the event (Hydro Tasmania 2010).

2.5. Surveying of Accidents

An important part of an accident investigation is to be able to record the scene and provide a permanent record for future use. Surveying has been traditionally defined *"as a science of determining the position, in three dimensions, of natural and man-made features on or beneath the surface of the Earth"* (J.Uren, 2010).

The progression of survey equipment has been substantial over the years. This has resulted in the surveyor’s role being ever changing and having to diversify with the advances in technology. This section will provide an introduction into the advancement in selected technology and discuss the progression in terms of accident investigation surveying.

2.5.1. Advances in Data Acquisition

In order to obtain the position of a point, it is essential to obtain distance measurements and angular readings in both vertical and horizontal axes from a known location. To help obtain these readings a number of instruments have been developed over the years. The key instruments that have relevance to accident surveying are discussed below.

2.5.1.1. Distance Measurement

Initially, measurement of a distance was determined using body parts, while other forms of units of measurement were developed over time, resulting in regional changes around the world. However, in 1875 the Metre Convention was signed establishing a common form of measurement (National Physical Laboratory, 2010).

A number of methods have been developed over the years in order to establish accurate length measurement e.g. Gunter's chains, steel tapes, conventional tape measurement, rules etc (Uren & Price 2010). These methods are quite self explanatory and will not be discussed here. However, there have been a number of instruments developed to obtain a distance, which will be reviewed below.

Electromagnetic Distance Measurement (EDM)

The origin of EDM using a light beam can be traced back to 1938 when Erik Bergstrand, a Swedish physicist began exploring the possibility of measuring light using an optical shutter. Bergstrand, used a crystal oscillator to emit pulses of light over a known distance. He then measured the phase difference in the electronic wave, between an emitted light source and the received source after being reflected off a prism (Evergreen Valley College 2012).

After nine years of research, Bergstrand began to achieve consistent phase measurement. Following this, he approached a Swedish company (AGA) and suggested that this method could be used in order to obtain a measurement. AGA used Bergstrand's research in order to build a commercial product and branded it as a Geodimeter, launched in 1948. This was the start of the electronic measurement age, the first Geodimeter weighed more than 200 lbs and had a range of 30 to 35 km (Evergreen Valley College 2012). Tests undertaken at the time proved that the instruments accuracy was comparable with the best conventional measurement techniques.

Geodimeter launched Model 2 in 1955 with an increased range of 50km. From there, the company evolved quickly throughout the 1960s (Evergreen Valley College 2012), focusing on reducing the weight of the instrument and the time taken to obtain a measurement.

In 1963, the original tungsten light bulb was replaced with a high-pressure mercury vapour lamp in the Geodimeter 4D. This was a key development in EDM technology as it meant that the instrument could be used in daylight (Evergreen Valley College 2012).

The next major advancement came in 1966, when George Lesley replaced the mercury lamp with a three-milliwatt helium-neon gas laser and the instrument was renamed as the Geodimeter 4L (Evergreen Valley College 2012). The major benefit of using a laser was an increase in range of the instrument through moderate haze or bright sunlight due to the properties of a laser’s waveform (NOAA 2012).

Technological advances continued with the discovery of semiconductors changing the manufacture of the EDM again. In addition, transistors replaced the vacuum tubes which eliminated warm up time and considerably reduced measuring time (Evergreen Valley College 2012). The instrument that incorporated this technology was called a Geodimeter Model 6.

The invention of light emitting diodes (LEDs) followed and this reduced the size of the light source, while providing improved power consumption. LED and semiconductor technology was included in the Wild D1 10 Distomat. Wild continued to experiment with LED technology and designed an instrument that could measure 912 metres in 1966 and a commercial product was launched in 1969. At the same time, another manufacturer Hewlett Packard (HP) released its own EDM HP 3800B, which also incorporated LED technology and had a range of 2 miles (Evergreen Valley College 2012). These advancements began to expose surveyors to a form of distance measurement which was both accurate and fast in its application.

Tellurometer Distance Measurement

In 1955, a South African named Trevor Wadley was tasked by the South African Department of Trigonometrical Survey to develop an instrument of measurement with an accuracy better than 1 in 100,000 at distances of up to 30 miles for civilian and military applications (Sturman & Wright 2008). This system had to work off line of sight while providing accuracies of a few inches and being small enough to be carried by a man.

Wadley, developed the first prototype in remarkable time and tested an instrument on the 14th June 1955. The system comprised of two basic components, a master and a remote unit, where these components had to be set at either end of the line measured (Sturman & Wright 2008). A radio link was first established between the master and the remote, with the phase difference of the electromagnetic wave emitted, measured in units of time. The time was then converted into a distance by multiplying the result by the speed of a radio wave, then corrected for the refractive index of air. After further trials, the first Tellurometer MRA1 was put into production across 5 countries by 1957 (Sturman & Wright 2008).

Following this success, in 1959 the MRA2 was developed with this instrument housing both the Master and Remote function in the same unit. As the requirement for measuring a line was to measure the length from both ends to provide redundancy in the result. Therefore, the MRA2 proved beneficial as only one instrument was carried to each end, with half the number of batteries. Additionally, the MRA2 had the capability to automatically calculate the distance measured on board the instrument in both meters and centimetres (Sturman & Wright 2008).

In 1960, the next advancement in Tellurometer technology was achieved with the launch of the MRB2. This instrument was designed for hydro graphic applications, with one instrument fixed to a point on the land and another onto a ship that was always moving. The MRA3 followed with improved accuracy, utilising transistor technology and giving the operator a choice of three different measurement units (Sturman & Wright 2008).

In 1964, Tellurometer produced another new instrument the MRA101, which incorporated most of the circuitry on a Printed Circuit Board (PCB) and was considerably lighter than the MRA3. In addition, the development of the PCB allowed the instrument to be produced easily and a reduced cost, making the MRA101 the cheapest instrument intended for civilian use (Sturman & Wright 2008).

In 1966, the American Army specified the need for a similar instrument to the MRA101 but made more rugged with improved accuracy, considered fit for military use. The MRA4 was developed with military grade components, this included better sealing of the instrument and also improved temperature operation. The MRA4 also provided improved accuracy, however the additional components made the instrument bigger and heavier (Sturman & Wright 2008). Due to these drawbacks, in 1971 another instrument was introduced, the CA1000. The CA1000 was a completely redesigned instrument, incorporating a Gunn Diode which improved the power consumption and made significant weight savings. This resulted in a 16.4 kg weight saving of the physical instrument, due to the improved power consumption, which meant that the CA1000 required a much smaller and lighter battery (Sturman & Wright 2008).

The British Army then requested its own instrument to different specifications and oversaw the development of the MRA5 in 1973. One example of a modification was that the MRA5 provided the option to connect an antenna in various positions on the instrument or up to 25m away on top of a mast tip (Sturman & Wright 2008).

In 1983, two other instruments were introduced, the CMW6 for civilian use and the MRA6 for military applications. However, there was no difference between the instruments, apart from the name tag and the accessories supplied. Improvements of these instruments over the MRA5 included reduction in weight and improved range performance (Sturman & Wright 2008).

In 1985, the last development in terms of land based instrumentation using microwave emission was introduced in the form of the MRA7. The MRA7 mass was 4kg and had a number of safety additions that prevented the instrument affecting communications and data linkage in deep mines. However, the range and accuracy was similar to that of the MRA3 that was developed 30 years earlier. The modern version of the MRA7 is still used and developed to this day with few reported problems (Sturman & Wright 2008).

2.5.1.2.Angular Measurement

Theodolite

The evolution of the theodolite began in a description of an instrument in a book by Leonard Digges in 1571, entitled Pantometria (Surveyors Historical Society 1994). The instrument called a "Theodolitus" consisted of a graduated horizontal circle, mounted centrally on a vertical column, to which a graduate semicircle was attached. The surveyor would sight to objects and read the difference on the scale in order to obtain the angle. Following this in 1653, William Leybourn described an instrument called a theodolite made to a similar specification (Wallis 2005). A drawing of Leybourn's theodolite is shown in Figure 17.

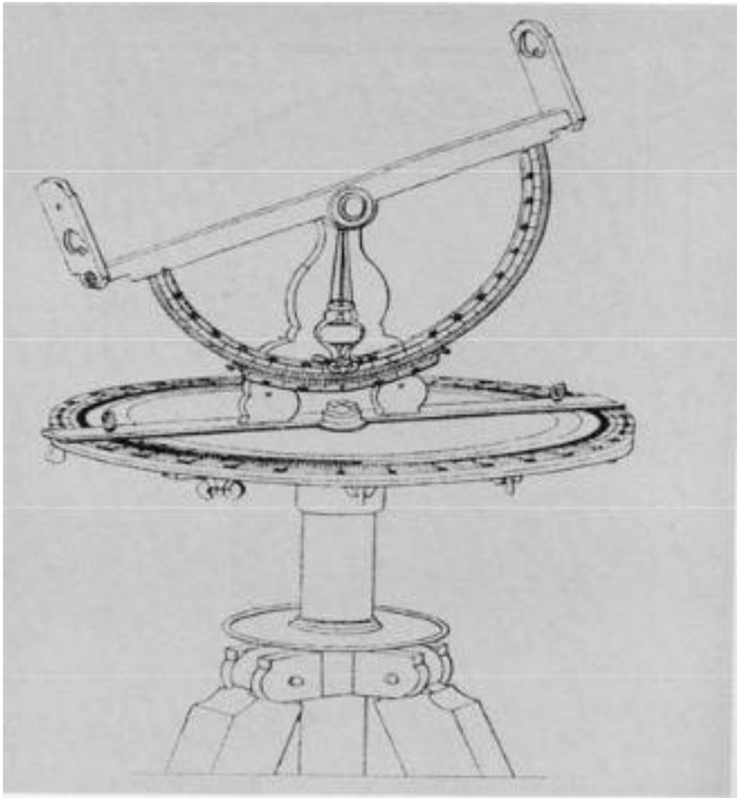


Figure 17: Leybourn's Theodolite (Wallis 2005)

The theodolite continued to develop, with advancements in dividing of angles to improve the accuracy of the measurement. This was achieved with the invention of Vernier dividing circles and the development of the dividing engine (Wallis 2005). The dividing engine was the invention of the instrument maker Jesse Ramsden in 1773. The dividing engine was integrated into the theodolite and an instrument called the great theodolite was created for use in the first ordinance survey in southern Britain in 1787 (Surveyors Historical Society 1994). The completed instrument had a horizontal circle of 36 inches with 6 micrometers each capable of reading to one second of arc. The great theodolite is shown in Figure 18.

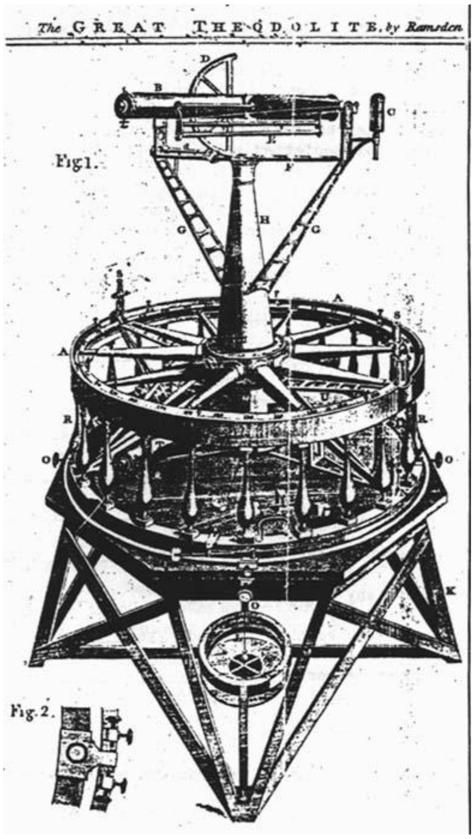


Figure 18: The Great Theodolite (Surveyors Historical Society 1994)

As theodolites developed, makers tried to make the instruments smaller and lighter. This was achieved through improvements in dividing circles which also became smaller while maintaining a high degree of accuracy. The theodolites described above continued to be produced until the late 20th century (Wallis 2005).

The next fundamental change to the theodolite, came with the introduction of the glass circle theodolite by Heinrich Wild in the 1920s (Wallis 2005). The TH1 theodolite designed by Wild, was produced in collaboration with Zeiss of Jena. The TH1 read an accuracy of 2 seconds of arc by digital micrometer and was the smallest\lightest instrument ever produced, with the exception of the Kern DKM1 (also designed by Wild) (Wallis 2005).

The TH1 theodolite used glass circles that were etched with graduations of angular measurements that could be read through a magnifying scope on the instrument (National Ocean Service 2012). An example of the reading window of the Wild T2 theodolite is shown in Figure 19.

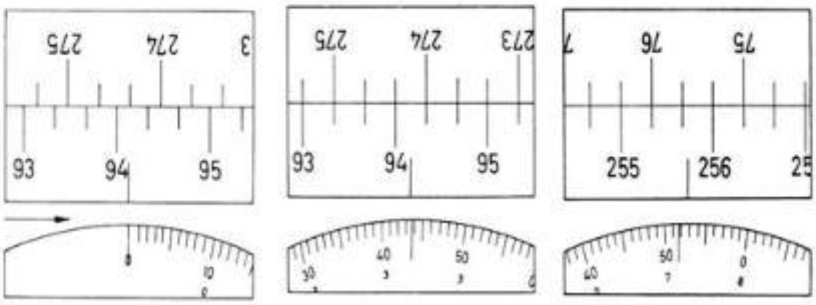


Figure 19: View of Angular Reading on Wild T2 Theodolite (Wallis 2005)

By 1969 the survey industry had changed considerably, driven by changes in technology and also increased investment in the construction industry. Companies began to make the instruments smaller, while also mounting distance measurement devices onto conventional angle measurement equipment (such as a theodolite).

The next major development in surveying came with the invention of the microchip in 1979. Electronic theodolites were combined with microchip technology and the total station was born, the name derived from a Hewlett Packard model. Although the technology was in its infancy it began to revolutionise the surveying industry (Tiller 1990).

Additionally, the development of tilt sensors also played a big part. The development of electronic circle measuring systems meant that angles could be obtained digitally. In most electronic theodolites or total stations this was achieved by using a photo lithographically coded circle on the base that rotated with the movement of the instrument. The movement of the coded circle is detected by a photodiode. Put simply, electronic measuring systems consist of glass circles with black and white segments (forming a binary code) etched into them which change when the instrument is turned. Light is passed through the glass, stationary photodiodes read the varying light intensity, this signal is then passed through an incremental decoder and that converts the signal into an angle (Tiller 1990). The initial electronic instruments were not much larger than the conventional analogue equipment, however they required external power supplies that added extra weight. As the electronics industry progressed and the components improved, less power was required. Also, advancements in power storage have provided smaller and more efficient batteries that could be stored within the instrument itself (Wallis 2005).

In the early development of electronic circle measuring devices, the accuracies that the systems could obtain were limited, as the circle had to be divided many times in order to obtain a high degree of accuracy. For example, in order to obtain a 1'' accuracy the circle would have to be dissected 1,296,000 times (Kennie & Petrie 2009).

The accuracy required of the circle measuring devices is dependent on the survey being undertaken, with instruments having varying degrees of accuracy and cost (Caulfield 2009). Below is a list of the possible instrument accuracies and the effect they have on a reading (Caulfield 2009).

20'' is equivalent to 10mm error at a sighting distance of 100m
10'' is equivalent to 5mm error at a sighting distance of 100m
5'' is equivalent to 2.5mm error at a sighting distance of 100m
1'' is equivalent to 0.5mm error at a sighting distance of 100m

A vertical angle is obtained using a very similar method to that of the horizontal measurement stated above. However the difference comes when the instrument is switched on, since the telescope could be in a position that isn't perfectly horizontal. With this in mind, the photo lithographically coded circle has an indication of where the exact horizontal position of the telescope is and angles are calculated relative to this (Tiller 1990).

The second unique feature that was developed in electronic theodolites was the ability to compensate the vertical and horizontal angle readings with regard to tilt in the instrument, as a difference in the vertical axis of the theodolite will result in a change in the angle reading. Therefore, electronic tilt devices were developed in order to prevent this and apply any correction to the reading when it is computed. A compensation system can be based on the reflection of a light spot from a liquid surface. Liquid by its nature will always remain level and therefore is used as a bench mark for the system (Kennie & Petrie 2009). A light source is passed through various pieces of optical equipment with the electrical current emitted changing in relation to the liquid. This current difference can then be computed into a value for inclination of the instrument (Kennie & Petrie, 1993).

Modern theodolites incorporate high levels of computing power that allow calculations to be made on board the instrument, increasing the speed of the surveying process considerably (Wallis 2005). A sectional image showing the major components of a modern total station is shown in Figure 20.

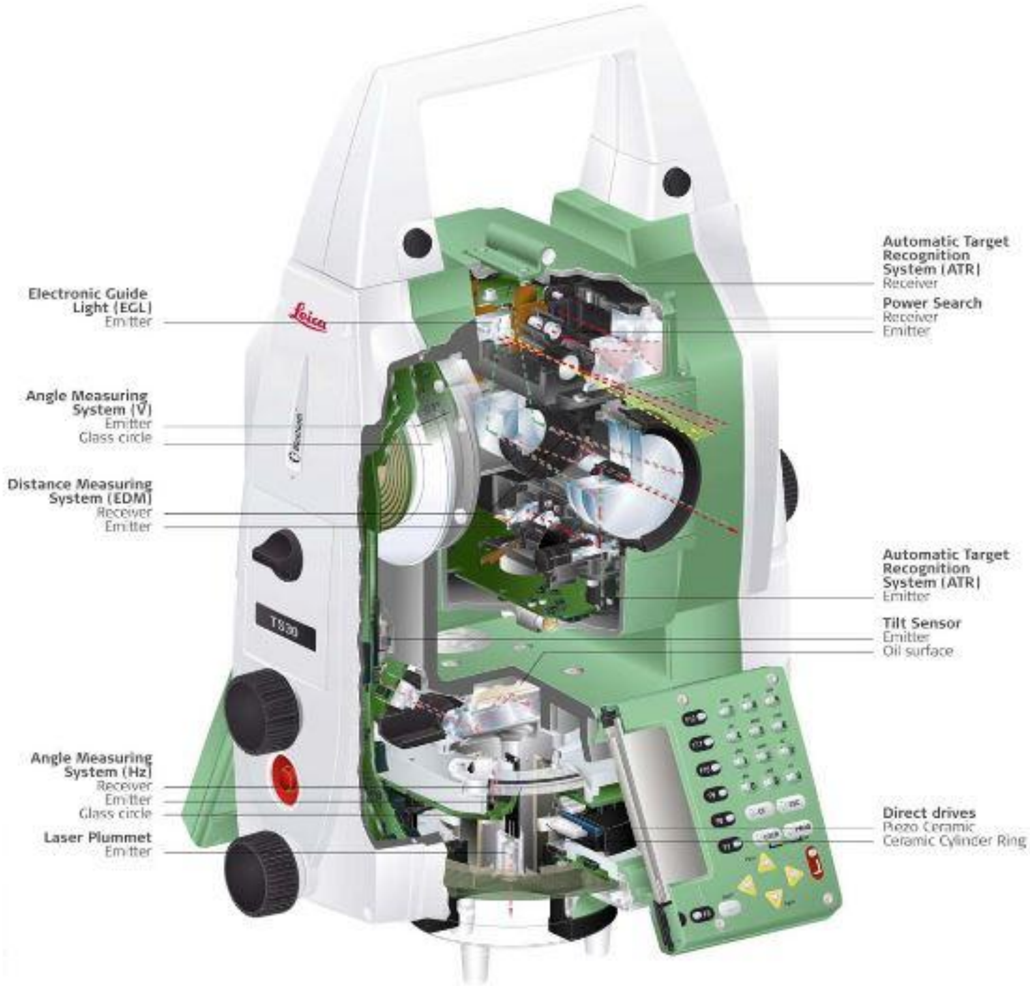


Figure 20: Modern Leica 1200 Total Station (Easydrive 2013)

2.5.1.3.Global Positioning Systems(GPS)

The history of GPS began with the launch of the Russian satellite Sputnik in 1957. The Massachusetts Institute of Technology (MIT) explored tracking Sputnik using radio waves, since MIT noticed that the satellite's emitted signal varied in strength depending on its position. These changes in the signal provided the ability for researchers to accurately predict the position of the satellite over time (Faucheux 2011).

Following this in the early 1960s The American Department of Defence (DOD) wanted to develop a global, all weather, continuously available and highly accurate navigation system. This system could be used for a broad spectrum of uses while having the ability to deploy a precision weapon system (Parkinson 1994).

In order to achieve this, the US Navy sponsored two programs Transit and Timation:

Transit was a program developed by the John Hopkins Applied Physics Laboratory under Dr. Richard Kirschner and became the first operational satellite based navigation system in 1964. Transit consists of 7 low-altitude polar orbiting satellites that submit very stable radio signals, which users exploit to determine their position. This is achieved by measuring the phase shifts in the signals transmitted by the satellites. Originally, Transit was developed to meet the US Navy's requirement to be able to locate a submarine’s relative position to ships on the ocean surface. Transit was made available for civilian use in 1967 and was quickly adopted by a large number of commercial marine navigators. However, Transit was susceptible however to a number of errors in respect of coverage and accuracy (Pace et al. 1995).

The Timation project team developed a system utilising highly stable space based clocks in order to achieve a precise time transfer between the satellites and a receiver (Pace et al. 1995). The difference in time determined the distance of the satellites from the receiver and by utilising a number of satellites, a position could be found through triangulation (Kaplan & Hegarty 2005). Initially, the system used two satellites and allowed for two-dimensional navigation (Pace et al. 1995), which was considered appropriate for marine vessels travelling at sea level (i.e. zero elevation).

At the same time as the Transit and Timation projects were being undertaken, the US Air Force was developing its own system '621B'. System 621B used Pseudorandom noise (PRN), which involved modulation of signals sent from 3 satellites based at different inclination angles. Although, system 621B was still under development it provided the theory to obtain three-dimensional measurement (Kaplan & Hegarty 2005).

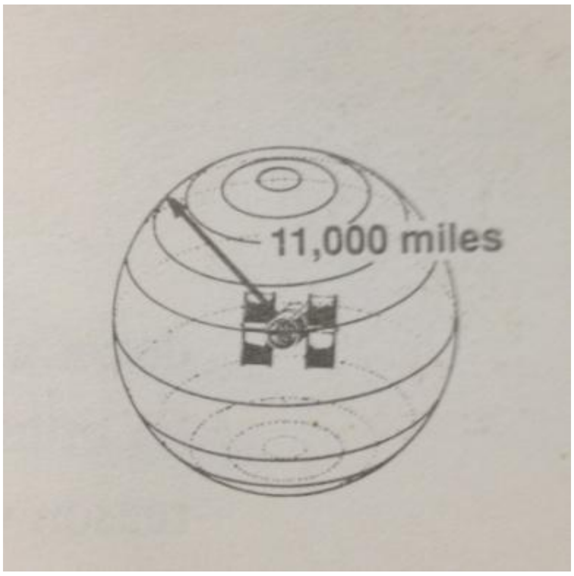
In 1969, the Office of the Secretary of Defence (OSD) consolidated the three programs from the Air Force and Navy to establish the Defence Navigation Satellite System (DNSS). Additionally, the OSD established the Navigation Satellite Executive Steering Group to oversee the developments made by the

DNSS. From this collaboration, the NAVSTAR GPS program was formed in order to establish a satellite network that would provide stable and accurate location measurement in three dimensions (Kaplan & Hegarty 2005).

Fundamentally, GPS is a navigation technique that is based on a number of satellites that are continuously broadcasting data on their positions as they orbit the earth. The user uses a GPS receiver in order to measure the time taken for a signal to cover the distance from the satellite (Price 1983). This process is undertaken using a number of satellites at the same time, enabling the user to obtain a three-dimensional position, from a minimum of three satellites (Hurn 1989).

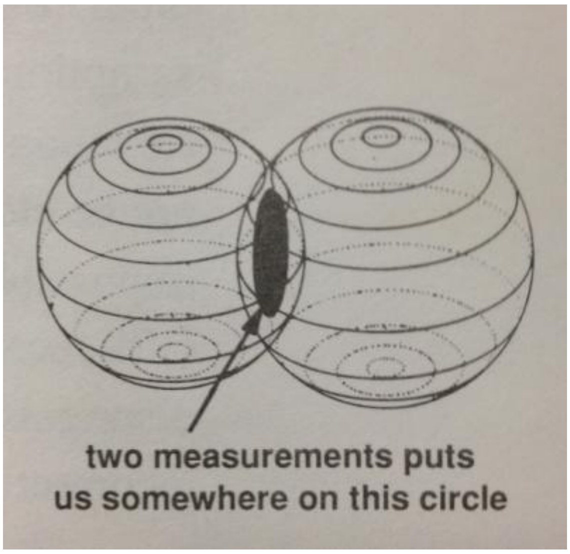
For example:

The surveyor receives a signal from satellite A, and determines that the distance from the signal emitted by the atomic clock on the satellite is calculated to be 11,000 miles. This means that the position of the receiver is somewhere in the sphere around the satellite with a 11,000 mile radius.



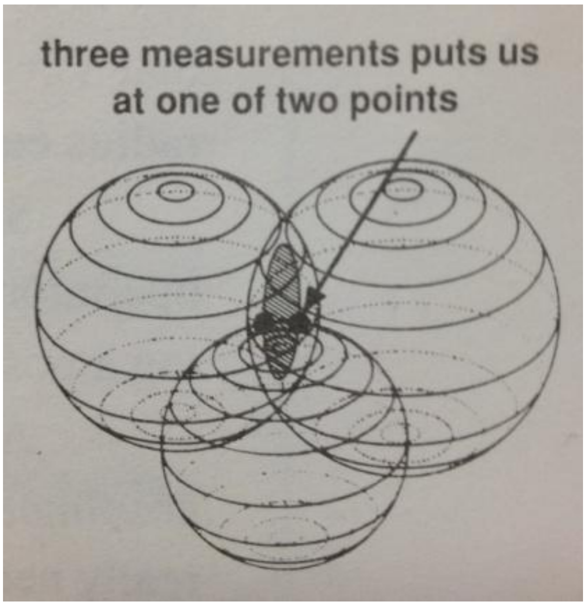
GPS Position Using 1 Satellite (Hurn 1989)

Now when the surveyor receives a signal from another satellite i.e. Satellite B, this is 12,000 miles from the receiver. This then means the only place the receiver can be, is somewhere in the dissection between the two spheres.



GPS Position Using 2 Satellites (Hurn 1989)

Following this, if the surveyor also receives a signal from a third satellite i.e. Satellite C, this is 13,000 miles away from the receiver. This then means that the receiver is in one of two positions where the sphere from satellite C dissects A and B.



GPS Position using 3 Satellites (Hurn 1989)

In order to determine in which of the two positions the receiver is located, a forth satellite could be used, with the intersection providing the users location. This would be the conventional practice today, as receivers have improved dramatically. However before these improvements the position could be obtained by elimination, as one result would be highly improbable as the point may not be even close to Earth (Hurn 1989).

This example was a simple one, as receivers and surveyors have to account for error that can arise from a number of factors. However, these methods will not be discussed here as GPS has little relevance to this research, except in the orientation of survey instrument locations in the absence of other geo-referenced points.

2.5.1.4. Laser Scanning

The first development of laser scanning technology originated in the 1960s, when early laser scanners used lights, cameras and projectors to record objects in 3D. There were multiple limitations in this approach, particularly with regard to the speed and accuracy of the data recorded. In 1985, a breakthrough in development of laser scanning occurred, when laser measurement technology was implemented into the system (Hoover 2011).

Laser scanners of this type appeared on the market in 1997/8. However, there is considerable debate as to which company were first to release the technology. There were two clear pioneering organisations, these being an Austrian company called Riegl and an American company called CYRAX (Staiger 2011).

Modern laser scanners capture data using EDM and electronically capture angular measurement to compute a position, much like the technology used in total stations and their development has largely been driven by similar technological advancements. Fundamentally, there are two types of laser scanners available;

Pulse Based Systems (Time of Flight): These instruments emit a laser light pulse that is transmitted through a telescope to a target, where the pulse reflects off the object and returns to the instrument. The time taken for the round trip is accurately timed and then converted into a distance (Höglund & Large 2003). Time of Flight instruments obtain measurements in a way that is very similar to that of total station measurement. However, a laser scanner can accurately gather positional data of an object up to a 1000 times faster (Hiremagalur et al. 2007).This is driven by the high computing power of the instrument and its indiscriminate data collection since the instrument does not have to be pointed at a reference object.

Phase Based Systems: These instruments use the phase shift of an emitted beam to one returned, to determine a distance. Where, the target distance is proportional to the phase difference and the wave length of the amplitude modulated continuous laser beam signal. The measurement signal is modulated onto a carrier frequency and is comparable to the principle by which music is transmitted via a radio signal (Höglund & Large 2003). Also, the amplitude of the returned waves provides information on the signal strength, which can be affected by a variety of different factors e.g. atmospheric factors, or the material of the sighted object (Hiremagalur et al. 2007). These methods can be expressed in the schematic shown in Figure 21.

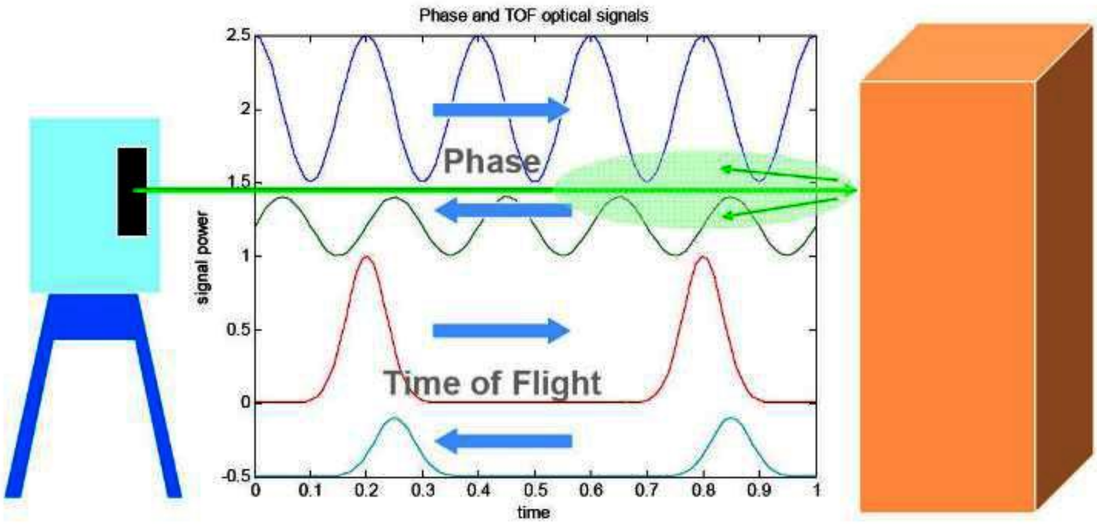


Figure 21: Schematic Demonstration Phase and TOF Measurement Techniques (Hiremagalur et al. 2007)

Due to the intensity of the beam that is emitted in the pulse, Time of Flight (TOF) scanners can offer long range measurement as the signal is less susceptible to retardation (Höglund & Large 2003). However, due to the TOF methodology of calculating distance from a round trip measurement, a disadvantage is lower measurement frequency by comparison to phase based systems (Staiger 2011). Modern phase based systems are capable of recording 1 million points per second. Due to the number of factors that have to be considered, equipment selection is largely governed by environmental constraints of the surveyed area.

Since the appearance of the first laser scanners, there have been considerable improvements with regard to measurement speed, accuracy and general usability. In addition, the price, size and weight of the equipment has also been reduced with technological advancements. The development of laser scanners can be divided roughly into 4 main generations (Staiger 2011):

1st generation (1997-2002): These laser scanners were all pulse based systems. Instruments invariably looked like prototypes, being bulky, with external power supplies and data storage devices. The measurement frequency used, lay between 1 and 5 kHz, providing a range of 50 to 200m (Staiger 2011).

Figure 22: CYRAX 2200 (CyArk 2001)

2nd generation (2002-2007): These instruments became faster and with greater range, but the power supplies and data storage remained external. In addition, in this period the first phase based instruments began to appear on the market (Staiger 2011). Phase based instruments were considerably more compact but still relied on external additions.

Figure 23: Z and F Imager 5003 (Zoller and Frohlich 2012)

3rd generation (2007-2009): Again the speed and range of the instruments improved, for example the Riegl LMS Z-420i has a range of up to 1km. In addition, manufacturers started to integrate power supplies and data storage within the instruments, thus improving usability. Also, digital imagery began to be mapped onto point clouds to provide visual and geometrically accurate 3D recorded environments. Laser scanners became aligned with conventional surveying equipment through the use of dual compensators, target identification and GPS attachments to aid in geo-referencing surveys (Staiger 2011). Advancements were also made in onboard computing where many instruments could be operated remotely via a wireless internet connection.

Figure 24: Riegl LMS Z-420i (Riegl 2014)

4th generation (2009-onwards): This generation of laser scanners have power supplies and data storage fully integrated within the instruments. Improvements have been made again in range, speed of data acquisition, and accuracy with instruments offering data collection of up to 1 million points per second and others with ranges of 6km. In addition, Riegl introduced instruments with full waveform analysis, allowing the instrument to receive multiple returns from one measurement (Staiger 2011). Manufacturers also added the ability to automatically detect targets placed within the surveyed scene to improve the integration of laser scanning into conventional surveying processes.

Figure 25: Leica ScanStation P20 (Leica Geosystems 2014)

Terrestrial laser scanners have become very popular and are increasingly used in a variety of different surveying applications. They have the ability to measure millions of accurate 3D data points that collectively are referred to as a point cloud. The point cloud in many applications requires post processing to extract the relevant information by the end user (Hiremagalur et al. 2007). With this in mind, throughout the development, there have been considerable advancements in software applications used to process the data obtained.

2.5.2. Developments in Accident Surveying

The process of gathering data has changed very little over a number of years although technology has advanced. Traditionally, surveys were carried out using tape measures and theodolites, with plans then being hand drawn by the surveyor in the office. This can be demonstrated by a historical review of notable accident surveys given below:

2.5.2.1. Accidents in Mines by Arthur Robert Sawyer (1886)

This book (Sawyer 1886) is one of the earliest publications detailing accidents in an underground environment. It seeks to reconstruct events in an attempt to investigate the cause of the accident in order to prevent reoccurrence. Sawyer states in the preface of the book *"My intention, besides describing the mode of timbering and supporting the roof generally, has been to show how some of these accidents are caused, and to point to different precautions which, in my opinion, would lead to their diminution in the mines ..."*. Sawyer undertook a detailed examination of 284 accidents over a number of years**,** during his time as HM Inspector of Mines, This examination resulted in the production of a number of plans and sections designed to illustrate how and under what circumstances the accidents occurred. An example of one of the illustrations of the site of the accident is shown in Figure 26.

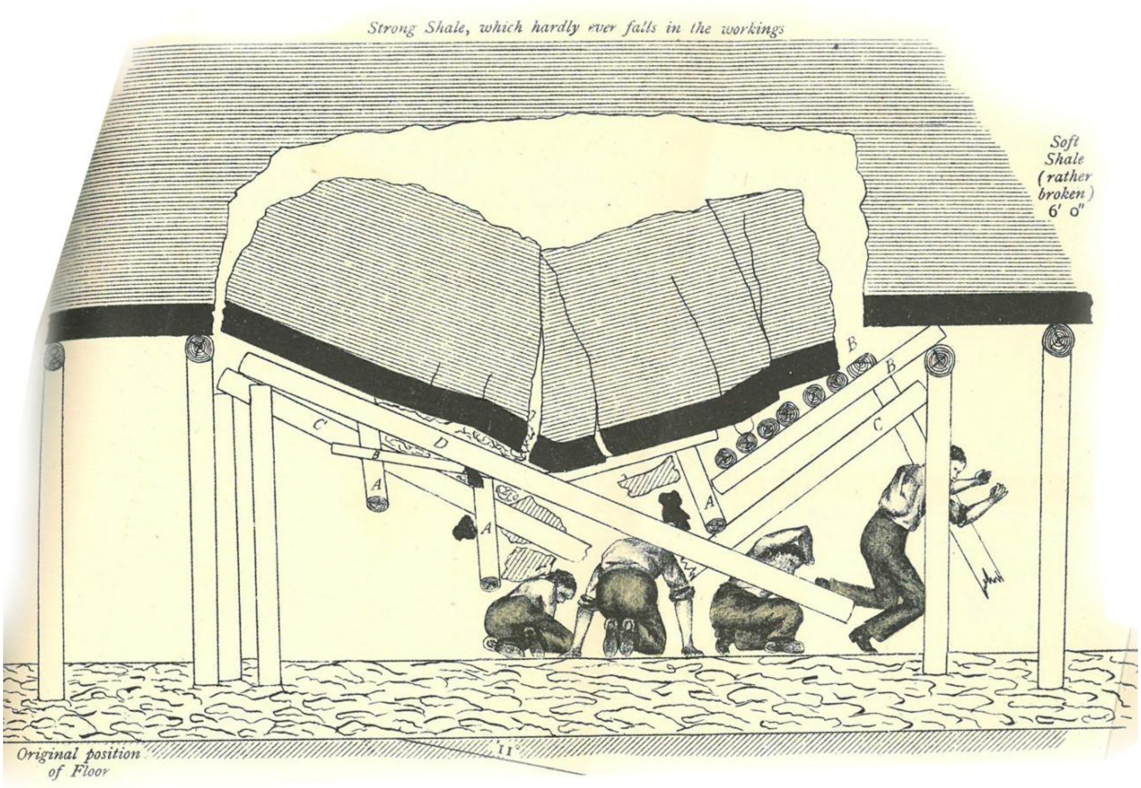


Figure 26: Illustration of an accident by R.Sawyer

Sawyer provided, in all cases, a plan view and in many instances supplemented this by a sectional view produced in two dimensions (2D). The representations are extremely detailed and would have involved a considerable amount of time in taking measurements at the site of the accident. Given the limited surveying equipment and techniques which would have been available at the end of the 19th century, it is commendable that one person would have devoted so much time to producing this evidence. The drawings represent geo-spatial data and cover the same criteria which is still specified when undertaking a detailed survey today, some two centuries later.

2.5.2.2. Minnie Pit Explosion (1918)

In contrast to the previous example which illustrates attention to detail over a small reference area, accidents can occur over a wider locality, in which, the same attention to detail may not be appropriate. The following example is given from an explosion in a mine where a large geographical area was affected.

In 1918, an explosion occurred at Minnie Pit in which 155 men and boys were killed (Baker 2002). The Minnie Pit explosion is a good example of how an effective accident investigation could save lives, but if ignored, could result in tragedy. The Minnie Pit had suffered two previous explosions in 1898 and 1915. The explosion in 1898 resulted in no loss of life and the other in 1915 resulted in 'limited loss of life' (9 miners) as it occurred on a weekend (Lumsdon 2010). Having two explosions should have indicated underlying problems and raised concerns, however *"Coal Barons of the day were more interested in production than in safe working conditions"* (Lumsdon 2010). An expanded section of the plan is shown in Figure 27.

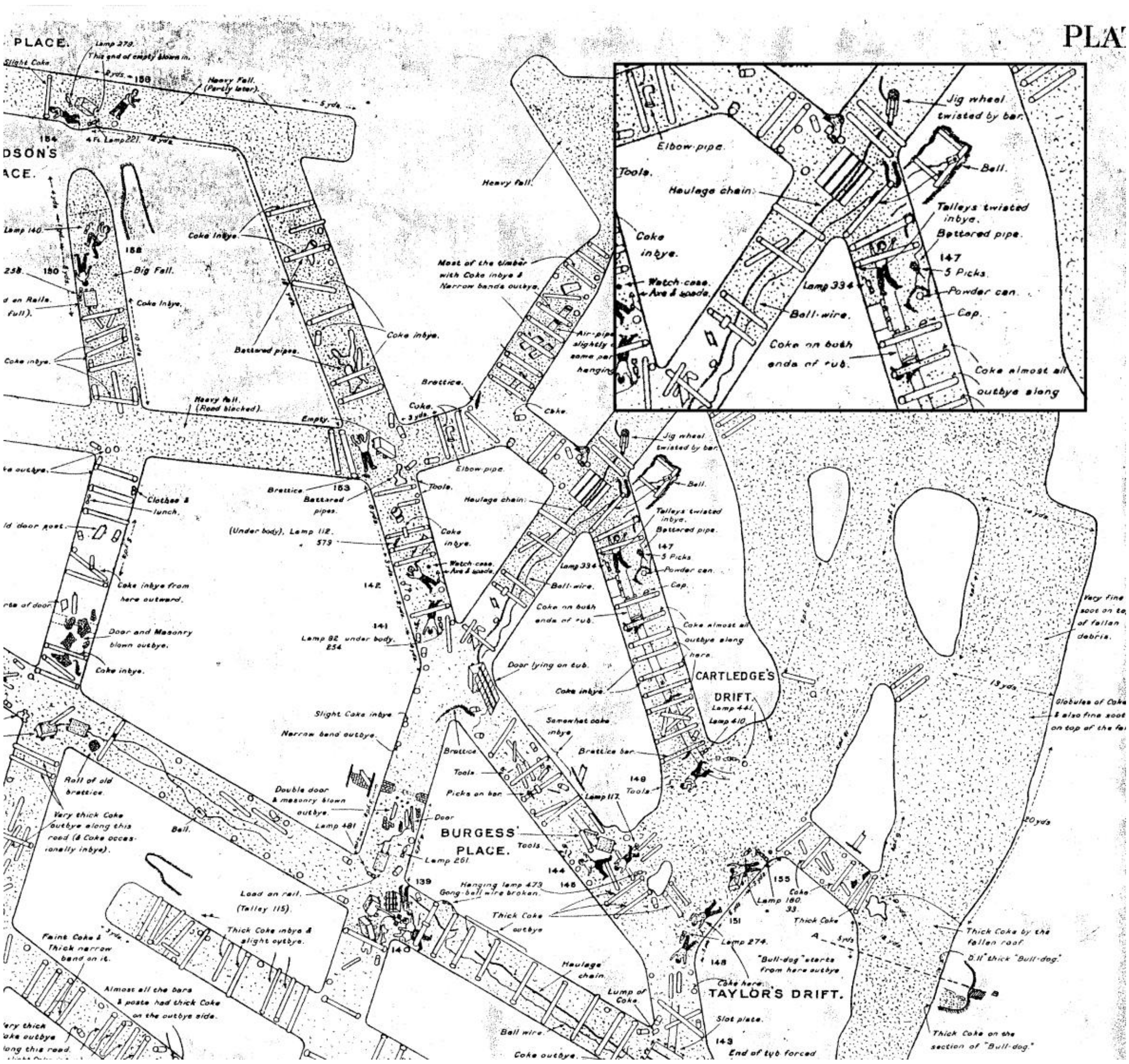


Figure 27: Plan of Minnie Pits accident area

The plan of the incident in 1918 can be seen to identify geo-spatial data. However, the plan does little more than provide a basic record of key features, such as the location of fatalities and equipment involved in the accident, and would not be used to recreate events.

2.5.2.3. Tower Colliery Explosion (1962)

An accident report of an explosion in Tower Colliery in Glamorganshire has been reviewed, where sadly 9 miners were killed during a explosion (Leigh 1962). HM Inspector of Mines, Mr Leigh concluded that the explosion was caused *"by a severe short circuit to earth in an electric cable in the presence of a body of inflammable gas".* In order to help explain the circumstances surrounding the accident, while illustrating the components involved, a combination of photographs and 2D plans were used in one of the earliest attempts to aid in the understanding of the complex inter-relationships between features at the scene of an underground accident.

Photography is recognised as a valuable tool which is used to illustrate an environment to persons unconnected to the event, e.g. a coroner's court.

Plans of the accident site and the ventilation course through the mine were also used to recreate and record the scene. The accident plan is shown in Figure 28.

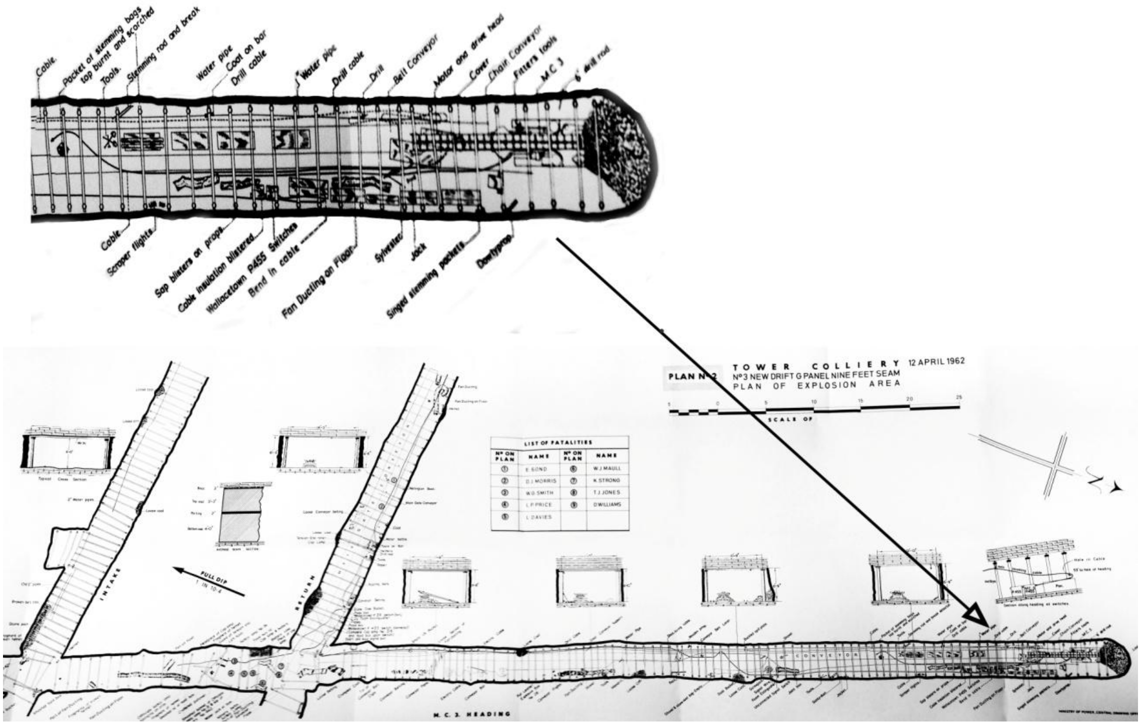


Figure 28: Accident plan (Leigh 1962)

The plan of the accident site includes the positions of supports, equipment and the resting places of the fatalities after the explosion. Additionally, sectional drawings of various key locations within the accident site were used to illustrate a different viewpoint of the relevant equipment. The plan is to scale and illustrates the position of the workings relative to north.

A ventilation plan is also included in the survey of the accident, which is important in the evidence since the accident involved an explosion of inflammable gases.

In this case the use of plans and photography aided in the explanation of the environment. However, without a connection to the accident or a sound knowledge of an underground environment, such representations can still be confusing.

2.5.2.4. Bilsthorpe Colliery (1993)

More recently, in 1993, an extensive fall of ground occurred at Bilsthorpe Colliery in Nottinghamshire in which 3 men were killed and three others were trapped, but fortunately rescued (HSE 1993). In order to demonstrate the circumstances surrounding the accident, the investigator investigated the approved methods of support which were employed at the mine. These are represented in a number of 2D sectional drawings with annotation, detailing the positions of roof bolts and supporting beams, in order explain the bolting system visually.

Photographs were taken at key locations showing the area of collapse and surrounding strata. In addition, diagrams in section have been produced in order to reconstruct the roof conditions before the fall.

A number of 2D plans were produced in order to illustrate the accident. The first of which, shows geotechnical data linked to a database of installed support in the accident area.

Another plan was produced in order to demonstrate the local geology of the accident area, where possible failures may have occurred. A plan was produced in order to show where the accident occurred in relation to other workings. Finally, a detailed plan of the accident scene with the position of the men rescued and the locations of fatalities was included in the report. This is shown below in Figure 29.

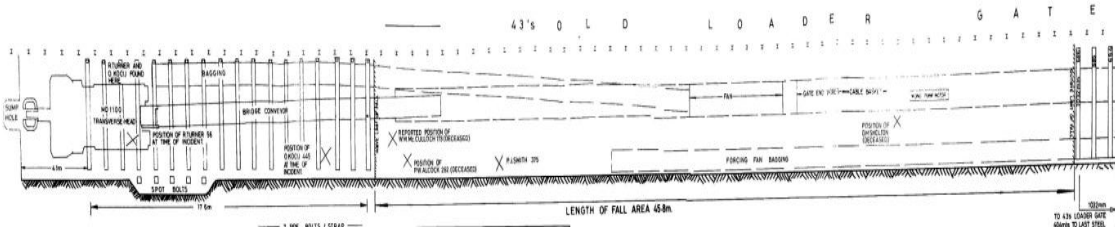


Figure 29: Bilsthorpe accident plan (HSE 1993)

The report also contains a number of witness statements and expert reports, which relate to the accident. This allowed the investigator to develop a sequence of events, in order to identify the cause of the collapse.

Although the information supplied within the investigation report of Bilsthorpe Colliery is extensive it is presented in a 2D format which can be problematic in the explanation of the event to someone from a non technical/ mining background.

Summary

It can be seen from this review of survey methodology and deliverable data, that over the last two centuries, little has changed in respect of survey plans following an accident, although the instrumentation has progressed considerably. This was largely due to the instrumentation that was available to surveyors, with the equipment being linear based in terms of measurement and with theodolites being used for angular readings. This has restricted the possibility of enhancing survey deliverables, due to subjective, discrete point collection from the available equipment. However, recent developments in survey equipment such as laser scanning technology allow diverse data capture in 3D, which could have a profound effect on accident investigation.

2.5.3. The Use of Digital Data in Accident Investigation

Over recent years, there have been considerable technological advancements in everyday activities, which have created an increased reliance on the use of digital data (Schofield 2009). The development of smart phones is a perfect example to illustrate this, providing the user with a magnitude of different functions, from taking phone calls, storing data and accessing the internet with a vast amount of applications available on a device small enough to fit in a pocket.

In many cases technology is driven by consumer demand for the products with companies continually developing new products to gain an edge over their industry rivals. However, the legal system can be slow to accept the technology. The delay is largely due to the need for the development of legislation surrounding the admission of digital evidence within the judicial system (Schofield & Goodwin 2007). This, in turn, can create complications within the accident investigation process when new technologies are incorporated, particularly if there has been a breach of the law in the events surrounding the incident.

Members of the jury often rely on oral evidence presented by the prosecution and the defence. In many cases witnesses will be called and give evidence on behalf of the court. Witnesses can be ordinary people who hold information that is relevant to the court or they can be in the form of an expert that has been called in order to provide evidence given their specific expertise. In certain cases, expert witnesses may have to provide complex descriptions regarding the events, environment and relevant scientific data. With this in mind, for a number of years technology has begun to play a part within the modern courtroom to aid in the explanation and demonstrating possible hypotheses (Schofield 2009).

2.6 Summary of Literature Findings

It can be seen that there have been a number of advancements within the geospatial industry, particularly in recent years. However, in relation to accident investigation, the final deliverable data has largely remained static, with the surveyor tasked to represent complex 3D environments using 2D representations. It has been highlighted in the review of accident investigation, that incidents are multi casual events which are hard to envisage.

Computer generated models have assisted in the re-creation and explanation of events, while providing a visual representation of a scene. However, the literature review has highlighted that there has been little research undertaken in the use of laser scanning technology to aid in the creation of accurate virtual environments.

With this in mind, the author believes that there is considerable scope for development in this area. Therefore, in order to explore the possibility of deploying a laser scanner in the recording and recreation of incident scenes, the technology will be applied to a number of case studies.

The author has identified industrial applications and potential commercial sectors, where laser scanning and 3D methodologies could be applied, namely;

- Fire Investigation and Fire Safety
- Industrial Accident Investigations
- Mining Incidents

The application of laser scanning in these areas will now be discussed in the subsequent chapters.

3.0. Chapter 3: Applications of Laser Scanning and 3D Modelling within the Fire and Rescue Service (FRS)

This chapter is presented in a number of case studies written in the style of academic papers

Case Study One: The Application of Laser Scanning and 3D Modelling in Fire Investigations

Work was undertaken in conjunction with the British Research Establishment (BRE), 3D Mine Surveying International (3DMSI), Cornwall Fire and Rescue Service (CFRS) and Fire Investigation UK (FIUK), in order to evaluate the use of laser scanning technology in the fire investigation process.

This case study can be seen in video format, offered as a service for FIUK:

FIUK.(2012). Forensic Laser Scanning. Video. Retrieved September 12,2014, from www.fireinvestigationsuk.com/services/forensic-laser-scanning/

Case Study Two: The Use of Augmented Reality in the Extrication Process of Road Traffic Collisions (RTCs)

A concept application of augmented technology, developed by the author, after discussions with Cornwall's Fire and Rescue Service (CFRS), with the aim to provide improvements within the extrication process following a RTC.

Case Study Three: The Application of Deformation Monitoring as a Risk Assessment Tool in Fire Incident Management

Work was undertaken in conjunction with CFRS and 3DMSI to evaluate the technology with reference to the management of the scene of a fire.

3.1. The Application of Laser Scanning and 3D Modelling in Fire Investigations

Abstract

Fires can have devastating effects on people and the environment, resulting in considerable financial implications for a country's economy in terms of anticipation, response and consequence.

Effective fire investigation is vital in order to examine the circumstances surrounding an incident. It is essential in order to learn from the event and assist in the prevention of future fires, while recording the data to develop more efficient fire protection systems.

This paper considers the incorporation of laser scanning and 3D modelling into the scientific approach to fire investigation. It also explores the benefits and limitations of the technology with reference to the origin and cause of fire.

3.1.1. The Problem

The impact from fire is substantial, with a reported 380 fire-related fatalities in Britain between 2011-2012. Fire causes some of the greatest losses to human life around the world, second only to natural disasters (Sandercock 2008). The figure above, however, is the lowest recorded number of fatalities in 50 years, and three quarters of these fatalities, occurred in dwellings (Department for Communities and Local Goverment 2011). This reduction is linked to improvements in fire safety over the years (DeHaan 2002), relating to building design, response and awareness. There can never be a financial figure put on the loss of a life, but fire accounts for a significant cost to the economy (Department for Communities and Local Goverment 2005).

The Department for Communities and Local Government study 2011 demonstrated that the costs incurred to the economy with reference to fire, can be broken down into three separate categories (Department for Communities and Local Goverment 2011):

- Costs in anticipation
- Costs as a consequence

- Costs in response

Costs in Anticipation

These are expenses that have been spent on measures to prevent fires and mitigate damage from fire development. These costs include (Department for Communities and Local Goverment 2011):

- Active Systems: These are measures activated in the presence of a fire and which are used in order to suppress the development of a fire, for example sprinkler systems.
- Passive Systems: These are static measures that are designed to confine a fire to an area and/ or aid in the safe evacuation of a building, for example fire walls or fire doors.
- Resource and capital cost incurred in relation to training and fire safety
- Insurance against fire

Costs as a Consequence

These are wide-ranging costs that are incurred as a result of a fire and include (Department for Communities and Local Goverment 2011):

- The total costs, related to the loss of business
- The cost of damage to property
- The total cost of fatal and non fatal injuries
- The costs to victims and for the police and criminal justice/ prison service

Costs in response

These are costs that are a result of a reported incident. This is largely the cost of the Fire and Rescue Service responding to a scene, including the cost of response to false alarms.

After consideration of all contributing expenses, a review of the 2008 data, estimated that the cost of fire in that year, was £8.3bn(Department for Communities and Local Goverment 2011). This demonstrates an increase of 7.2% from 2003 where the total cost was estimated at £7.7bn (Department for Communities and Local Goverment 2005).

A breakdown of the costs for 2008 is summarised in Figure 30, with reference to the separate categories stated previously.

Area	Anticipation (£m)	Consequence (£m)	Response (£m)	Total (£m)
England	£3,185	£3,285	£1,807	£8,277

Figure 30: Estimates for the Total Cost of Fire (Department for Communities and Local Goverment 2011)

Apportioning this to the population of the UK, the cost of fire is equivalent to £161 per person (Department for Communities and Local Goverment 2011) which represents a considerable cost to the UK tax payer. In addition, of the total cost of fire in 2008, arson accounted for 27% or £2.3bn. With this in mind, it is essential that the causes of fires are established through effective fire investigation.

3.1.2. Fire Investigation

The results of fire investigations can be fed back to a governing body that can perform statistical analysis of the origins of fires, in order to establish measures that may prevent similar incidents or mitigate the damage of fire (BRE 2013). In addition, if a death has occurred as a result of a fire, a coroner will request a report in order to establish the cause of death. Finally, if the fire has been as a result of arson, the investigation is undertaken in order to assist the police in apprehending the perpetrators (Fire Safety Advice Centre 2011).

Efficient fire investigation is an integral part of obtaining a deeper understanding of the origin and cause of a fire. The origin of a fire can be defined as "the area in which a fire or a explosion initiated" (Fire Investigations UK 2012b) and the cause as "the circumstances, conditions, or agencies that brought about or resulted in the fire or explosion incident, damage to property resulting from the fire or explosion incident, or bodily injury or loss of life resulting from the fire or explosion incident" (National Fire Protection Association 2004).

It is paramount to identify the origin of a fire in order to accurately obtain the cause of the fire, following which, an ignition source of significant energy, can be determined (Fire Investigations UK 2012b). One important factor that needs to be noted, in the investigation for arson, is that "Fires are often ‘staged’ to appear to be accidental. However, by conducting a full and thorough fire investigation using the scientific method it is possible to demonstrate that the ‘staged’ fire was, in fact, a deliberate act" (Fire Investigations UK 2012b). This is particularly pertinent for insurance companies especially when a claim is involved. However, arson is one of the most complex crimes to investigate due to the destructive nature of the fire (Sandercock 2008).

Once the cause and origin has been established, an investigator will begin to understand the development and spread of the fire. The development of a fire can be affected by a large number of factors from sources of fuel to environmental aspects, such as ventilation (Fire Investigations UK 2012a).

Determining the cause, origin and development of a fire can be a complex process which requires the adoption of a logical and systematic approach to investigation (DeHaan 2002).

3.1.2.1. Fire Investigation Process

The scientific method is a model that can be applied to many scientific and engineering problems. This model is shown in Figure 31 and its application to fire investigation was assessed in the National Fire Protection Association. *NFPA 921 Guide for Fire and Explosion Investigations* (2004) as summarised below (National Fire Protection Association 2004).

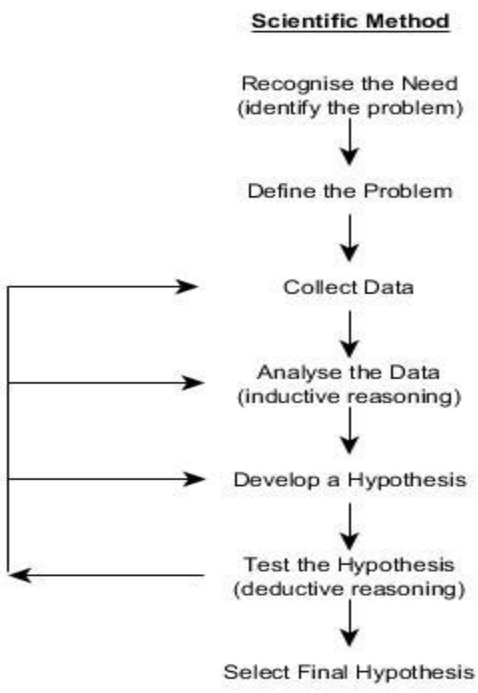


Figure 31: The Scientific Method (National Fire Protection Association 2004)

Recognise the Need

Firstly, the investigator must determine that the problem exists. With reference to fire investigation, the cause should be identified and reported in order to aid in the prevention of future incidents.

Define the Problem

With reference to a fire, the investigator needs to determine the scope of the investigation. For example, it may be simply to determine if the fire was accidental or deliberate (Ackland 2012). In this case, the investigator should conduct a proper cause and origin investigation.

Collect Data

The fire investigator should examine the scene and begin to establish relevant information. This can be in the form of visual observations or from other forms of direct data collection such as interviews with eye witnesses.

When collecting information from witnesses, it is essential that the investigator has a good understanding of interviewing techniques. Initially, the incident commander in charge of the fire scene should be interviewed as they may hold useful information. This officer may have already interviewed the person who discovered the fire and also bystanders, owners and fire fighters etc. This information will give the investigating officer an insight into a variety of different factors such as, if there had been forced entry to the building, colour of smoke (providing a indication of the materials involved in the combustion), internal doors wedged open (providing additional oxygen encouraging the fire to spread) etc (Fire Safety Advice Centre 2011). The information gathered from witnesses is crucial to provide insight into events prior, during and after combustion.

Analyse the Data

All the data that has been collected is then analysed by the investigator. Using their expert knowledge, training and experience, the investigator will try to establish the sequence of events surrounding the fire. The investigator should only consider fact with subjective information being ignored.

Develop a Hypothesis

The investigator should then consider all of the relevant information, trying to determine the "seat of the fire" or origin area. This is generally the area that is most severely burnt, as it would have been burning the longest. However, this is not always the case (Fire Safety Advice Centre 2011). Once the origin of the fire has been determined, the investigator must begin to establish what was the cause. This is generally done by excavating the seat of the fire in order to look for possible sources of ignition (Fire Safety Advice Centre 2011).

Test the Hypothesis

The investigator should now consider whether the hypothesis that has been deduced, will stand the test of careful and serious challenge. This is achieved by the principle of deductive reasoning, where the investigator considers their hypothesis in relation to all known facts. This can be done either through experimentation or cognitively by the investigator. If the hypothesis fails then it should be discarded and another hypothesis established.

Select Final Hypothesis

Once a hypothesis stands to scrutiny, it can be selected as a final hypothesis. The process and hypothesis should then be documented and submitted to a governing body. The report should be clear, concise and with no ambiguities (Fire Safety Advice Centre 2011).

3.1.2.2. Application of Laser Scanning in Fire Investigations

This paper seeks to show how laser scanning may be used as a technique in the investigation of fire incidents by recoding the scene in high detail   This is demonstrated by the application of laser profiling, data processing and 3D modelling as part of a case study.

Laser scanning technology although in its infancy has been used in a number of different applications shown in Figure 32. Laser scanning is particularly versatile in its application since it can be undertaken utilising a moving platform (dynamic laser scanning) or from a fixed location (static laser scanning).

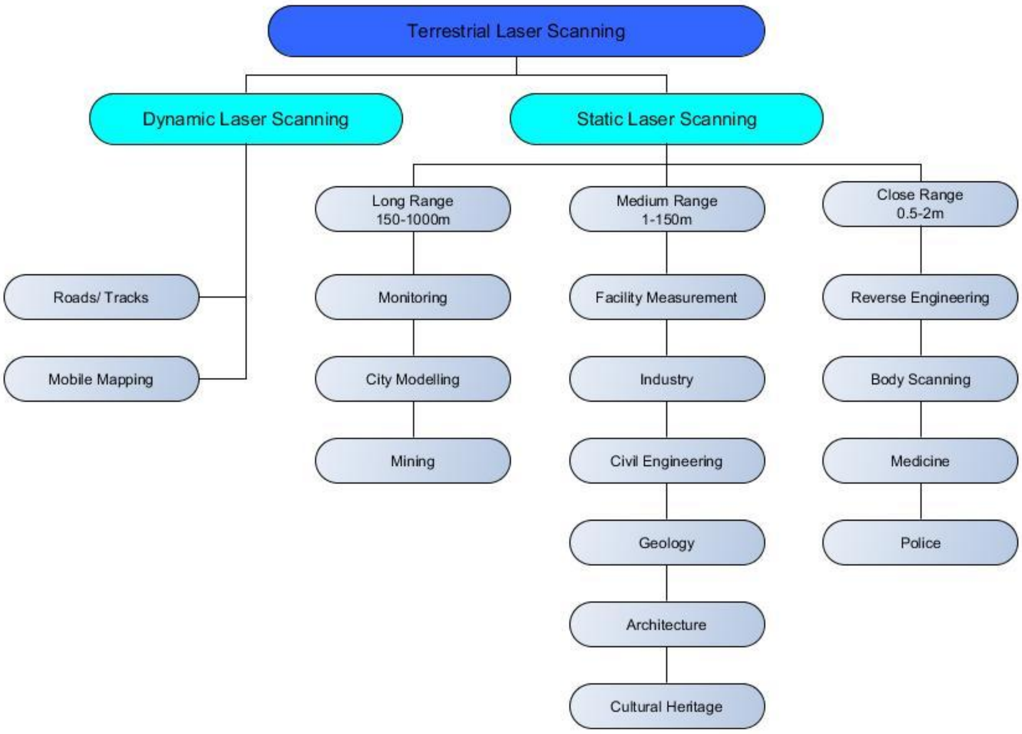


Figure 32: Applications for Laser Scanning Equipment (Quintero et al. 2008)

3.1.3. Case Study: Building Research Establishment Staged Burn

On 23rd May 2012, the Building Research Establishment (BRE) and Fire Investigation UK staged a test burn at BRE's burn hall facility in Watford, UK, to demonstrate the spread of fire in a controlled environment for research and promotional purposes. The author was asked to record the scene, pre and post combustion using a laser scanner while undertaking subsequent data processing and analysis, to explore the benefits of incorporating this methodology into the fire investigation process. Such work had not been previously undertaken in these circumstances.

A set was constructed and fitted to resemble a typical staffroom in a commercial setting. This consisted of a timber frame construction with plasterboard finish and including services found in an internal room, such as electrical trunking and lighting. This setting was chosen because staff welfare facilities are one of the more common locations of origin for a fire in a commercial building.

The contents of the room consisted of a table and chairs, white goods, a kitchen space, television, sofas and soft furnishings. These items are typical of the items that could be found in welfare facilities in a staff room. A photograph of the set prior to combustion is shown in Figure 33.

Figure 33: Photograph of Set Before Ignition

As part of the burn demonstration, a 3D survey was undertaken to capture the 'as-built' room prior to ignition, and again after combustion. This was in order to evaluate the application of laser scanning in a fire investigation setting.

3.1.3.1. Methodology

In order to capture and recreate the constructed staff room prior and after combustion, there are a number of stages that have to be considered which will be discussed in this section.

On Site Survey

In order to capture the scene in full, a number of laser scan positions have to be used and joined later through a process called registration. This ensures that all objects are recorded from all angles, without "gaps" in the data. In addition, as a photo realistic model was required, from each scan position, a series of photographs were also taken to allow the point cloud (survey data) to be texture mapped with colour pixels, corresponding to specific objects captured within the scan.

The survey was carried out with a Leica HDS6000 laser scanner and panoramic camera system to capture the photographs. In addition, a number of Leica black and white "tilt and turn" targets were used to help reference the scan locations together.

Processing of the Data

Singular point clouds encounter problems with ‘blinding’, this being where the scene is obscured and the point cloud is therefore missing data. In order to overcome this, multiple laser scans are taken to obtain a complete data set for a scene. The point clouds from these multiple scans are then joined together in the process known as registration. During this, the user picks common geometry or points (targets can be used) that remain the same between the laser scan positions, which can viewed side by side in the software (Leica Cyclone), illustrated in Figure 34. Once enough points (at least 3) are matched between the point clouds, a registration adjustment is processed by the software and an error value is obtained. . The surveyor must consider the error value in order to establish that the point clouds are constrained in a manner that represents the scene that has been surveyed. As if the registration process has not been properly preformed the data may become misaligned and unreliable, without a consistent surface between the locations.

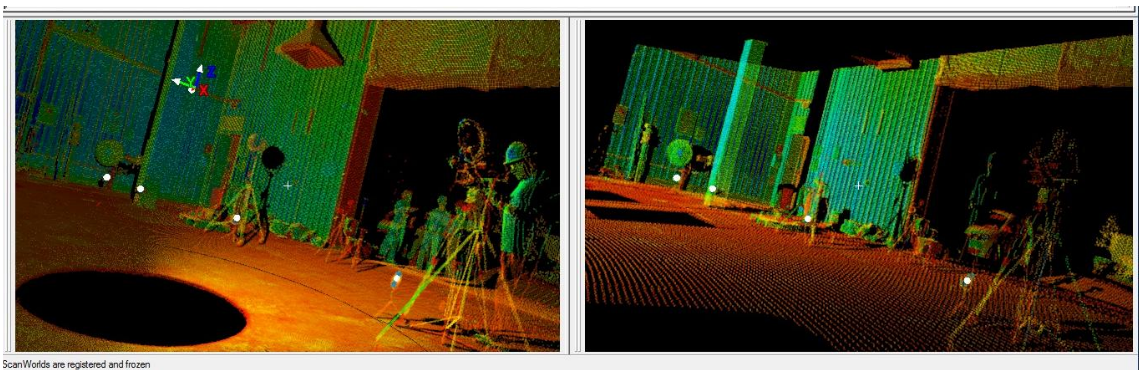


Figure 34: The Registration Process

In this particular case, photographs were taken from the same focal point as the laser scanner, in full dome 360^{o} field of view. This means that the photographs can be applied to the point cloud, in order to display the true Red Green Blue (RGB) environment, which was considered necessary by the author and the BRE, in order to best demonstrate the capabilities of the equipment and provide similar visual representations to a photograph or video commonly used in conventional fire investigations. An example of a photo textured point cloud is shown in Figure 35.

Figure 35: Photo Textured Point Cloud

The point cloud can be very dense, since by its nature, it is made up of millions of discrete data points. For technical work and measurement this is an advantage, but for visualisation purposes, when the user tries to zoom and focus on an object, some clarity can be lost. In order to maintain clarity, a mesh has to be made. The mesh is a number of polygons, that connect the points together to form a surface. This is done by using 3D meshing software. An example of a meshed object is shown in Figure 36.

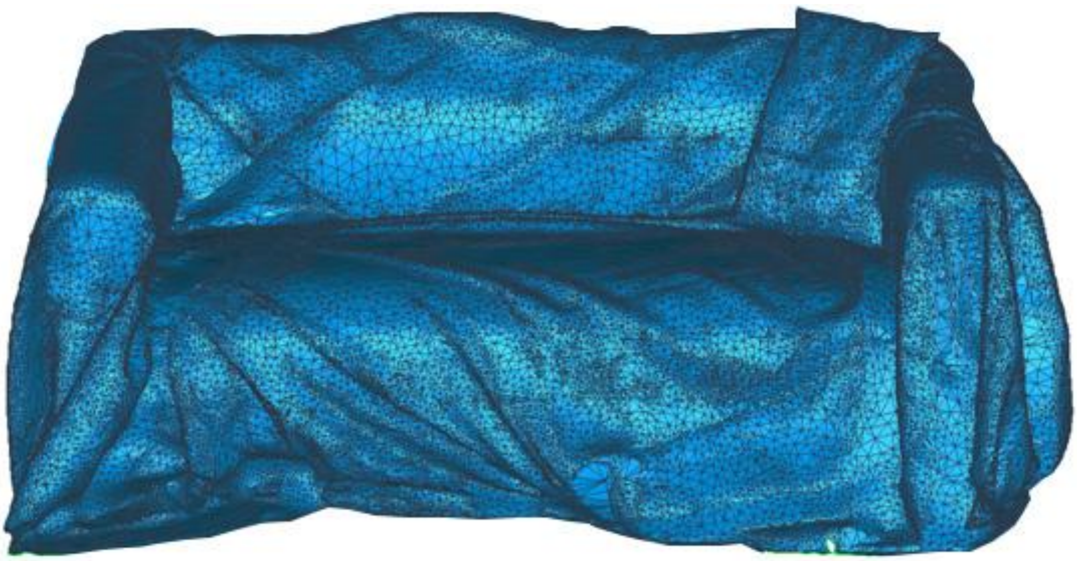


Figure 36: An Example of a Mesh Model

Once the model is meshed, some of the geometry can be lost. This is due to the vast amount of points that the computer uses for surface creation and the limitations of the hardware capabilities of the machine used. For example, the author's laptop, with an Intel I7 processor, 8GB of RAM and 2GB dedicated graphics card, will struggle to remain stable when creating meshes of over 4 million polygons.

The process of meshing can be very complex where the point cloud has to be separated into smaller objects to retain accuracy. To facilitate this, the mesh or point cloud can be taken into a modelling program (such as 3DS Max) in order to "build" the model using clearly defined edges that best represent an object's geometry. This is needed since, when a mesh is created around a sharp corner, a great number of polygons are needed to maintain the geometry, which tends towards the formation of a unwanted smooth or rounded corner. This process is also vital to aid computer performance by reducing the model's size and complexity. However, this should be undertaken with care in respect of ornate geometry that requires a high polygon count to represent the surface accurately such as the settee shown in Figure 36. An example of the polygon reduced model is shown in Figure 37.

Figure 37: Reduced Polygon Mesh

It can be seen from the image above that there is no texture applied to the mesh. 3DS Max can then be used to add materials and lighting to the scene, which can add realism and create a model. See Figure 38.

Figure 38: Modelled and Finished Mesh

The process was then repeated for the scene after combustion. An example of the mesh model of the burnt area is shown in Figure 39. Owing to the complexities of a post fire scene, where objects could be melted or deformed in the intense heat, thus forming complex geometry, the production of a 3D model of the scene can be a intricate process. This is due to the number of polygons that are required in order to recreate the surfaces accurately. This is illustrated well in Figure 39, given the evident distortion of the surfaces post fire.

Figure 39: 3D Model After Combustion

In the author's experience 2D plans are often requested in addition to the 3D model. However, 2D plans can easily be produced from point cloud data which can far exceed the detail that can be captured using conventional surveying methods in a narrow timeframe. An example of a 2D plan produced from the laser scan data is shown in Figure 40.

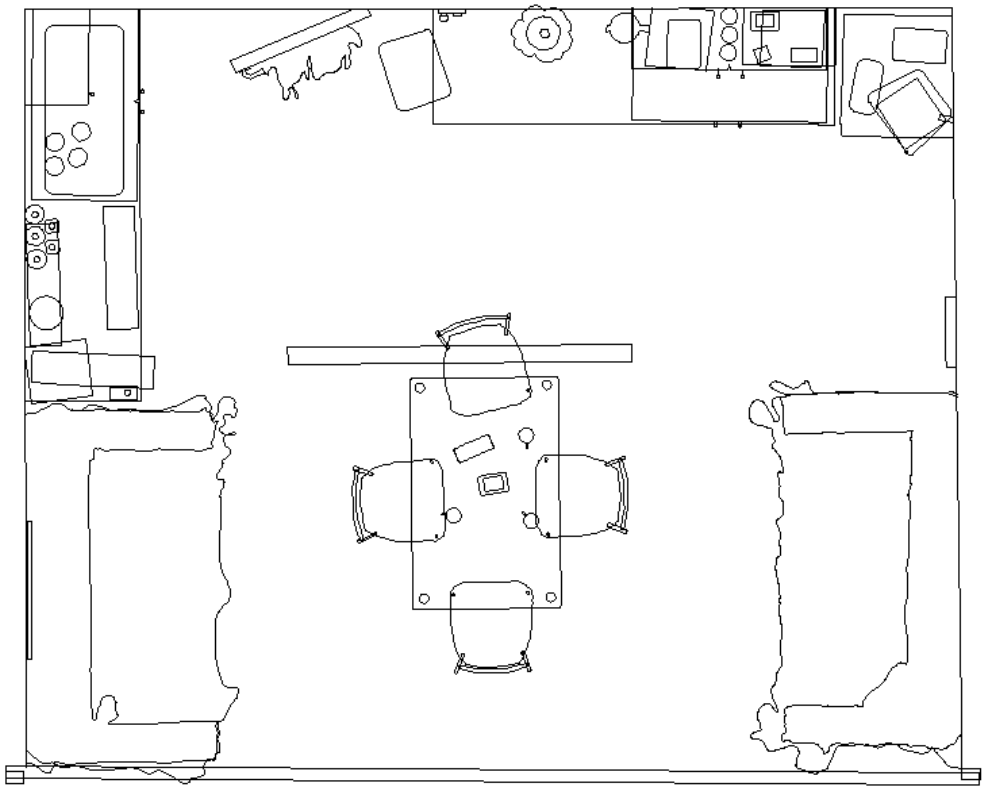


Figure 40: 2D Plan of the Scene

As this particular fire was staged, an investigation into the cause and origin of the fire was not required. However, the model produced, allowed the scene to be observed in a virtual 3D form, that could be shared to people unrelated to the event itself in order to assess what may have been the cause of the fire in a virtual setting. The modelled burnt environment photographically overlaid showing rising burn patterns, gives an indication as to the origin of the fire. Rising burn patterns are formed from the intense burning in an area, which can indicate the seat of the fire, where the soot has been burnt from the wall in the intense heat starting at the lowest point of burning. This can be obtained by using conventional means however, the 3D survey complements the process. In addition, it allows the investigator to look at the incident from angles that would possibly not be assessable within the scene.

Although the fire was staged there are a number of key benefits and limitations in reference to fire investigation that are explored in the next section.

3.1.4. Incorporating Laser Scanning into Fire Investigations

It can be seen from the case study that laser scanning can be undertaken during the fire investigation process, although it is important that the survey of a scene is conducted as soon as possible to ensure that the scene remains true to the time of the incident. However, this can be problematic in terms of a fire or explosion, as the investigation can only be undertaken after emergency response has occurred and it is safe to do so.

3.1.4.1. Benefits of Using Laser Scanning

There are a number of benefits that can be achieved by incorporating laser scanning into the fire investigation process:

Documenting the Scene

It is important for an investigator to document the scene rapidly in order to provide a permanent record of the environment to complement their investigation (Leary 2000). With this in mind, a laser scanner has the ability to capture millions of accurate 3D data points, that coupled with photography, can create a geometrically, true RGB and complete representation of the scene,

The non-contact nature of laser scanning also reduces the risk of site contamination and the facility to operate remotely, increases the safety of accident survey.

Real-time data access can facilitate data analysis by the creation of 3D models and can provide critical and accessible measurements which might otherwise be missed in traditional fire scene surveys.

Scene Revisits

The laser scan data collected by a surveyor can be archived and then referenced at any time allowing the investigator to virtually revisit the scene any number of times, whilst protecting and preserving fire scene evidence for future use.

Testing Hypotheses

Laser scan data creates a true representation of the objects and surrounding environment of a fire scene. This data can then be incorporated into specialist fire investigation software, in order to validate the hypotheses established during the investigation process. In addition, by reconstructing the scene to a pre combustion state, computational fluid dynamic (CFD) software can be used in order to simulate the development of a fire throughout an incident, for example JASMINE (BRE 2009). This can be a considerable help in understanding of the nature of a fire and of its spread (Delemont & Martin 2007) (Shen et al. 2008).

Data Clarity

The development of a visually and geometrically accurate 3D model allows a person to observe the relationship between every object in the scene and the surrounding environment. The production of a fly through video stopping at key areas of the investigation process, such as photographs taken in the investigation, can bring clarity to an observer's mind. This is particularly useful when explaining a fire's development to people unconnected with the event and possibly from a non technical background, such as a jury, when modelling can be used to support expert witness statements (Nystrom 2014; Eyre et al. 2015; Eyre et al. 2014).

Witness Statement Verification/ First Person Viewpoints

As discussed previously, first responders to a fire scene can hold key information for a fire investigation. With this in mind, by positioning a camera virtually in the location of a witness, what they have seen can be demonstrated, which can be useful in explaining the events to other people. In addition, other witness statements may not be accurate and the camera can be used in order to verify the statement given and the investigator can then make an informed decision on a person's reliability.

Insurance Purposes

The destructive nature of fire is considerable and the costs as a consequence are substantial. An accurate 3D survey of an incident scene can assist loss adjusters in assessing claims for damage incurred. In addition, where there may be a dispute between two insurance companies, for example when damage occurs to two dwellings of close proximity, an accurate survey can add clarity as to who is responsible for the subsequent claim.

Safety

Fire incident scenes can be inherently dangerous, posing considerable risk to an investigator undertaking an investigation. However, by incorporating a laser scan survey the scene can be recorded remotely, which accompanied by witness statements, can allow a form of fire investigation to be undertaken which would not otherwise have been possible.

Burn patterns often indicate seats of fire and in addition, white areas, where soot has been burnt off the wall, can indicate the origin of a fire, as this is the area of most intense burning (DeHaan 2002). A characteristic of infra-red laser light is that, it is absorbed by black and is reflected by white material. With this in mind, a scene can be laser scanned from a safe distance and the differences in the intensity (reflectance) values of the point cloud can be examined in order to try and establish the origin of a fire. The rising burn patterns indicating the seat of the staged fire is shown in Figure 41. Additionally the Figure shows a photograph alongside the point cloud data, showing intensity values (with areas of higher intensity being shown in a bright green). This is a planned development that needs to be explored in detail through further work.

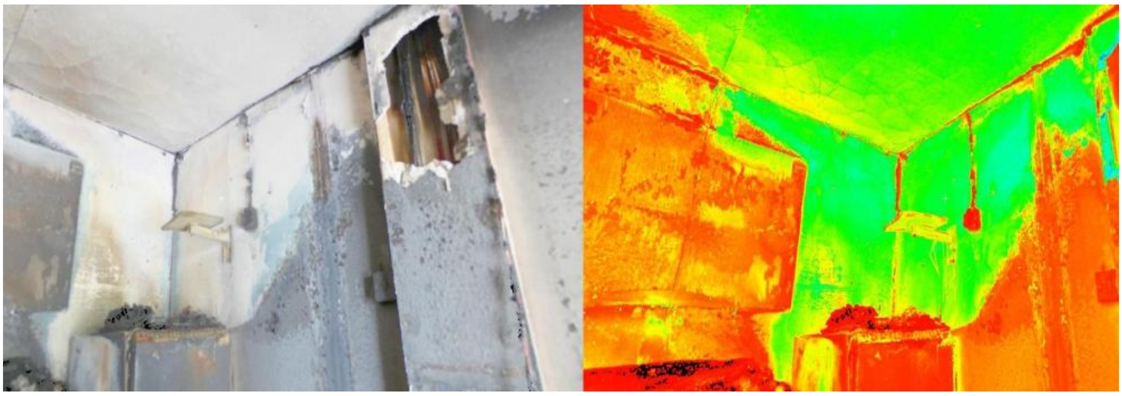


Figure 41: Rising Burn Patterns of the Seat of the Fire

3.1.4.2. Limitations of Laser Scanning Technology

Laser scanning technology has a considerable amount of potential in this sector but is not without its limitations:

Cause Analysis

Laser scanning technology has the ability to record a scene, but has little relevance to cause analysis as it will only record what the equipment can "see". An investigator will still have to exhume the seat of a fire in order to establish the cause of the fire. Other senses are also needed in accident investigation, which the single sense laser scanner cannot detect, for example the smell of accelerants often associated with cases of arson.

Expense

As laser scanning technology is still in its infancy and developing, the costs associated with the equipment and software are considerable. Justifying the cost of using the technology is questionable in many cases. However, the costs associated with the introduction of new technology invariably fall over time as the technology matures. As such, cost-benefit analyses can show that where there has been a major financial loss, loss of life or arson, the profile of the fire may be significant or become a criminal matter, thus justifying the costs currently associated with a 3D survey.

Limited Reliance on Measurements

In many fire investigations, there is only a limited need for the large number of measurements that a laser scanner can produce. In many cases, a conventional investigation using photography, video, witness statements accompanied by measurements and a sketch plan produced by the investigator, often suffices. However, the use of this technology by the fire investigation community is gaining significant momentum through proven laser scanning success.

Difficulties in Modelling Data

Due to the destructive nature of fire, what is left after combustion is complex in its geometry. Although the laser scanner is optimised to record this data, creating solid mesh models of this information is time consuming and problematic, requiring high levels of skill in both operation and processing.

3.1.5. Conclusions

The results of the case study investigation have shown the potential benefits for the use of laser scanning. This could aid a fire investigator and support expert witness documentation. It is accepted that laser scanning technology can never become a replacement for conventional fire investigation and can only complement the processes undertaken by a skilled investigator

The justification for the use of a laser scanner is largely restricted due to financial implications and although of benefit, the incident has to be high profile in order to justify its use.

Laser scanning, however, provides a large number of benefits to insurance companies in trying to investigate claims as a consequence of an incident, such as, providing ‘as built’ survey data to categorise damage, identification of boundaries to properties in a dispute and aiding in the identification of arson.

The author believes that there is considerable potential in incorporating this methodology, where a structure has been heavily affected by the fire and is in a unsafe condition, hindering access and preventing the possibility of performing a conventional fire investigation.

In many cases, this can result in a limited fire investigation or sometimes no investigation at all. With this in mind, a laser scanner operated from a remote location could provide the investigator with information that would be otherwise unattainable. The surveyed environment could then be compared to plans of the building (which can be converted into 3D models) and witness statements, in order to try and establish the potential cause and origin or the fire. In addition, the reconstruction can be used to gain greater understanding of how the fire spread and developed throughout the structure. The outcomes of this evaluation, can then be used by governing bodies such as the BRE and may have an effect on future building design.

As previously stated, the use of a laser scan's intensity values could provide information relating to the area which has been burning the longest and therefore possibly indicating the seat of the fire. In this case study, using a staged environment, where the cause and the origin of the fire was known, focus could be placed on the area in which the fire began and rising burn patterns were detected. However, further work is required in order to establish if this could be used in all 'real' cases, where the cause and origin was unknown.

Laser scanners are impressive instruments providing the ability to record a scene in unprecedented detail, with each 3D point (having its own unique co-ordinate) being used to obtain distances between anything within the recorded environment. The need for such a magnitude of different measurements provided using a laser scanner may not always be apparent to a fire investigator. However where the laser scanner comes into its own with the considerable benefits (detailed in this paper) that can be obtained in recording complex geometry (far surpassing conventional methods), e.g. the recording of objects that have been deformed by the fire.

Having the capability of capturing this information in 3D provides numerous benefits in the explanation of the scene and also gives the ability to view the scan virtually from multiple different angles. Therefore, the fundamental benefit is having the ability to record the scene accurately in a 3D form, with the added possibility of obtaining measurements which may only be recognised as having relevance later in the investigation process. In addition, the ability to record complex forms could have an impact with regard to any assessment of the material properties of the combusted object and they succumbed to the fire.

The amount of complex geometry found in fire scenes, is however a problem when using the recorded information for creating deliverable data from the point cloud, in terms of a making mesh model. The high polygon counts associated with modelling data of a complex form is substantial, leading to increases in the skill required, the size of the related model, the computing power needed and the time taken to execute the process.

With this in mind, in order to perform this stage (modelling the data), the fire must be of high consequence, for example in terms of loss of life, major financial loss or arson. In addition where possible, areas or objects which still contain simple geometry should be modelled to a low polygon representation. This allows the user to reduce the size of the final model, which limits the computing power required to display it and simulate further analyses.

There are numerous methods that can be used in order to reduce the polygon count of models and make them smaller in size, while retaining the object's visual representation (largely used in the film or computer game industry). Two such processes are known as normal and displacement mapping.

Fundamentally, in both methods, the user creates a low polygon version of the high polygon mesh model to which "maps" are applied to mimic the original geometry.

In respect of normal mapping, the map in question is a rendered image from the high polygon mesh model, containing the lighting information of the reference object. The normal map can then be applied to the low polygon version of the original geometry, to create a very similar appearance when the final render is produced.

Displacement maps are created from a photograph of reference geometry, where the user creates a greyscale representation from the image. The second stage is to "paint" areas black in colour, which need to appear indented upon final render.

However, normal and displacement mapping should be handled with care particularly if the resultant models are going to be used for CFD modelling or cause analysis. This is owing to the resultant geometry not significantly representing the reference geometry and therefore the results can be affected.

To conclude, laser scanning and subsequent 3D modelling can enhance the fire investigation, if the case is significant to support its use (in respect of time and cost) and the complexity scene warrants it. Additionally, when the technology matures and the costs of the equipment subside, laser scanning may become more frequently used in such investigations, providing more enhanced deliverables.

3.2. The Potential Use of Augmented Reality in the Extrication Process of Road Traffic Collisions (RTCs)

Abstract

As the number of vehicles on the road are ever increasing, there are a number of implications associated with it, such as increased congestion, pollution and sadly, accidents, with Road Traffic Collisions (RTCs) being a leading cause of death and injury worldwide. In recent years, there has been considerable focus on the safety of vehicles to help alleviate some of the injuries sustained in RTCs. However, many of the safety systems introduced can become a hindrance when considering the removal of casualties following an RTC. In the UK, the responsibly of extricating persons from a vehicle lies with the Fire and Rescue Service (FRS).

This paper explores the current methodology, employed by the UK FRS, for the extrication of trapped persons and the potential problems that can be encountered with vehicle safety systems. Following this, the author introduces the concept of using augmented reality to aid FRS crews in the extrication process, by visually displaying the locations of safety systems on a crashed vehicle. Discussion will be made of how this may be integrated into the extrication process and the possible benefits that could be obtained in its adoption.

3.2.1. Introduction

Year on year, there has been an increase in the number of vehicles on the roads in the UK. The latest figures from the Department for Transport (DfT) show that the number of licensed vehicles reached a record 34 million in March 2013 (Department for Transport 2013). This is a 27% increase with reference to data gathered in 1994 (Department for Transport 2013), indicating a significant rise in congestion on UK roads. Figure 42 provides data for licensed vehicles by body type from 1994 to 2011.

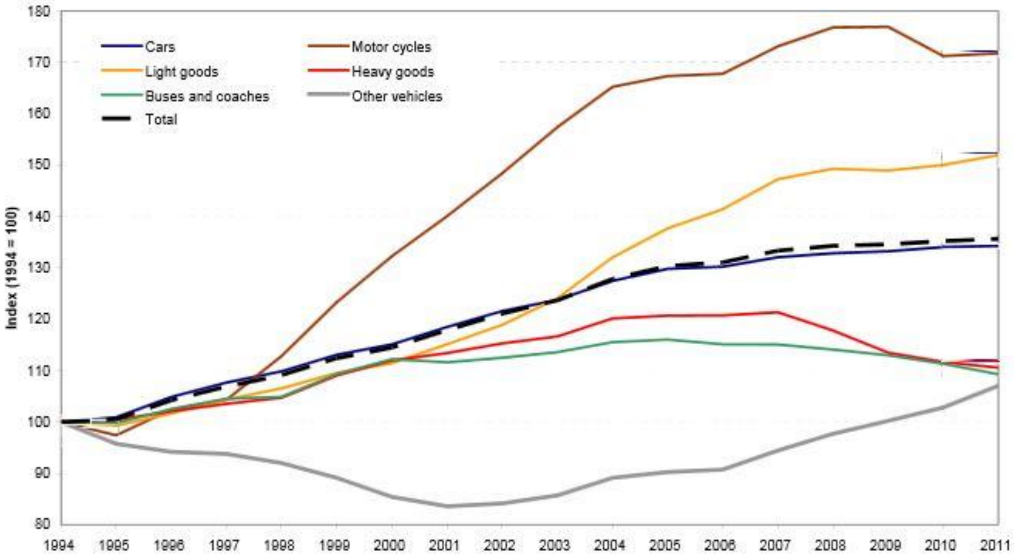


Figure 42: Licensed vehicles by body type: Great Britain, 1994 to 2011 (Department for Transport 2012)

Technological advancements have resulted in vehicles travelling at higher speeds than a number of years ago, with the quickest production vehicle currently reaching a top speed of 268 mph (Top Car 2013). There have been several studies undertaken which demonstrate the relationship of speed to the number of accidents, for example, (Taylor et al. 2000) which found "the results of the road-based and driver-based studies are mutually re-enforcing and provide clear evidence that, in any given situation, higher speeds mean more accidents".

Road traffic and self inflicted injuries are the leading causes of injury related deaths worldwide, accounting for 6 of the 15 leading causes of death of 15 to 44 year olds (Krug et al. 2000). Within the UK in 2010, Road Traffic Collisions (RTCs) made up around 85-90 % of all accidents (Reeve 2010). With these figures in mind, it could be assumed that the number of fatalities resulting from RTCs would be on the rise also. In reality, however, the number of fatal accidents have been in decline for a number of years (Department for Transport 2012). The decline in fatally injured and seriously injured casualties can be seen in Figure 43.

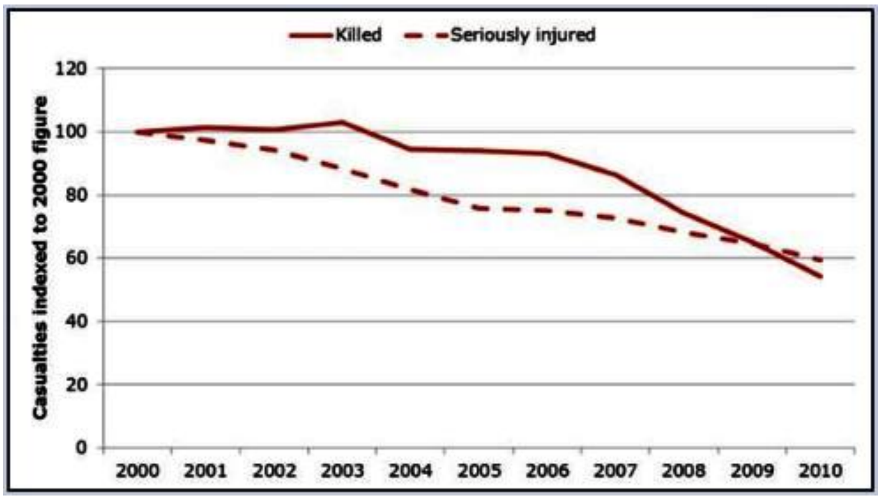


Figure 43: Number of Fatally and Seriously Injured Road Accident Casualties Indexed to year 2000 (Reeve 2010)

The reduction in road traffic collision rates have been due to a multitude of factors. These include the introduction of various regulations over at least 20 years with the aim to reduce injury rates in road traffic collisions (Broughton 2003). In addition, car manufacturers have not only invested in performance, they have also focused on increasing safety both inside and outside of vehicles.

The age of a car has a direct correlation to the severity of injuries sustained by occupants in RTCs (Reeve 2010). The sharp decline in the number of fatal injuries with reference to vehicle registration year is shown below in Figure 44, and is likely to be related to improved safety systems within vehicles.

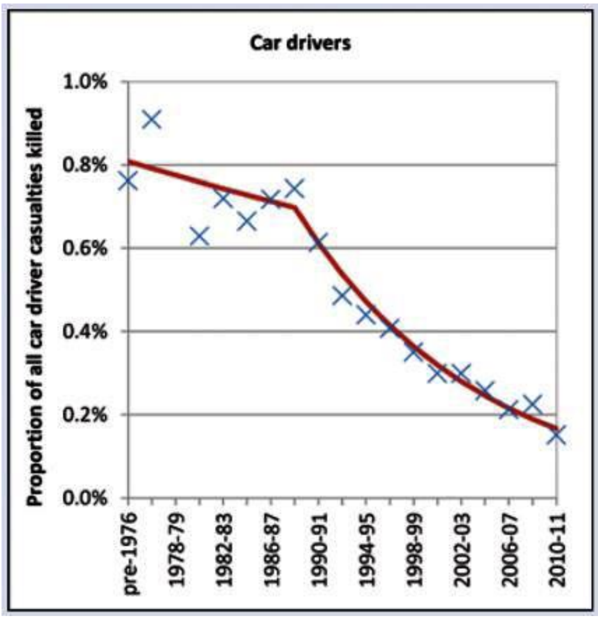


Figure 44: Proportion of Car Driver Fatalities Between 2000 and 2010-by registration year (Reeve 2010)

Car manufacturers principally use two types of safety systems to protect vehicle occupants, which can be classified as active or passive in nature (Derbyshire Fire and Rescue Service 2011).

Active safety features refer to measures that have been developed to avoid an accident. Thus active systems operate prior to a collision occurring. Passive safety features refer to measures that are designed to alleviate the consequences of an accident. Examples of both can be seen in Table 2:

Active Safety Systems	Passive Safety Systems
• Power steering	• Driver and passenger airbags
• Anti-lock braking systems	• Side and curtain airbags, foot well, knee airbags
• Traction control	• Front and rear crumple zones
• Independent suspension	• Side impact bars
• Tyre technology	• POP UP rollover protection devices
• Variable intermittent wipers	• Seat belt tensioners/ G force limiters
• Moving headlights, xenon bulbs	• Collapsible steering column
• Crash avoidance systems	• Laminated glass
	• Steering wheel and fascia paddling
	• Active headrests

Table 2: Examples of Active and Passive Safety Systems (Derbyshire Fire and Rescue Service 2011)

Passive safety systems will be the focus of this paper as these present a major risk to fire and rescue personnel in the extrication process. These can include passive systems that have already been deployed or remain un-deployed, but could be accidentally triggered.

3.2.1.1. The Role of Fire and Rescue Service Regarding RTCs

The Fire and Rescue Service (FRS) in the UK is legally obligated to attend RTCs under the Fire and Service Act 2004 Part 2. According to the Fire and Rescue Services Act 2004 (Fire and Rescue Services Act 2004):

(1) A fire and rescue authority must make provision for the purpose of—

(a) rescuing people in the event of road traffic accidents in its area;

(b) protecting people from serious harm, to the extent that it considers it reasonable to do so, in the event of road traffic accidents in its area.

(2)In making provision under subsection (1) a fire and rescue authority must in particular—

(a) secure the provision of the personnel, services and equipment necessary efficiently to meet all normal requirements;

(b) secure the provision of training for personnel;

(c) make arrangements for dealing with calls for help and for summoning personnel;

(d) make arrangements for obtaining information needed for the purpose mentioned in subsection (1);

(e) make arrangements for ensuring that reasonable steps are taken to prevent or limit damage to property resulting from action taken for the purpose mentioned in subsection (1).

The increased focus on safety by car manufacturers has no doubt led to a reduction in fatal RTCs. However, this has resulted in the emergency services being faced with the challenge of extricating casualties who are surviving high speed impacts (Derbyshire Fire and Rescue Service 2011).

3.2.2. Current Practices of the Fire and Rescue Service Personnel with Regard to RTCs

In order to maintain a time effective casualty rescue, the FRS service operate "A Team Approach" with regard to RTCs (Derbyshire Fire and Rescue Service 2011). The methodology of the FRS will be discussed within this section, with reference to the management of risk and the hazards encountered on the scene of a RTC. There are a number of tools and operations used by the FRS within the extrication process. However, these will not be discussed as these have little relevance to this paper.

3.2.2.1. The Process of the "Team Approach"

There are a number of key operations that have to be undertaken in order to manage an accident scene effectively (Derbyshire Fire and Rescue Service 2011).

- *There must be a clearly identifiable Incident Commander (IC) in charge, for liaison between services and command and control FRS personnel.*

- *Naturally in a 'persons trapped' incident, there will be a casualty requiring some degree of medical attention.*

- *The vehicle will require stabilising in order to minimise unwanted movement and to facilitate safe entry into the vehicle by emergency service personnel.*

- *Equipment will need to be placed and set up in a designated area (equipment dump) so that it is available for immediate use.*

- *Crew personnel will need to be designated as tool operatives. Each tool operator will have to have someone detailed to work with them to provide 'hard' protection between the casualty and the tool.*

- *The IC will have to formulate a rapid extrication route and main extrication routes, and then brief all personnel involved, whilst constantly liaising with medical staff as to how the casualty is to be extricated.*

In addition to the above, there are six key elements that need to be undertaken in order to achieve a well controlled rescue. The process is shown in Figure 45.

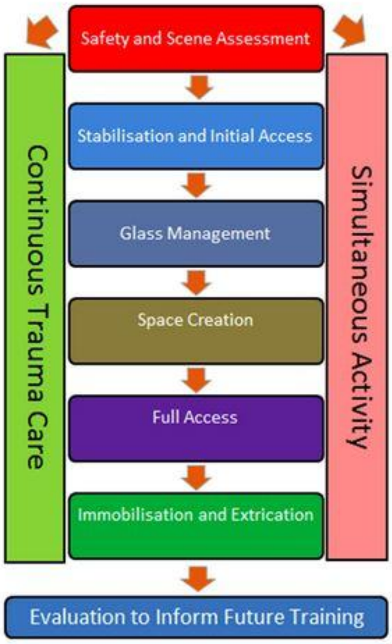


Figure 45: The RTC Rescue Process (Dunbar 2013)

With prior knowledge of the factors associated with the management of RTC rescues, the roles of the FRS personnel can be pre-determined and allocated prior to the dispatch of personnel to the scene.

The fire appliance dispatched to the scene should contain 5 members, with predefined roles shown in Figure 46.

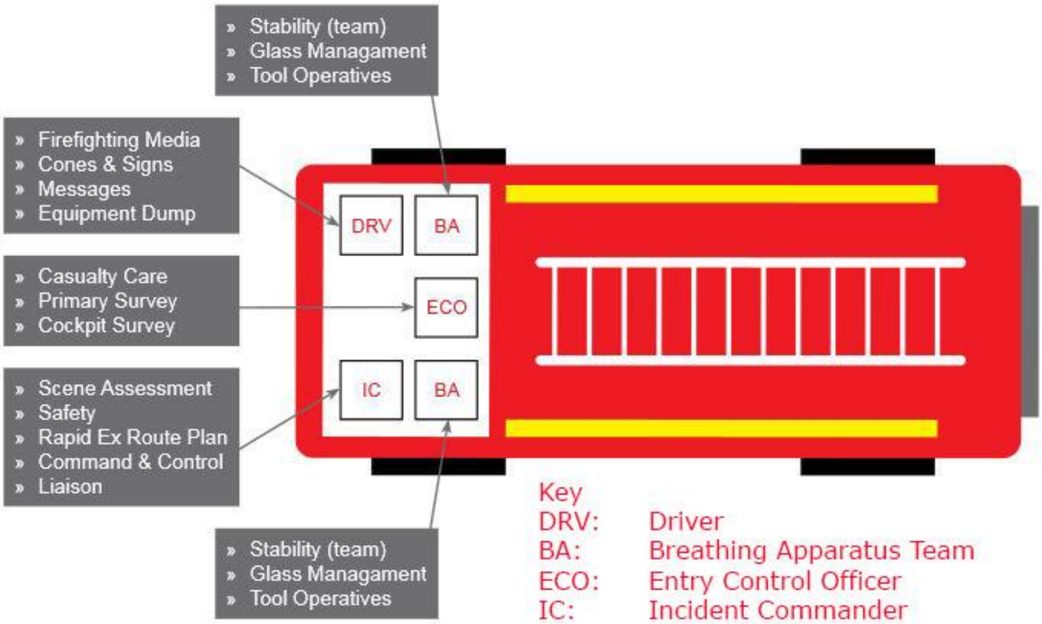


Figure 46: Recommended Structure for an Efficient Team Approach to an RTC (Derbyshire Fire and Rescue Service 2011)

By predefining the roles of the crew before attending a RTC, this encourages synergy between team members, resulting in improved efficiency in terms of time and management of operations.

3.2.2.2. FRS Management of Risk within RTCs

Upon arrival at an accident scene, the FRS will aim to protect the scene with appropriate signage (if this operation hasn't already been undertaken by the police) (Calland 2005). The incident commander (IC) will then determine that no obvious hazards exist, before he/she can then task others to undertake a more detailed reconnaissance of the scene. Following this, the IC will undertake a 360 degree survey of the scene and perform a Dynamic Risk Assessment (DRA). The DRA will identify any hazards for which controls can be established, while the 360 degree survey will allow the IC to establish an adequate rescue plan (Derbyshire Fire and Rescue Service 2011). Furthermore, the 360 degree survey is used to help identify key factors such as the number of casualties, type of ignition system, stabilisation issues, make and model of the vehicle, location of the fuel filler in addition to other hazards and issues regarding scene safety (Derbyshire Fire and Rescue Service 2011).

Once the IC has deemed it safe to do so, other personnel can then perform a closer inspection of the vehicle(s), known as a cockpit inspection. The cockpit inspection is used to identify hazards that may aid or hinder the extrication process, which may include (Derbyshire Fire and Rescue Service 2011).

- access points
- other casualties
- passive safety systems
- casualty contact
- access points and checking door operation

3.2.2.3. Identification of Passive Safety Systems by FRS Personnel

As stated earlier, passive safety systems are designed to improve safety and reduce injuries to a casualty involved in a RTC. Unfortunately, for the FRS personnel trying to save the victims, these passive safety systems can cause injury or even death. For example, airbags deploy with a force of 3000-4000 pounds per square inch within the first few centimetres of the airbag deployment. An adult's chest can withstand a force of 3000 pounds per square inch, but this, combined with the possibility of a firefighter's extrication tool being struck by airbag deployment, could result in fatal injury (Solar 2008).

The consequences of accidental airbag deployment can be demonstrated in the following two examples from the United States (Solar 2008):

> Example 1:
>
> In 1996, a police officer accidently deployed a side impact airbag while trying to help a woman out of a crashed vehicle. The woman's condition was not considered life threatening. However, the airbag deployed and forced the woman into the roof of the vehicle. She later died from the impact from the airbag deployment.
>
> Example 2:
>
> In 1999, two firefighters suffered injuries after being struck by an airbag during the extrication process. Airbags are only one example of a passive safety system that can pose a risk to FRS personnel during the extrication process. Therefore it is imperative that these systems are identified and control measures are put in place in order to ensure a safe extrication process.

Currently, the FRS rely on the experience of the personnel themselves, on information obtained from the Mobile Data Terminal (a computer used within the fire appliance) and on "peel and reveal". The "peel and reveal" technique refers to removing the interior trim panels in order to assess that it is safe to cut the vehicle (Derbyshire Fire and Rescue Service 2011).

The process of "peel and reveal" is essential to ensure the safety of the crew and casualty during the extrication process, due to the hidden dangers within modern vehicles. For example, the Volvo XC-90 contains 16 airbags, but does not have any visual labels to indicate their locations (Derbyshire Fire and Rescue Service 2011). With this in mind, it is easy to see how mistakes could be made if the FRS didn't perform the "peel and reveal" technique.

In addition to passive systems that may cause harm to the FRS personnel and/or the casualty, modern car manufacturers have started to use boron steel in the manufacturing process, for the pillars and floor of vehicles. Boron steel is a high tensile steel that cannot be cut using hydraulic cutters or reciprocating saws, and so it must be identified in order to protect the equipment used in the extrication process (Derbyshire Fire and Rescue Service 2011). The location of boron steel may also affect the preferred extrication route of the casualty. For example, it may not be possible or time effective to perform side extrication if boron metal is found in locations where the FRS have to cut.

Many RTCs involve casualties that require a time critical extrication. Upon arrival of all key emergency services at the scene, the "Platinum Ten" minute principle should be applied. This is the term used by emergency services to describe the first ten minutes on scene of an accident during which life support to the casualty must be established. Depending on the severity and condition of the casualty, life support can be established in-vehicle or in the back of the ambulance (Watson 2001). With this in mind, the FRS crew plan to make their first cut in the first 5 minutes of arrival on scene (Calland 2005).

Considering all the factors associated with current practices of the FRS, this paper will explore whether or not technology could play a part to aid in more effective extrications.

3.2.3. Augmented Reality

The author realised the potential to gather manufacturers data on passive safety systems and incorporating them within a database, to be augmented on a crashed vehicle via a mobile device. Augmented Reality (AR) "is a technology that allows digital information to be overlaid graphically onto views of the real world (Evans et al. 2001). AR is the application of computer generated models or objects to the real world through a digital device, such as a computer or Smartphone. The added information can be shown graphically in the form of 3D models or text, that have been predefined on a computer by the user. An example of AR is shown in Figure 47.

Figure 47: An Example of Augmented Reality (Fuld 2012)

AR technology has advanced considerably over recent years in terms of the detail, materials and lighting effects that can be applied to augmented models, which help to enhance the realism of the model. This is illustrated well in Figure 47.

3.2.3.1. How it works

There are three principal methods in which you can "trigger" AR to display:

- Geo-referenced data
- Markerless trackers
- Marker tracked data

Geo-referenced data

Models produced on the computer can be referenced to a real world co-ordinate system. The user can then use a mobile device such as a smart phone in order to obtain their position and orientation. Modern smart phones have the ability to obtain a GPS co-ordinate that, coupled with a built in digital compass, allows them to be used as the location device to orientate to a predefined 3D model.

There are some limitations to geo-referencing, the obvious being that GPS only works outside. In addition, the accuracy of the GPS that can be obtained by a smart phone is currently only around 10m, although there is an option to use a computer and external GPS unit for higher accuracies such as the work undertaken by (Evans et al. 2001). However, this methodology reduces the portability of the equipment.

Markerless trackers

Recent advances have been made in this field, for example the 3D tracker that has been developed by Inglobe Technologies (Inglobe Technologies 2013). The 3D tracker computes the geometry of a object in order to "trigger" the AR model to display.

There are some limitations with 3D tracking, in that the object used as the trigger, has to accurately represent the predefined model, when programming the augmented reality. For example, if this methodology were to be used on a crash damaged vehicle, there may not be enough common geometry recognisable, to "trigger" the AR. However, for vehicles with minor damage, this may not present an issue.

Marker tracked data

This methodology requires the user to link the model to a predefined marker. When a camera is pointed at the marker this will form the "trigger" for the AR. An example of an AR marker is shown below in Figure 48.

Figure 48: An Example of an AR Marker

The device used for the AR computes the differences between the white and dark areas in order to distinguish between different markers.

There are some limitations to marker technology, the obvious being that the marker has to be visible to the camera within the scene that the user wants to augment. In addition, the camera and the object have to be relatively "square on" to the marker (with some flexibility) to ensure recognition.

3.2.4. Application to RTC Management

As previously discussed there are a number of hazards that FRS personnel face when performing extrications following a RTC. The author realised, it is possible that a database of the passive safety systems of vehicles can be categorised and augmented through a mobile device, in order to display them on the vehicle involved to minimise these hazards. A prototype system was devised and developed using magnetic targets (marker tracked), a mobile device linked to a pre-programmed virtual model and interactive headset display. However, as commercial application of this design may be forthcoming, information regarding its development will be limited within this paper.

Figure 49 shows the application of AR reality using the locations of passive safety systems to a vehicle in a mock situation. It can be seen from the image that the locations of the SRS system, Boron steel (blue), side impact bars, type of glass and also the locations of the door hinges (green) can be observed.

Figure 49: AR Example onto a Vehicle

After discussion and trials with the FRS, AR is considered to have substantial potential benefits in the extrication process and could then be used by the IC in the following cases:

- 360 degree survey of the scene
- Dynamic Risk Assessment (DRA)
- Formulation of an extrication plan
- Overall management of risk

3.2.4.1. 360 Degree Survey of the Scene

As indicated previously, upon arrival at the scene of an RTC, the IC will perform a 360 survey of the scene in order to assess the incident and make decisions on the observed information. Considering this, the IC could place AR markers onto the vehicle in order to clarify the location of the passive safety systems that may pose a risk to the extrication process. The extra information that can be observed may result in different decisions being made. For example, the AR model may inform the IC that the vehicle contains magnesium materials which would require a different methodology to firefight the vehicle if combustion occurred.

3.2.4.2. Dynamic Risk Assessment

As stated previously, the IC will undertake a DRA in order to assess the possible hazards that could be detrimental to the extrication process. With an understanding of the number and location of passive safety systems, the IC can make a more informed decision regarding the management of risk on scene, in order to ensure the safety of emergency service personnel and of the casualty. For example, the AR model may indicate that the vehicle contains a hybrid drive system, involving considerably different risks to that of a conventional combustion engine.

3.2.4.3. Formulation of an Extrication Plan

When formulating an extrication plan, the IC must consider a route that is efficient, with regard to time, the resources available and also considering the medical state of the casualty. If the AR indicated to the IC the location of any boron metal within the vehicle, the extrication plan might change considerably. As previously stated boron metal has a higher tensile strength than the conventional tools used by FRS personnel can cut. Thus, early identification of boron metal may be crucial in the extrication plan that has been formulated by the IC, in order to save time in dealing with the arising situation.

3.2.4.4. Overall Management of Risk

The scene of a RTC can be strewn with hazards and can also become a hive of activity with emergency services personnel all trying to work together in a confined space. Therefore, information regarding the hazards obtained early through AR may prove crucial in maintaining the overall safety of emergency personnel.

3.2.5. Possible Benefits of AR within the Extrication Process

There are a number of possible benefits that could be obtained from incorporating the methodology discussed above in the extrication process, which include improvements in:

- Emergency Services Safety
- Casualty Safety
- Injury Statistics
- Tool Life

Emergency Services Safety

Within the management of an RTC scene, it is paramount to ensure the safety of the emergency services personnel. As previous stated, passive safety systems are designed in order to reduce injuries during road traffic collisions. However, these systems pose a direct risk to emergency services personnel in the extrication process, having the capability to harm or kill. Early identification of the locations of these systems are crucial in order to control risk associated with extrication.

Casualty Safety

During the extrication process it is possible for the emergency services personnel to accidently activate a passive safety system. In order to reduce the possibility of accidental injury of the casualty, certain control measures are applied. These range from steering wheel airbag suppression systems to informing the casualty of glass breakage when FRS personnel are creating space. Many of these controls are designed in order to maintain the position of a casualty, so as to reduce the possibility of further spinal injuries.

Injury Statistics

Improved safety systems within modern vehicles have resulted in a higher survival rate from RTCs. In addition, this has increased the number of time critical extrications that the FRS currently undertake. Effective management on the scene of an RTC through the "team approach", is focused on creating synergy between members, to reduce the time taken to release the casualty, adhering to the "platinum ten" minutes principle. AR may aid in timely removal of a trapped person(s), which will provide the opportunity for enhanced medical attention in an ambulance or hospital, thus improving injury statistics.

Tool Life

With modern vehicles incorporating boron steel into the construction of the pillars, there is a possibility that FRS personnel may inadvertently try and cut boron steel with conventional equipment. As boron steel has a higher tensile strength than conventional tools can cut, this can cause damage to the tool. Through early identification of the locations of boron steel this will improve the life of the tools used by the FRS.

3.2.6. Conclusion

Modern vehicles are more technologically advanced than ever before. However equipment and knowledge of passive safety systems within the FRS has not been able to advance at the same rate. In addition, increasing numbers of licensed vehicles on the roads leads to the potential for increased congestion and likelihood of accidents. This is set to continue, therefore it is essential that the FRS have the ability to ensure safe and timely extrications from vehicles in RTCs, in which technological advancements like AR could make a valuable contribution.

The focus of vehicle manufacturers on safety has been to use active safety systems to reduce the possibility of an accident, but if an accident occurs, for passive systems to be activated to alleviate the consequences of the incident. However, little is currently being done by manufacturers to reduce injuries that may arise from the extrication process, particularly, as a casualty's injuries do not cease to exist after the accident occurs.

The number and location of passive safety systems vary greatly between vehicles, thus posing a considerable problem (detailed in this paper) to FRS personnel when undertaking an extrication of a trapped person.

Currently, the FRS are heavily reliant on the experience of the attending personnel and on the 'peel and reveal technique' to establish the locations of passive safety systems. Some of the problems of passive safety systems are that if one of these systems were accidently activated during the extrication process, this could compromise the safety of the emergency services personnel and also of the casualty within the vehicle. It is also known, that a small movement of a casualty with spinal injuries can have detrimental effects, in regard to additional damage caused. In addition, the focus on extricating the casualty quickly is also present to ensure that medical attention is established as soon as possible. Therefore, being dependent on the time consuming task of removing interior panels is an obstacle to the narrow time constraints which have to be adhered to.

The use of AR in the extrication process expressed within this paper, is a novel application of a developing technology, with a number of possible benefits that could be obtained if implemented. However, the prototype and trial developed by the author, has highlighted a number of problems which are currently being rectified to create a reliable product.

The fundamental problem is establishing the location of passive safety systems and developing a database for every vehicle currently on the road. Obviously, to undertake the task of locating every safety system manually would be very onerous and completely unpractical given the continual supply of vehicles being developed by manufacturers and sheer number of vehicles on the road. Therefore, a project such as this would have to be taken in conjunction with the motor industry.

When constructing vehicles, manufacturers produce 3D models of every aspect of the design process, which could be utilised to create augmented products such as the one highlighted in this research. Given the number of passive safety systems and the risks they pose to personnel, manufacturers should release the data to FRS as part of their duty of care to customers and the emergency services. Following this, the step to incorporate AR, would be relatively easy and could form a long term solution to the risks.

Another aspect that has to be addressed, is the AR trigger system chosen and the practicality of its deployment in a RTC scene. The prototype incorporates a marker system using magnetic targets that can be placed on the crashed vehicle. Marker tracked targets, have a number of different problems, which have been found through this research. For example, the placement of the target onto the vehicle in order to establish the accurate projected location of the safety systems can by problematic. Therefore, work is currently being undertaken to ensure synergy in the placement of targets in strategic locations of the vehicle.

Initially, the author believed that a marker-less tracker based system would be the preferred option. However, this can be problematic where a vehicle has sustained considerable damage and the reference geometry does not represent the crashed vehicle in its current state.

In many cases, only a small amount of the vehicle may be needed to initiate the trigger of the AR, for example, a particular shape of a car's wing or headlight could be the pre-programmed target shape. However, if the car has sustained damage in this area, the AR may not trigger and therefore the system will become redundant in an emergency situation. Considering this, a marker system was incorporated into the prototype containing four simple targets, which can be placed on each side of the crashed vehicle. The AR model then gives a indication of the location of the passive safety systems, types of glass and other aspects such as boron metal which will affect the operations that the FRS will undertake.

In addition incorporating a marker system, if the target is not exactly located in the correct position, it will still provide the IC with information, aiding in effective decision making and formation of an extrication plan.

The author plans to create a system that uses a combination of these two trigger methods, allowing the system to be dynamic and react to the situation in which it is applied.

Currently, the author has produced a prototype system that has been proven to work on a restricted number of vehicles with mock safety systems augmented. Proof of concept is considered to be established and commercial application is now being sought.

3.3. The Application of Deformation Monitoring as a Risk Assessment Tool in Fire Incident Management

Abstract

The management of emergency situations is essential in order to ensure effective operations while the safety of personnel and the public is paramount.

When managing a fire incident an Incident Commander (IC) is sometimes faced with difficult decisions when considering the structural integrity of a building and determining an efficient fire-fighting strategy. This is particularly the case where there may be persons trapped within the structure and time is of the essence to ensure their survival.

The IC has to make difficult decisions under considerable pressure of the situation. This paper will evaluate the application of new surveying technology as a deformation monitoring tool, to assist the IC in the real-time assessment of a building's structural capacity, providing the IC with up to date information on possible failures, which can be incorporated into the management of the scene and the control of risk in an ever changing environment.

In addition, this paper highlights the need for effective incident management with an historic review of fire-fighter fatalities in the UK and the increased legal scrutiny that ICs face when performing under intense pressure.

3.3.1. Introduction

The author was asked to attend a major building fire by the Incident Commander of the Fire and Rescue Service (FRS), in order to examine the use of laser scanning in an emergency situation. The aim was to explore where the equipment could be used to record the scene in high detail, helping in the discovery of the cause and origin of the fire, alongside conventional fire investigation practice. It was also considered, that the 3D survey could be used in respect of loss adjustment undertaken by representatives of the affected insurance companies, to aid in the classification of subsequent claims. While attending the scene an observing the events unfold, relating to fire suppression methodologies, the author realised the potential for the use of laser scanning for deformation monitoring to maintain the safety of FRS personnel and overall management of risk. This section discusses incident management and deformation monitoring in a high pressure emergency situation to aid in effective decision making, with focus on how laser scanning could be employed to this effect.

Fire fighters often operate in environments that expose them to serious chemical and physical hazards from the effects of a fire. These hazards are wide ranging and include trauma, burns, smoke inhalation and other health or physiologically related injuries (Guidotti & Clough 1992).

This has resulted in many losing their lives performing their job trying to save others. Between 2007-2008 the Fire Brigades Union reported that 8 fire-fighters died while on duty, 5 of which being on scene at a fire (The Fire Brigades Union 2008). This makes 2007-2008 the worst year since 1985, with 4 of the 5 fatalities taking place in one incident (The Fire Brigades Union 2008).

3.3.1.1. Review of Recent Building Related Fire-fighter Fatalities

This section will highlight case studies of recent fire-fighter deaths:

Gorteen House Hotel, Northern Ireland 2003 (The Fire Brigades Union 2008)

A fire-fighter in Northern Ireland was killed on 1st November 2003 at the Gorteen House Hotel. The incident occurred due to structural failure when a flat roof suddenly collapsed, with the fire-fighter falling into the fire below. Other crew members managed to rescue him, but he later died from his injuries.

Bethnal Green, London 2004 (The Fire Brigades Union 2008)

The Fire and Rescue Service (FRS) was called to attend a fire at a three storey structure on Bethnal Green Road in London, where two people were rescued from a roof. Unfortunately, during the operation two fire-fighters were overcome in the basement of the building, when they were sent to ventilate the fire.

Harrow Court, Hertfordshire 2005 (The Fire Brigades Union 2008)

Hertfordshire Fire and Rescue Service (HFRS) were called to a fire in a burning block of flats in Hertfordshire on 2nd February 2005. Two fire-fighters tragically lost their lives when they were overcome by heat while tackling the fire on the 14th floor of the block of flats.

Atherstone-on-Stour, Warwickshire 2007 (BBC 2013)

Warwickshire Fire and Rescue Service (WFRS) were in attendance of a fire at a vegetable plant on the 2nd November 2007 in Atherstone-on-Stour when four fire-fighters died. The four men died when the structure of the building collapsed. Three WFRS managers were charged with gross negligence manslaughter but later found not guilty.

Shirley Towers, Southampton 2010 (BBC 2012b)

Hampshire Fire and Rescue Service (HFRS) were attending a blaze at Shirley Towers in Southampton when two fire-fighters lost their lives. The two men became trapped by the fire and died after being overcome by the heat.

With these deaths in mind, learning from the mistakes made in the past and the effective management of incidents is crucial in order to prevent further fatalities.

3.3.2. Fire Fighting Strategy

Upon arrival on scene the Incident Commander (IC) has to decide on the methodology best suited to the situation. The IC must decide on a strategy that can be offensive, defensive or a combination of both to tackle the fire (Lee 2009a).

Offensive Fire Fighting

This is a methodology where "water or other extinguisher is taken directly to the seat of the fire" (East Glenville Fire Department 2009).

Defensive Fire Fighting

This is a methodology where the fire is fought externally as conditions are considered to be too dangerous inside the structure (Santonio Fire Department 2009). The decision is based on a number of factors including resources, persons trapped, structural stability, life hazards to fire-fighters and exit strategies (Lee 2009c).

3.3.2.1. Selecting a Strategy

Upon arrival at an incident, the IC should familiarise themselves with the environment, while establishing information about the fire and its development. A 360 degree walk around survey should be undertaken in order to observe the incident from all visible areas, noting the condition and position of hazards that could be encountered (Lee 2009c).

During the walk around, the IC will be gathering site specific information that may or may not point towards the use of a particular strategy such as hazardous materials, building construction and entry points (Lee 2009c). The IC will pay particular attention to the structure to identify indications of collapse such as (Lee 2009b):

- Cracks or separations in the walls, floors, ceilings or roof structures
- Loose materials that could fall from the structure
- Evidence of previous structural stability problems that have been rectified
- Walls that appear to be leaning
- Distorted structural members
- Unusual noises of strain
- Structural supports that have been under prolonged fire exposure
- Heavy machinery or equipment on floors above a fire
- Structural members becoming detached
- Unsupported petitions or walls

In addition, the IC should establish the time in which the fire has been burning. With this information the IC should begin to formulate a action plan (Lee 2009c).

The Incident Commander may consider the conditions suitable for an offensive strategy. However, the IC will continue to evaluate the situation through Dynamic Risk Assessment (DRA) and may decide to change the methodology at a later time (Lee 2009a).

An IC is ultimately responsible for the safety and welfare of everyone on an incident scene, and should make informed decisions based on expertise and not gamble with lives (Lee 2009a).

3.3.3. Case Study: Falmouth Beach Hotel Fire, Cornwall UK

On 30th April 2012, a fire destroyed the Falmouth Beach Hotel; a prolific building on the sea front of Falmouth Bay (Hardy 2012). An image of the front of the hotel is shown in Figure 50.

Figure 50: Image of the Falmouth Beach Hotel

The fire spread quickly through the building due to gale force winds that fanned the flames. At the height of the fire, there were more than 100 fire-fighters deployed to bring the incident under control (BBC 2012a).

The IC decided to adopt a defensive fire-fighting strategy in order to tackle the incident due to the structure's instability and the ferocity of the fire. In addition to the conventional 360 degree visual inspection undertaken by the IC, a helicopter was deployed by a local naval base RNAS Culdrose, in order to allow the officer to assess the structural conditions from the air (Hardy 2012).

The decision by the IC to implement a defensive strategy, was the correct one as the fire caused the hotel's roof to collapse (BBC 2012a). However, at the time of the incident the decision to undertake this strategy may have taken careful consideration, as not all of the guests were accounted for until the next morning (Hardy 2012).

Following the incident it quickly became apparent that the fire was accidental and caused by a roofing contractor (Hardy 2012). However, a record of the building was created if later required, and the importance of an assessment for deformation monitoring in fire incident management was highlighted to the author.

As part of the Camborne School of Mines ongoing research programme, the author attended the scene, in order to laser scan the incident to provide an accurate visual record of the event, which could be used if necessary in the future. An image of part of the survey data is shown in Figure 51.

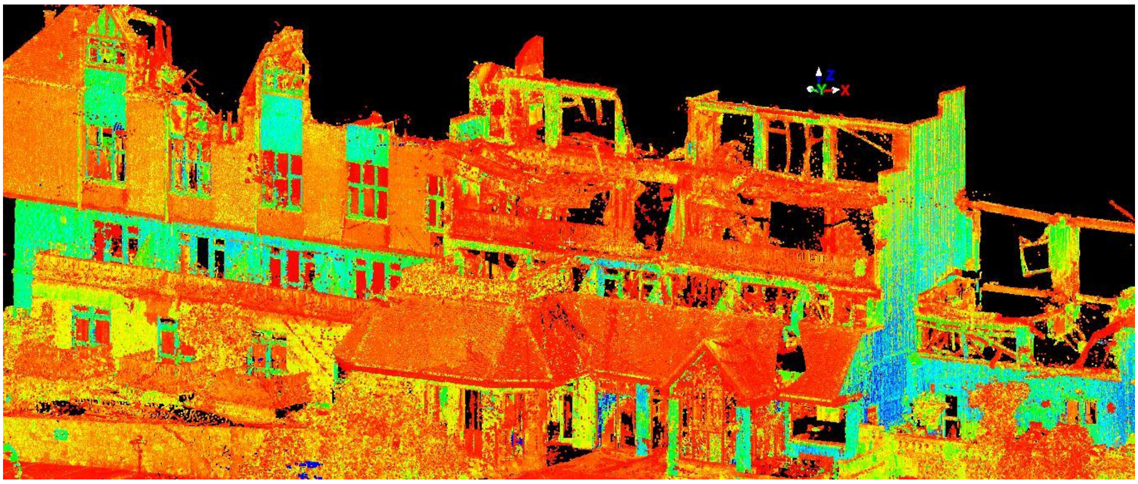


Figure 51: Falmouth Beach Hotel Survey Data

An image of structural instability is shown below in Figure 52.

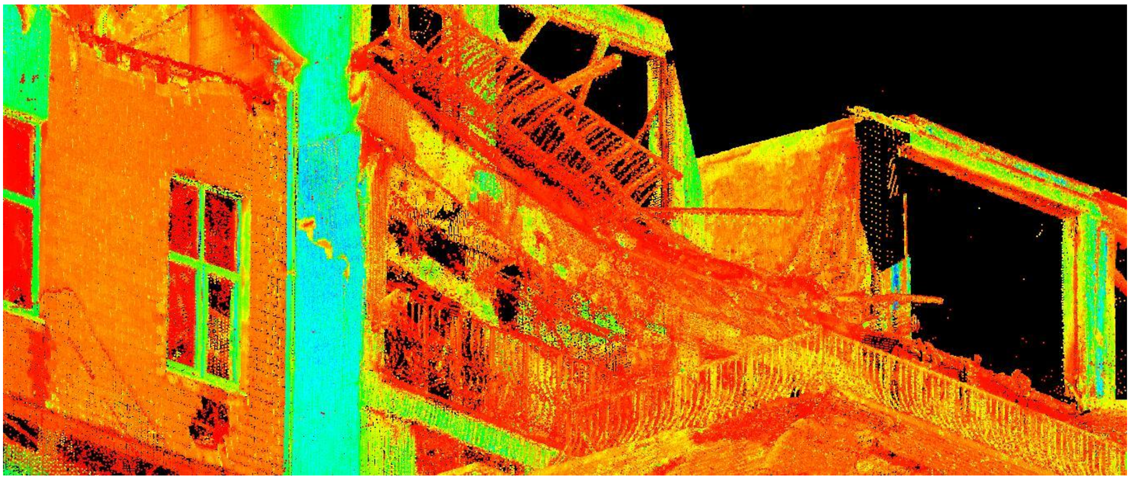


Figure 52: Laser Scan of Unstable Structure

In Figure 52, the density of the data collected can be seen, providing a record of areas that have been heavily affected by the destructive nature of the fire.

Additional laser scans can be taken of the same area and then quickly compared in order to assess the building for structural integrity.

3.3.4. Deformation Monitoring

There are various methods that can be utilised in order to monitor a surface for movement which can be used in situ or remotely. The established methods are summarised as follows:

3.3.4.1. In Situ Monitoring

Analogue Measuring Equipment

Analogue measurement equipment allows an engineer to record measurements of a surface manually and reference them to future measurements to detect movement. An example of an analogue measurement device is a tell tale. Tell tales are measurement devices that can be fixed in situ across a crack to monitor if it is increasing in size. The most common tell tale consists of two overlapping pieces of plastic, one having a marked grid and the other having a red cross indicator (The Helpful Engineer 2011). Once installed, an initial reading is taken and then compared to future measurements to assess any movement.

In addition to tell tales, reference markers can be fixed to the structure and measurements can be recorded at different intervals, using an instrument such as a micrometer (Read & Stacey 2009).

Digital Measuring Systems

There are various digital sensors available to measure movement of a surface such as Digital Extensometer Technology with Eddy Current Transducers (DETECT). DETECT systems are in situ devices that use electronic transducers to determine movement. These sensors are widely used in underground mining operations (Hyett 2004). In addition, digital sensors can be connected to data loggers in order to record historical data.

Global Positioning Systems (GPS)

GPS has been in common use for deformation monitoring since the 1980s, monitoring civil structures for movement (Khoo et al. 2010). Advancements in GPS technology and wireless communications have allowed for accurate measurement, recorded by using networks of corrected GPS units. In addition, once positioned, the sensor can then relay live data back to a computer (via wireless internet link) for comparison, without repeat human interaction and operating in all weather conditions (Khoo et al. 2010).

In order to obtain a 3D measurement using a GPS monitoring system, the receivers must have a unobstructed view of at least 4 satellites. In addition GPS systems do not require line of sight measurements which other remote monitoring applications, such as total stations demand.

Summary

As in situ monitoring systems require to be fixed to the structure they have implications in fire incident management. They are problematic in terms of safety, fitting the system to a possibly unstable building. In addition, the time taken to fit the device and record data would make their use impracticable.

3.3.4.2. Remote Monitoring

Total Stations

Information regarding this technology has been detailed in the literature review of this PhD and will not be discussed again in this case study.

The use of total stations with reference to structural monitoring in an emergency situation, could become problematic, as measurements would first have to be taken, then processed and evaluated. With this in mind, using total stations may not meet the time constraints required.

In addition, total stations are single point measuring instruments, recording movement of set positions. This may have implications as the target locations (set positions) may not give a true representation of a structure’s movement.

Photogrammetry

Photogrammetry is a measurement technology that relies on the operator to take two or more images of a surface from known positions of varying angles. The focal length of the camera is considered and then the images can be joined together forming a 3D model of the structure (Transportation Reseach Board 2012).

Improvements in digital photography and image processing techniques have made photogrammetry a relatively inexpensive method for deformation monitoring (Transportation Reseach Board 2012). However, as with total station surveying, the data has to be processed after collection and again may not meet the time constraints of an emergency situation.

Slope Stability Radar

These systems work by recording the time taken for a signal, with known amplitude, wavelength and velocity, to travel to a reference object and back to the receiver, with differences in the phase of the wave, then being computed in order to establish a distance (Read & Stacey 2009). The angular measurement is obtained in reference to the location of the instrument.

The accuracy of radar has been explored, with equipment manufacturers specifying accuracies of less than 1mm within distances of 2500m (Pienaar 2012). Radar based systems have been used in open pits in mining applications to provide real time monitoring of rock faces (Farina et al. 2012). In addition radar technology is not affected by atmospheric conditions to the same extent as light based distance measurement, as radar operates on different wavelengths (Transportation Reseach Board 2012).

Data from the instrument is typically sent electronically to a computer where it is plotted and analysed for an immediate visual review. However, data can be viewed on the unit itself and comparisons can then be made between each radar pass (Read & Stacey 2009).

LiDAR (Terrestrial and Mobile)

LiDAR (Light Detection and Ranging) equipment works in a similar way to total station measurement. However laser scanning technology is able to perform the measurements much faster, up to 1 million times a second.

LiDAR based systems provide a high resolution survey of an area known as a point cloud. The resolution is considerably higher than a radar based system, however due to atmospheric effects, LiDAR is not as accurate (Transportation Reseach Board 2012).

LiDAR systems can be operated from a static position (terrestrial) or on the move (mobile). Terrestrial systems allow data to be gathered from one position and then the instrument is physically moved to a new position (if required), the data then being joined together through registration. Mobile based systems incorporate an inertial measurement unit (IMU) that feeds data back into the system regarding the instrument's location and which compensates for movement of the equipment when in transit (Transportation Reseach Board 2012).

Summary

Upon consideration of different remote monitoring technology, a radar or LiDAR based system could be incorporated into the assessment of deformational risk in a structure, as these systems have been widely used for similar purposes in other industries.

3.3.5. Applications to Fire Incident Management

3.3.5.1. Benefits

There are a number of key benefits of incorporating an effective deformation monitoring system with regard to fire incident management:

Safety

FRS personnel safety is vital when managing an incident, making sure that all employees go home safe at the end of a shift. Incident commanders are often faced with the decision of risking the lives of fire-fighters to try and save victims who may not be saveable (Lee 2009a).

Improvements in monitoring will aid in the prediction of building collapse and therefore allow either the removal of FRS personnel from a structure or highlight the areas which are safe to operate in.

Improved DRA

Fire can often be unpredictable in its development, therefore a Dynamic Risk Assessment is undertaken to compensate for an ever-changing environment. Currently, ICs make decisions about the condition and structure of the building through experience and the information available. This is often obtained through visual inspection of a structure's condition, this inspection being by its very nature 'line of sight' and may not necessarily give a clear picture of what is happening behind an obstruction.

With this in mind, by incorporating an effective monitoring system which gathers "live" data on the condition of the building(s), informed decisions on a fire-fighting strategy can be made by the IC.

Remote Monitoring

When an IC makes an initial 360 walk around survey, they make decisions based on the conditions of the building at that point of time. However, any time after that this information is technically "out of date", this means the structure has to observed a number of times throughout the operations in order to make sure the conditions have remained consistent. By capturing data either continually in areas which are not in direct line of sight to the IC, a system can be created that data for these areas will still be analysed.

Improvements in Causalities Injuries

Undertaking an offensive methodology, with up to the minute information, to tackle a fire is more effective to mitigate its effects. Therefore, if incorporating an intelligent monitoring system can allow more fires to be tackled offensively then this may have a correlation to improved injury statistics.

Data Acquisition

Once recorded the information of a structure’s deformation can be archived. This will allow the information to be analysed and used in future incidents and provide a deeper understanding of structures under combustion. The information could also be evaluated and have an impact on building standards relating to fire prevention.

3.3.5.2. Limitations

Incorporating monitoring technology into fire incident management is not without limitations:

Visibility of scene

As laser scanning and radar equipment measure what the instrument can "see" (line of sight), this could have implications when recording a specific area of a structure e.g. with the addition of debris and obscuring factors, not everything would be seen when the instrument would be used from a ground level. Therefore, fires that are in areas of considerable height, such as a block of flats, may not be in view of the instrument.

Establishing Trigger Values

In order to calibrate the software, a value for "considerable" movement must be set in order to allow for comparison of data and indicate movement. Without a "trigger value" there could be possible problems in the software constantly identifying marginal movement, which may not have an impact on a building’s structural capability.

Cost

As laser scanning and radar technology is still within its infancy, much of the equipment is very expensive. Justifying the cost of the equipment to a public sector that is currently undergoing tough economic times, could be problematic.

Availability of equipment

Due to the cost of the equipment individual fire and rescue services may only be able to afford one instrument. With this in mind, this may have implications in assigning the resource to an incident and decisions would have to be made when allocating the equipment.

3.3.6. Conclusions

The number of fire-fighter on duty fatalities in recent years has been higher than in previous years due to the accidental deaths that have occurred. By implementing a robust monitoring system, deaths as a result of structural collapse could be reduced.

Although the cost of the equipment is currently high as the technology becomes more established, the costs will reduce. In addition, can a cost be put on a human life and especially one that has been sacrificed for the benefit of others? In relation to the deaths of the four firefighters in Atherstone-on-Stour, the investigation costs totalled £4.6m. The prevention of future incidents could justify the initial outlay of the equipment and avoid anguish being felt by families.

Finally, given that a charge of gross negligence manslaughter can be faced when an incident goes wrong, providing an IC with as much information as possible regarding the structure of a building, will hopefully reduce some of the immense pressure of an emergency situation, thus allowing them to perform their job more effectively protecting the lives of the public and FRS personnel.

As the Incident Commander is only able to be in one place at one time, the use of a scanning system that could be fitted on top of a fire engine would be of considerable benefit, if the vehicle was positioned strategically. If the device has an integrated system that can detect deformation through periodic scanning and comparison of the datasets. A traffic light system could be employed, similar to that used in the mining industry to monitor movement in slopes, where personnel are alerted via electronic communication if a trigger limit is exceeded. This could be highly beneficial to scene safety and the reduction in pressure placed upon the IC.

Considerable thought will have to be placed on the establishment of the trigger values to initiate an alarm, thus ensuring that the system is robust enough to warrant its effective deployment in the management of a fire scene. For example, if a slate were to fall from a roof, the system may consider this to be a considerable movement and it would trigger an alarm. However in practice, this may not be an indication of the structure failing, requiring the subsequent fire fighting strategy to be changed or the withdrawal FRS personnel for their safety.

Therefore, calibration of the system would be required and established by applying the technology to a number of similar cases. In respect of applications where laser scanning and radar is currently applied, for example monitoring a slope in the mining industry, establishing trigger values is a relatively simple task as the slope will be constructed in a way to ensure limited movement and could be considered stable for the majority of the time.

This is not the case in terms of fire, where the scene can be very unpredictable, particularly in areas which cannot be seen, such as a void or the internal areas of a building. Therefore, development of as a system which could be used in fire incident management would have to be calibrated to ignore small items. This could be achieved by considering the model as a whole or in large sections to help classify movement.

However, the system must be sensitive enough to detect relatively small movements (of large structures), thus becoming a key benefit as a relatively small movement may not be visible to the naked eye. An electronic indication can then be sent to the IC, thus encouraging him/her to investigate the matter further or highlight the area as one that requires attention.

In addition in many cases, the IC is limited in respect of their field of view, this being restricted to ground level. In the above case study, a helicopter was deployed to provide the FRS with assessment of the scene from above, thus giving the IC information that was previously unattainable. However, the cost of implementing a solution such as this is substantial and therefore not practicable in many cases.

Considering this, if a system was developed that is elevated, providing information that could not be seen from the ground, this could be of significant benefit to FRS. However, the system would then have to compensate for potential movement of the equipment in which it has been fixed, such as the systems used in mobile mapping systems, this being considerably more expensive than conventional terrestrial (static) based systems.

The system could be detachable from a piece of equipment like many mobile scanning platforms currently available. Therefore, the instrument could be utilised in the subsequent fire investigation following the incident, such as the one explored previously within this PhD research study.

4.0 Chapter 4: Applications of Laser Scanning and 3D Modelling within the Industrial Accident Investigation Process

This chapter is presented in a number of case studies written in the style of academic papers

Case Study One: The Integration of Laser Scanning and 3D Models in the Legal Process following an Industrial Accident

Work was undertaken in conjunction the UK Health and Safety Executive (HSE) and the Health and Safety laboratory (HSL) following a fatal accident which led to a legal prosecution. The technology was used retrospectively, after the event, in order to reconstruct the environment both virtually and physically for the benefit of the court.

Case Study Two: The Use of Laser Scanning as a Method for Measuring Stairways Following an Accident

Work was undertaken in conjunction the UK Health and Safety Executive (HSE) and the Health and Safety Laboratory (HSL) following two fatal accidents. The technology was used to evaluate its use in determining accurate measurements for variations in rises and goings, with the additional benefits that could be obtained from incorporating this technology by comparison to conventional approved methods.

Adapted from

Eyre, M., Foster, P., Hallas, K., & Shaw, R. (2015). The Use of Laser Scanning as a Method for Measuring Stairways Following an Accident. *Survey Review*, 20. doi:10.1179/1752270615Y.0000000014

Published in Survey Review ISSN -0039-6265

Case Study Three: The Integration of Laser Scanning and 3D Modelling in the Industrial Accident Investigation Process

Work was undertaken in conjunction the UK Health and Safety Executive and the police, following a fatal accident resulting from a fall from height. The technology was used to aid in the reconstruction of the event, helping the investigation team to verify statements and test hypotheses in a geometrically accurate virtual environment.

Adapted from

Eyre, M., Foster, P., & Speake, G. (2014, August). Surveying the Scene. *SHP Magazine*, P4. Retrieved from http://www.shponline.co.uk/features/cpd-articles/features/full/surveying-the-scene

Published in SHP Magazine, with Article and Video available also online:

4.1. The Integration of Laser Scanning and 3D Models in the Legal Process following an Industrial Accident

Abstract

Improved focus on health and safety has resulted in a considerable reduction in accident rates worldwide. However, incidents still occur with wide spread impacts on those involved and to the country as a whole through financial implications. In order to obtain a deeper understanding of an incident, it needs to be investigated to "peel back the layers" and examine both the immediate and underlying failures that contributed to the event itself. One of the key elements of effective accident investigation is recording the scene for future reference, thus aiding to help explain the event to others. In respect of this, survey methodology has been focused on the production of 2D deliverable data such as photographs or 2D plans of the scene.

In recent years, however, there have been major advances in survey technology, which have provided the ability to capture scenes in 3D to an unprecedented level of detail, using laser scanners. This technology has been widely accepted by many professionals and is gathering pace with continual innovation, into how to process the associated rich data set. As a result, laser scanning equipment is beginning to be used for a variety of applications including recording accident scenes.

On occasions, an accident investigation may highlight that a breach of the law has occurred. In the UK this results in the Health and Safety Executive (HSE) working within the British legal system with the aim of securing justice for those involved. The legal system is used to ensure a fair trial and provide a verdict and this in mind, the judicial system is beginning to be exposed to laser scan deliverables, aiding in the explanation of the circumstances of the incident to people unconnected to the event, such as a jury.

This paper highlights how laser scanning can be introduced as a tool in a court room, through discussion of a case study of a fatal accident,

thereby exploring the possible benefits and limitations of incorporating the technology, with discussion of both physical and virtual models.

4.1.1. Introduction

4.1.1.1. The Problem

Accidents occur resulting in life changing effects. However, industry is committed to reducing accidents, with improved health and safety performance, aiming to eliminate incidents at work. An accident can have wide ranging implications particularly if there has been a fatality. A recent survey undertaken by the Health and Safety Executive (HSE), revealed 118 people were killed while at work in 2011/2012 (HSE 2012a). However, in addition to fatal incidents, 40 million working days were lost through work related injuries costing UK businesses £2.5 billion (HSE 2004). The problem is not restricted to the UK, with an estimated 4.6 million occupational accidents occurring every year in the European Union, resulting in 146 million lost working hours (Rikhardsson 2004). Accidents have considerable physical and financial implications and studies have shown that for every £1 a business spends on insurance, it could be losing £8 to £36 in uninsured costs (HSE 2004).

Considering these figures, it is clear that there are humanitarian and financial benefits that can be achieved from managing risk more effectively. In recent years, this has been largely understood and businesses have placed great focus on health and safety, working with additional legislation. This can be demonstrated by examining fatal injury statistics. It can be seen the UK that in 1981, a total of 441 people were fatally injured while at work, compared to 118 between 2011/2012 as previously stated (HSE 2012c). There are a number of possible contributing factors that have resulted in this reduction, such as improved accident investigation and analysis (HSE 2004). However accidents are still occurring and the number of fatalities across all industries are still significant. Further improvements can still be made by concentrating on reducing the re-occurrence of similar accidents, complementary to investigation and analysis.

4.1.1.2. Accident Investigation

As an industrial environment is ever changing so is the risk associated with work activities. Therefore a dynamic health and safety management system has to be integrated into operations to manage risk effectively, thus reducing incident numbers. A robust system can be achieved with commitment to suitable safety controls, adequate supervision, monitoring and management which are essential in order to safely engineer work activities (HSE 2004). Many of these controls are found in effective accident investigation and lessons learnt from previous incidents.

4.1.1.3. The Requirements for Accident Investigation

The Management of Health and Safety at Work Regulations (1999) state in Regulation 5 that "Every employer shall make and give effect to such arrangements as are appropriate, having regard to the nature of his activities and the size of his undertaking, for the effective planning, organisation, control, monitoring and review of the preventive and protective measures". Despite these regulatory requirements, there is still no statutory duty in the UK to investigate accidents in the workplace. However, it forms an essential component of a formal health and safety management system certification, such as OHSAS 18001 or the forthcoming ISO 45001.

Certain incidents, diseases and injuries must be reported under the Reporting of Injuries, Diseases and Dangerous Occurrences Regulations 1995 (RIDDOR). This also forms an important component of an ISO 18001 together with other certification systems. Additionally, the report, 'Access to Justice' by Lord Woolf states that a business is expected to give full disclosure of the circumstances of an accident, if the injured parties are considering legal action (HSE 2004).

Accident investigation is essential to learn lessons of the event and establish controls that can be applied to an organisation’s safety system. On occasions, an investigation may identify breaches of the Health and Safety at Work Act (1974), in such cases there is a legal duty to enforce the law.

4.1.1.4. Decision to Prosecute

The HSE's role is to protect people at work and safeguard others from the risks associated with the way in which work is being carried out (HSE 2009). The HSE, on occasion, have to take enforcement action against duty holders to manage and control risks within the workplace effectively, preventing harm to personnel and the public (HSE 2009).

HSE ensure that duty holders comply with the law regarding health and safety. Dependent on the breach, it may be appropriate to serve the duty holder with an improvement or prohibition notice, or to withdraw approvals, or vary license conditions or issue a simple caution or ultimately to prosecute in a court of law (HSE 2009).

The decision is based on a number of factors. In the UK, the HSE take enforcement decisions in line with the Enforcement Policy Statement (EPS). The EPS is a series of principles, which the HSE follows in order to determine what enforcement action to take if and when necessary, for example when a breach of health and safety law has been identified (HSE 2013b).

An HSE Inspector has to ensure that enforcement action is proportional with regard to the health and safety risks and the seriousness of the breach that has occurred, against a benchmark (HSE 2013b). To facilitate this, a model has been created to maintain consistently, known as the Enforcement Management Model (EMM) (HSE 2013b).

Dependent on the seriousness of the breach and the risk arising from it, the inspector with the aid of the EMM, will then select suitable enforcement action to be taken. In practice, incidents that have demonstrated a high risk and/or extreme failure, will prompt the Inspector to pursue a prosecution (HSE 2013b). Particular attention must be taken by the Inspector with regard to the following circumstances (HSE 2013b):

- A breach in legislation has resulted in a death.
- There has been a failure to comply with previous enforcement action taken by an Inspector, demonstrating disregard for an improvement, or prohibition notice or a breach that was subject to a prior caution for the same breach.
- Deliberate false information being supplied that has the intent to deceive the Inspector.
- An intentional obstruction to an Inspector to carry out their duties

In addition to the above, if it can be demonstrated that the duty holder has failed to comply with legislation, this may prompt an inspector to pursue a prosecution (HSE 2013b).

Following a decision by an inspector to prosecute, the process will be peer reviewed by a independent person within the HSE (HSE 2013a), the review being normally undertaken by a Principal Inspector (PI). The PI will then examine if it is in the public interest to prosecute. The PI will assess a number of factors such as, if (HSE 2013a):

- the law has been properly applied
- the evidence is presented in an admissible form
- the investigation identified anything that undermines the prosecution or assists the defence
- HSE has adhered to the Human Rights Act 1998
- commencement of the case is in line with other proceedings
- the correct defendant(s) has been identified
- the investigation has been in accordance with the EPS

In addition, the decision may have to be reassessed if the circumstances surrounding the case are subject to change. However, if there is no change and the PI upholds the case the process continues and summons are served upon the defendant(s).

4.1.2. The Legal Process

Following an incident there are a number of processes that have to be undertaken before the case is completed. This process is shown in Figure 53.

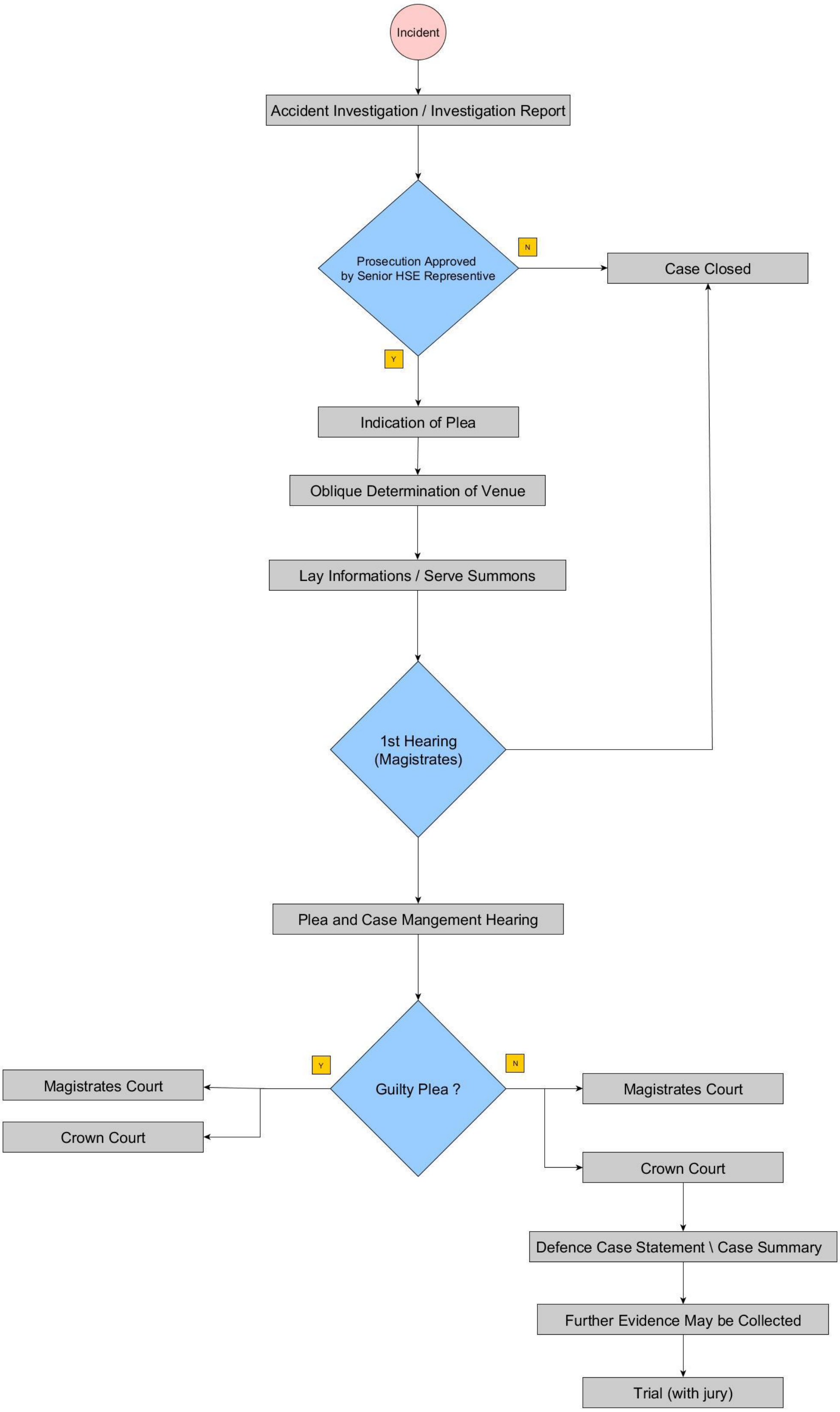


Figure 53: The Legal Process

4.1.2.1. The Role of Expert Witnesses

In certain trials, the views of an expert may be necessary to aid the court in particular aspects of the case. An expert is classified as a person who is required to give or prepare evidence for criminal proceedings (Ministry of Justice 2013). He/she may be called by the prosecution or by the defence and they must provide an unbiased and objective opinion regarding their specialist area (HSE 2013d). Their role is to assist the court on matters that are not within the everyday experience of a jury to aid them to make decisions on particular aspects of the case (HSE 2013d). It is for the court to decide if an expert's evidence is admissible and whether he/she is suitably qualified to express their opinion (HSE 2013d). On occasion, experts can identify with the side in which they are associated with, which can become problematic if an expert answers become biased and produce an objective opinion. To provide a check on this, when an expert is instructed to act, all documents of communication are submitted as evidence and this can be used by the opposing side in order to examine how the expert has came to their conclusion.

4.1.3. Case Study: Fatal Accident, 2010

4.1.3.1. Background of the Incident

In 2010, an elderly lady died after disembarking a passenger ferry at a quay, when she fell from some quayside steps into a river below (Birch 2013). The steps and landing platform within the quay are shown in Figure 54.

Figure 54: Step and Landing Platform

Subsequent to the incident and upon recommendation of the Health and Safety Executive (HSE), a number of changes were made to provide a safer means of access and egress to the ferry. One of the changes to the steps is shown in Figure 55.

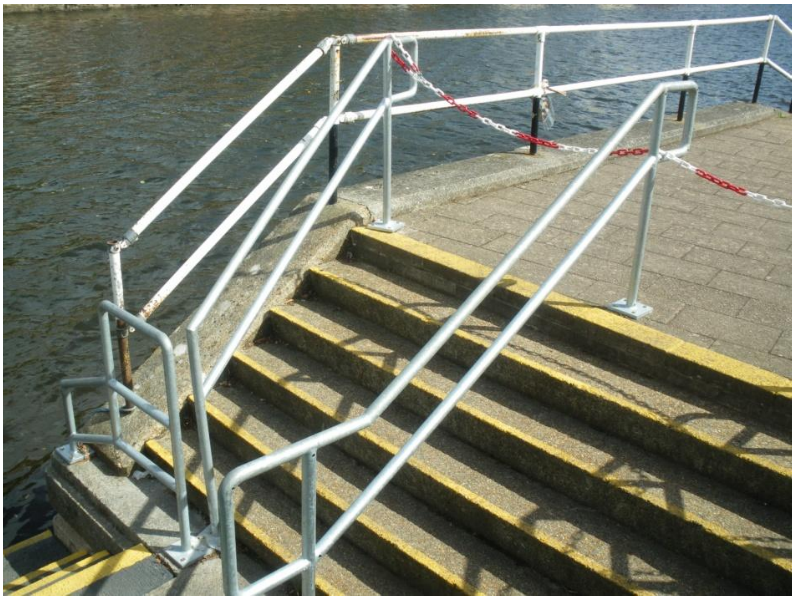


Figure 55: Changes to Steps Following Incident

The author was asked by HSE to attend and survey the scene, to provide a physical record of the environment and to demonstrate the various revisions that had been made to the steps after the incident, in the form of a 3D model.

4.1.3.2. Laser Scanning

Over recent years, laser scanning technology is beginning to filter into the legal system and data collected using laser scanners is being shown in court rooms particularly in the United States (Zmijewski 2013).

Survey Methodology

When undertaking a 3D survey, it is important to consider the best locations of the laser scanner in order to ensure (Quintero et al. 2008):

- Optimal scanner set up positions
- Full visibility of the scene
- Visibility of survey control
- Safety of the surveyor
- That the scene is within range of the instrument

In this instance, as the scene of the incident was outside, it can be classed as a dynamic environment with moving water, people and trees. Dynamic environments can be problematic to laser scan, as the instrument will be used to record the scene initially from one position. When the instrument is moved to another location and the survey is undertaken again, the scene may not necessarily be the same as when it was first recorded, e.g. if things have blown about in the wind. To control this, when undertaking this survey, targets were located in fixed positions that remained static within scans, thus maintaining accuracy within the registration process.

The key area which needed to be recorded was the bottom step of the quay and the infrastructure surrounding the stair area. Therefore, laser scan locations were selected in order to record the steps from all angles. In addition, laser scans were taken of the surrounding area in order to provide further contextual information. A plan of the scan locations is shown in Figure 56.

After each laser scan setup, photographs were taken using a panoramic camera mount, which allows the lens to be positioned in the same location of the emitted laser beam. In addition to the panoramic photographs, a further 34 photographs were taken with a standard 35mm lens in order to be used as a reference and to assist with a solid 3D model.

Data Processing

Time taken on site to record the physical data is relatively quick, particularly with the most recent instruments. Processing the data on a computer is the most time intensive aspect of using laser scanning technology. In addition, depending on the deliverables required by the client, the complexity of a project can vary greatly, from simple point clouds to full virtual 3D models and video animations, constructed from the survey data. In this particular incident, a virtual 3D model and video animation were required, these being played in the courtroom to demonstrate the safety improvements that had been made following the incident.

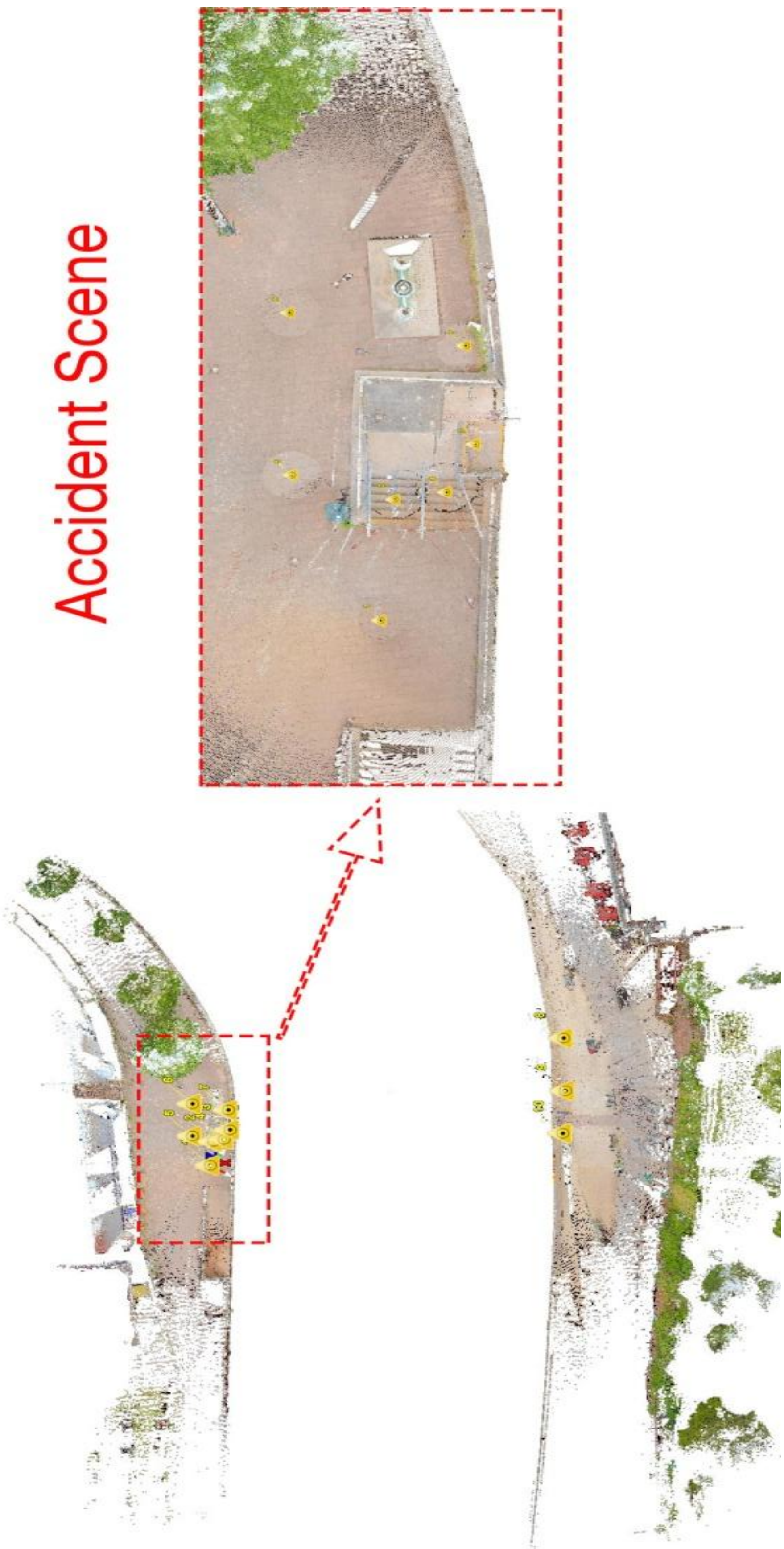


Figure 56: Plan of Scanner Locations

Registration

Firstly, the various scan locations had to be joined together (or registered) in order to produce a complete survey of the scene. This was done in Leica Cyclone. There are two principal methods of registration:

- Registration using vertex alignment of targets
- Registration using cloud constraints

Various targets can be purchased from equipment manufacturers, where the centre point remains the same in any rotation or tilt of the target. These allow the surveyor to take a laser scan from one position and move to the next rotating the target to suit. These targets are recognised by the software and a vertex assigned to the centre of the target. At least three targets are required between scan locations to ensure a mathematical match for the registration process.

In certain situations, it may be impracticable to position targets around the area to be surveyed. In such cases, the user can manually assign points in the software that are the same between the two scan locations. This is known as cloud to cloud registration. It is important when undertaking this type of registration that considerable overlap (40%) between the two set up locations has been obtained in order to ensure enough comparable data between scans.

As with all types of survey technique, registration will create some errors, that have to be assessed by the surveyor in order to ensure the integrity of the survey. In the above case, a combination of the two registration techniques were used, in that targets were used to control the survey and cloud constraints to "smooth" the point clouds, the result being a maximum alignment error of 13mm. In view of the equipment used and the environmental conditions, this alignment error was deemed to be within acceptable limits.

Application of Photographs

Once a geometrically accurate model has been created, photographs can be applied to the point cloud providing a true visual representation of the scene. As the photographs were taken from the same location as the laser scan, the images can be converted first into a panoramic equirectangular image and then to a cube map. The cube map can be imported into point processing software such as Leica Cyclone and then projected outwards texturing the survey points, the result of which is shown in Figure 57.

Figure 57: Photo-textured Point Cloud

In some cases, the data required by the client may be just a point cloud deliverable, which can be used to take measurements, create sections and see representations of an objects position in respect to others. In addition, fly though animations can be made at this stage using only point cloud data.

3D Modelling

As a point cloud by its very nature, is made up of millions of points, dense point clouds can be problematic given the hardware capabilities of a computer, having the result that not all points can be displayed. This is common in large scenes, where the computer cannot display the sheer amount of detail captured. Furthermore, as a point cloud is not a "solid" object and animations are needed, for example to test hypotheses and perform cause analysis, a mesh model is generally required.

In certain situations, solid virtual 3D reconstructions are required in order to better understand the events surrounding an incident and to maximise the benefits of the rich data set. In these cases, the point cloud is then used as a reference and the base for the creation of a 3D model. Using 3D modelling software, mesh models can be made by drawing around the objects in the scene. However, it is important to maintain the integrity of the survey data and not make assumptions on an object’s geometry.

Various software applications can be used to create models and they can be very specific to the task in hand, for example, organic or complex models may require specialist mesh triangulation software, so that they can be modelled accurately. Using this case study as an example, this point is illustrated with regard to the locations of the handrails as shown in Figure 55, which were very important to the case. Pipe modelling software was used in order to obtain a precise location of the handrails within the scene. This software is used extensively in the oil and gas industry, to model plants, where the data is captured using a laser scanner. With this in mind, it is very important to understand the scope of the assignment and consider what areas need particular attention and others that are there for contextual information, in which the accuracy can be assessed.

In order to demonstrate the integrity of the 3D model, specialist software can be used to demonstrate visually, the deviation between the point cloud and the virtual model as shown in Figure 58.

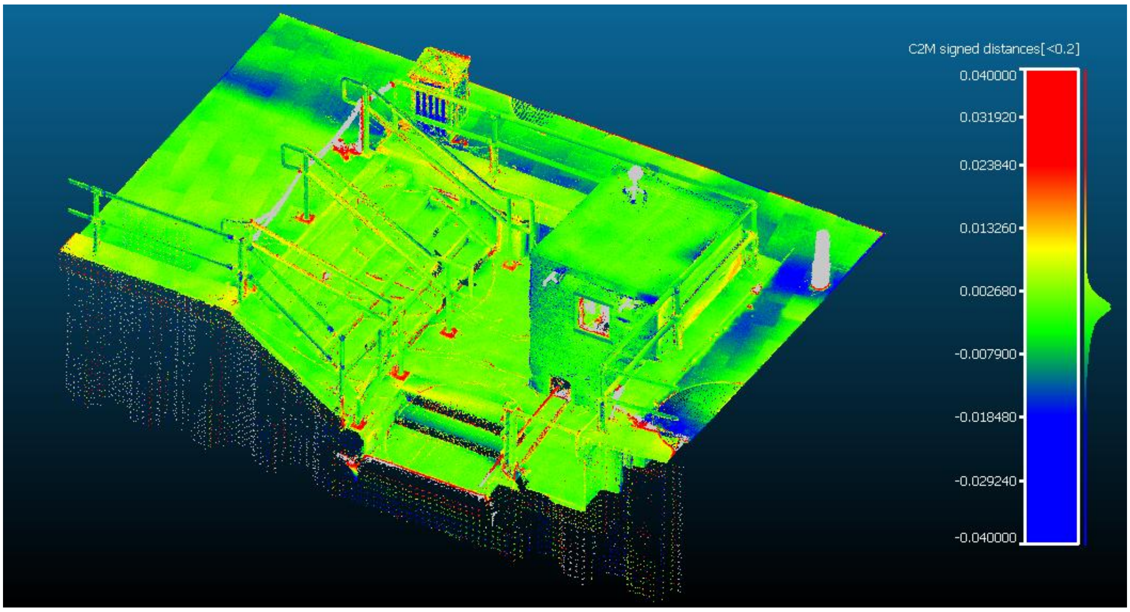


Figure 58: Deviation Analysis

This step is very important if the model is going to be used in a courtroom, where the surveyor may be asked questions relating to its accuracy and relevance to the case. With this in mind, the survey must be undertaken using a calibrated instrument, with the registration of the point cloud's accuracy being maintained with error kept to a minimum. An audit trail may be requested by the court with regard to the equipment specifications and the processes used to maintain the integrity of the dataset provided (registration statistics), in order to ensure that the digital evidence is admissible. The subsequent 3D model created from the survey data can then be checked against the point cloud data as illustrated in Figure 58, this then provides clarity on the objects geometry in relation the original dataset.

In this particular case, the quay area was modelled to a very high accuracy. A second check was also performed through a comparison between physical measurements taken on scene and ones from the point cloud to provide further integrity.

Once modelled, textures need to be applied to the surfaces in the form of photographs creating an accurate visual representation of the scene. In addition to photographs, lighting can be applied using certain modelling software to add realism, by casting shadows and adding a natural feeling to the "lit" environment. In addition, environmental conditions of the geographical location of the incident, such as time and date, can be applied to the model for more realistic lighting. A screenshot of the completed 3D model for the above case is shown in Figure 59.

Figure 59: Screenshot of 3D Model

Once a 3D model has been created, it can be used for various purposes e.g. in cause analysis to check the hypotheses of the investigator, examining if they are plausible in the virtual environment of the incident. In addition, 3D models can help explain the events surrounding an incident to people unconnected to an accident. In this case video animations could be beneficial.

Addition of Scaled 3D Person

Once the environment had been accurately modelled, a scaled person was constructed in order to demonstrate the body movement of the deceased climbing the steps. As the laser scan survey was performed retrospectively following on from the time of the incident, the body wasn't available for reference to create the model. Therefore, mean body data was used to scale a 3D skeleton which was then animated as an aid to explain the movement involved in climbing the steps. A profile view of the model in the scene is shown in Figure 60. However, there are a number of complications of using a 3D representation of an individual in a model, within the courtroom and was deemed inadmissible evidence.

Figure 60: Scaled Person In the Scene

Video Production

In order to produce a video animation of a scene, virtual cameras have to be located within the environment and paths created in which they are constrained to travel. A sequence of still images can be produced (or rendered) from the software, which can later be joined to create a video. In this particular case, the purpose of the 3D model was to demonstrate the changes in the steps and handrails. Animations were created from different camera locations that corresponded to photographs that were taken in the investigation process. An example of this is shown in Figure 61.

Figure 61: Comparison of Photograph to 3D Model

Following this, video blends were then used to represent a photograph location with reference to the 3D model providing a smooth transition. As there were a number of changes made to the steps, animations were made to illustrate this, where additions were shown in green and removals were illustrated in red. An example of this is shown in Figure 62.

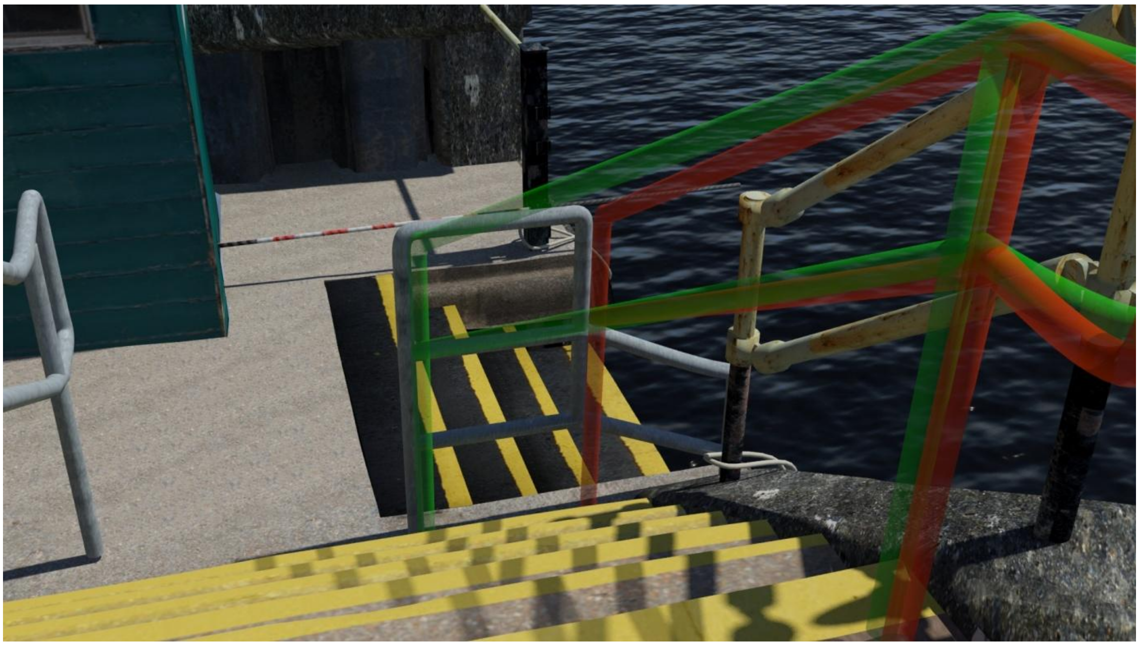


Figure 62: Illustration of Change to the Steps

Physical 3D Models

In addition to virtual reconstructions, physical 3D models can also be considered to aid in the explanation of events surrounding an incident. Using the measured data, physical reconstructions of an accident environment can be made.

Rapid prototyping machines have made the possibility of making accurate 3D models, a reality. This can be done in a number of ways, e.g. using a 3D printer. 3D printers allow a user to create a physical 3D model directly from a CAD program. 3D printers, print in thin layers of nylon, building up gradually until the design is complete. Complex geometry can be created using this method to a high degree of accuracy. However, the size of the model which can be printed is limited, with the largest printers only having a build tray of 1000 x 800 x 500mm (Stratasys 2013). As the technology is in its infancy, the price of 3D printing is considerable to create large models. However, hobbyists' machines can create small scale models at a relativity small expense. An example of a 3D printed model is shown in Figure 63 (Hall 2012).

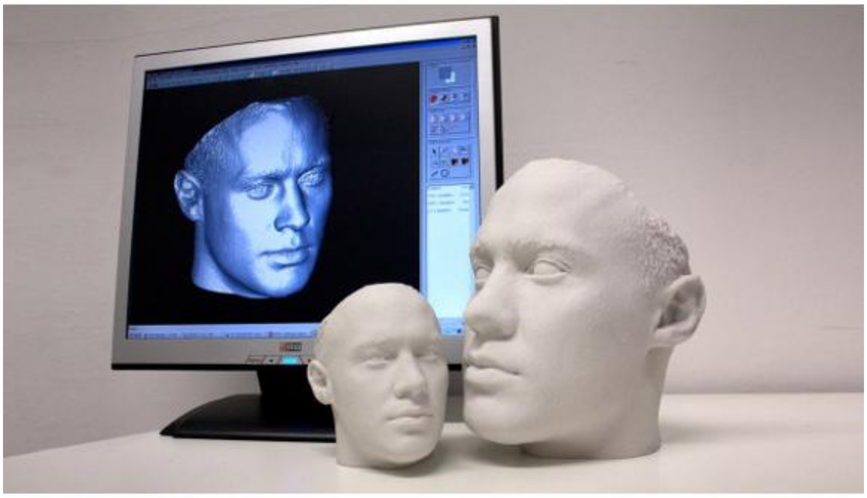


Figure 63: An Example of a 3D Printed Model

For large 1:1 scale models of "simple" geometry, such as the profile of the steps in this case study, models can be made from wood cut accurately to size and fixed together. An example of a constructed model for the above incident and its integration with the steps is shown in Figure 64. This constructed model was used in the courtroom in order to provide a visual reference to the jury on the dimensions of the steps and was of considerable use in assisting the explanation of the expert witness testimony.

Figure 64: 3D wooden Model of the Steps

4.1.4. Use within a Courtroom

There are a number of ways in which 3D technology can be used in a court room in order to help explain the circumstances regarding a case, providing descriptive, contextual and also measurement data as required. The information can be presented to the court as:

- 2D representations taken from the point cloud data, in the form of plans or rendered images from the 3D model. These would be submitted to the court within the jury bundle.
- 3D animations and videos that can be shown to the court on a screen within the court room.
- A physical 3D model that can be placed within the courtroom for illustration or a point of reference.

4.1.4.1. Benefits

There are key benefits that can be obtained by incorporating laser scanning technology into court proceedings and these have been demonstrated in this case study:

Explanation to People Unconnected to the Event

The data obtained through laser scanning can be very rich and provide a dense, full 3D representation of a scene, which when photographs are applied, becomes a realistic visual representation. This allows the court to observe the relationship between everything within the scene which is both geometrically and with true RGB colours. The 3D data can also be easier to understand in comparison to a number of photographs and 2D plans of the incident scene, improving data clarity to people unconnected to the event itself or from a non technical background.

Explanation of Complex Environments

Occasionally, accident scenes can be very complicated involving a number of different key objects and locations within the environment that contributed to the incident. A barrister has the task of trying to explain these, using conventional methodology and this can be very difficult, especially when referring to multiple pieces of evidence and written statements. A 3D model can provide the ability to demonstrate the scene visually, which can be easier for the audience to absorb.

Enables Incident Reconstruction

Once a 3D model has been created, animation paths can be set virtually within the software to demonstrate the events surrounding the incident to provide before, during and after representations. The information used to create this can be taken from witness statements in order to recreate those statements visually.

Demonstration of Environment in Different Stages

It may be necessary to demonstrate to the court, changes that had occurred in the scene over a timeframe. A model can be created of the scene from any point in time and can be used to create a visual display in 3D. This was a key component of the case study, as one of the purposes of the model, was to demonstrate the height of the bottom step at the time of the incident and the changes made to the set of steps following the incident as shown in Figure 62.

Witness Statement Verification/ First Person Viewpoints

A virtual camera can be located within the 3D surveyed environment, which can be used in order to demonstrate what the person would have seen. This can then be used in order to address the reliability of the witness account.

Site Visits

In certain circumstances it may be necessary for the jury to be taken to the scene to illustrate specific details concerning the case. However, the logistics of taking a jury to the scene may be difficult. For example, the scene may be inaccessible, demolished or time may be limited.

With this in mind, a 3D model (physical or virtual) may provide adequate information to aid in the explanation without the need for an "actual" scene visit.

Preservation of Evidence

Dependent on the timing of the court case with reference to the date of incident, there can be problems with demonstrating key details, especially if the environment has changed, e.g. when referring to a witness statement that was made at the time of the incident and it may be hard to envisage what the conditions were at the time. Once recorded the scene can be archived providing evidence of the true conditions at the time of an incident.

Testing of Theories

There can sometimes be conflicting views on the events surrounding an incident and the different explanations of these can sometimes be difficult to visualise. The use of a 3D model can become a valuable tool to aid in the explanation of the events and possible scenarios that may have been contributing factors in the incident.

4.1.4.2. Drawbacks

There are limitations to the use of 3D models that can occur within a court room:

Limitations in Technology Within Courts

As laser scan technology is relatively new, it’s use in a court room can sometimes be limited to the technology that is available (such as audio and visual display equipment). This can be the case particularly in older court rooms that may not have the facilities to show a virtual model in detail.

Confusion Caused by Models

Occasionally, in complex accident scenes, there may have been a number of changes that have been made to the environment over a length of time e.g. if a number of alterations have been made to the stair infrastructure in order to ensure that the site is safe. These scenes can sometimes be problematic to show as there may be considerable changes that have to demonstrated. This can make a video animation appear cluttered and hard to understand.

Trust in the Data

Again as laser scanning is relatively new, there may not be trust in the data produced. People may consider that, 3D models and environments that are created as computer generated illustrations, don't hold true geometric accuracy. However, education on the accuracy and acceptance of the data may come in time when the technology is used more frequently, in a world that is ever more media focused.

Cost

Due to the costs that are associated with the construction of either a virtual or physical 3D model it may not be appropriate to use in every case. Consideration must be given to the benefit in which adopting a 3D model will bring to the case and cost incurred must be agreed within the court by both sides.

Complexity of an Experts Statement

As discussed previously, there are a number of steps that have to be considered in order to produce a model for use in a courtroom. If a model has been produced for a case it may be necessary for the expert to explain the methodologies that have been undertaken. This can sometimes be confusing for people to understand particularly if they are not from a technical background.

Personal Interpretation

Data captured by a laser scanner is indiscriminate and can be modelled to a high level of accuracy. Despite this, there are still occasions where additions to the scene have to be made, sometimes without clear evidence for their existence and thus extreme caution in regard to their addition has to be exercised. For example, with reference to the above case study, the laser scan survey was taken retrospectively of the incident. This meant that the body was not available for accurate body measurements to be made and mean body data was used. This was not, therefore, a completely "true" representation (in the absence of an accurate pathologist's record). In addition, it was not known from witness statements where the walking stick was placed, either on the step or behind on the landing platform. In the video animation, the walking stick was placed on the step, which made its validity open to discussion and therefore it was not used in the proceedings.

4.1.5. Conclusions

The use of 3D models are very effective to stress a point of view, bringing the case 'alive' both to the witnesses and the court, through a virtual site reconstruction, with 3D models being used in a number of cases in recent years.

However, although to scale, many of the models have been computer generated representations of a scene and may not reflect the "true" geometry of the environment. This is particularly the case when considering complex geometry, and therefore laser scanning can offer a new aspect to this already exciting investigative approach.

It could be argued that when demonstrating a witness point of view, the use of a computer generated 3D model, may not truly represent the actual environment and cause ambiguity. However, as a laser scanner offers the ability to capture the environment to a high degree of accuracy from any given position, laser scanning can be used to help clarify this. The author has used the equipment within vehicles, for example, in order to demonstrate the view of a driver while considering the complex geometry within the cab. Performing this operation in the cab of a vehicle is relatively straight forward, as the location of the scanner is fixed, and only the height of the instrument is required to establish the drivers Field of View (FoV).

However, complications can arise in determining the exact placement of a witness in a open environment, unlike that of a driver in a constrained location. The operation of determining the placement of a witness, can also be performed virtually through the placement of a virtual camera within a generated model or positioning a laser scanner in the 'real world', but the same problem arises due to uncertainty of the exact witness placement.

Therefore, care should be taken when performing this operation in order to ensure the placement of the camera or scanner is accurate to the actual position of the witness. In addition, if a witness has problems relating to their vision, a scanner will not be able to account for this. However, in many cases this can result in the "evidence" becoming inadmissible in a court.

In many cases (such as in this case study), 3D models can be used to re-create the event, providing a chronology of an incident as it unfolds or of changes in the environment. However, as in this case study, the chronology should not be open to personal interpretation such as the placement of the 3D person detailed above. The inclusion of human figures in the surveyed environment is subject to considerable contest within a court. Using the above case study as an example, the fundamental problems (unknown to the author at the time) of using a 3D person was highlighted and will now be discussed.

Firstly, as the laser scan survey was taken retrospectively of the incident occurring, the body data of the deceased was not available to use. By using mean body data to create the scaled person, this opened the data to ambiguity as the model was being used to demonstrate the reach of the person involved. Therefore, the use of the scaled person could have been unreliable in court, owing to the model not exactly representing reality.

In addition, the placement of the foot could have also been contested, in much the same way as discussed previously in respect to witness statement verification. Therefore, this data was not used in the court case and the final rendered video did not include the animated person.

The fundamental benefit of the 3D model in the above case study was to demonstrate the changes to the stairs over the period between the incident and the subsequent court case. The model was needed owing to the sheer amount of changes that had occurred within the environment, resulting in the jury being presented with a large number of images of the infrastructure, which would have been hard to picture without the clarity of the 3D model.

However, one of the problems that had to be overcome was how to prevent the animation from becoming "cluttered" given the numerous changes that had to be expressed. This was resolved (detailed above in the paper) and it reduced the need for the jury to perform a site visit. In addition, a site visit may have added to the confusion as the scene did not represent the environment at the time of the incident.

This then leads onto the next significant benefit, in respect of the preservation of the scene and of complications regarding transient evidence. As the scene of a accident is in an immediate state of decay from the moment the event occurs, it is important to document the scene quickly.

The use of conventional surveying methodologies has numerous limitations with regard to the time taken to record the evidence, the density of the information that can be collected and human error associated with collecting discrete points of a scene. Most of these problems are resolved with the ability to capture the geospatial data through laser scanning, which is unrivalled by any other technique in a narrow timeframe. For example, the survey undertaken in the above case study was conducted in 10 laser scan positions, with the equipment set to capture the data in high resolution (approx 4 million points per scan), each scan taking 3.5 minutes. This resulted in a dataset of 40 million points, whereas to capture this amount of detail with conventional means would be unattainable.

However, the technology still has limitations and manufacturers are applying and adopting solutions continually. When new applications are developed, research is essential to assess their accuracy, before they are trusted to be referenced as evidence in a courtroom. In addition, the capability of the current technology needs to be explored and education needs to be focused through research, in order to assist a non technical person in their understanding of the accuracy that can be obtained and the drawbacks that can be associated in embracing new technology.

To conclude, the use of laser scanning surveys can be of considerable use in jury trials, for example, if the location supports the use of a high definition survey or if an object has be altered after the accident and has a specific influence on the case and needs to be recorded. However, consideration has to be made in its application and to ensure a fair trial, emphasis being placed on the facts of the case and personal interpretation controlled.

4.2 The Use of Laser Scanning as a Method for Measuring Stairways Following an Accident

Abstract

Stairs present significant potential for harm to their users. A fall on stairs, particularly in descent, often leads to serious injury or even death. The authors have been involved in the investigation of many workplace stair accidents. Proper forensic investigation into the cause of a stair accident has often found the incident to be wholly or partly caused by poor stair design. In order to establish the relationship between the stair design and a given fall, an onsite survey has to be conducted, determining the rises and goings along with other key dimensions.

The Health and Safety Laboratory undertake this survey using a digital inclinometer, a steel rule and a tape measure, whereas laser scanning is an emerging technique that now accessible to the surveyor to complement or replace traditional approaches. The laser scanner and associated software produces a dense point survey in 3D, allowing dimensional analysis of the features. The authors used both traditional and laser scanning techniques to study the scenes of two fatal stair falls.

The analysis presented, allows the suitability of laser scanning for stair fall investigation to be considered. However, for precise and accurate surveys, as required for stair assessment, the technology may not be the best solution currently available. Further classification of the error from laser scanning is needed, in order to consider if the error is relative and therefore can be mitigated. Laser scanners are impressive instruments, data from which can be used to create a virtual 3D environment that can be used to reconstruct and explain an event and contributing factors. The use of both traditional survey methods and laser scanning, currently provides the investigator with complimentary data, that allows accurate measurements to be presented in the context of the three dimensional environment.

4.2.1. Importance of Effective Stair Design

Stairs present significant potential for harm to their users. A fall on stairs, particularly in descent, often leads to serious injury or even death. "A fall on stairs occurs in the UK every 90 seconds" (BSi 2010) and in domestic premises there are over 500 deaths per year due to falling down stairs.

The authors have been involved in the investigation of many workplace stair accidents and further stair accident investigations have come to light anecdotally where a cursory investigation has revealed no obvious damage to the stair or loose component and so in those cases, the investigator has concluded that the fall was entirely the fault of the pedestrian. Proper forensic investigations into the causes of stair accidents have often found however, that the incident has been wholly or partly caused by poor stair design.

Below are definitions of common stair terminology:

Nosing: the leading edge of the tread. Some stairs will have material added to the leading edge, usually to add visual contrast, to protect the edge from wear or to provide enhanced slip resistance. This is known as a proprietary nosing.

Rise: the vertical distance between two consecutive treads, or between a tread and a landing.

Going: the horizontal distance between two consecutive nosings.

Pitch: the angle between a line joining consecutive nosings and the horizontal.

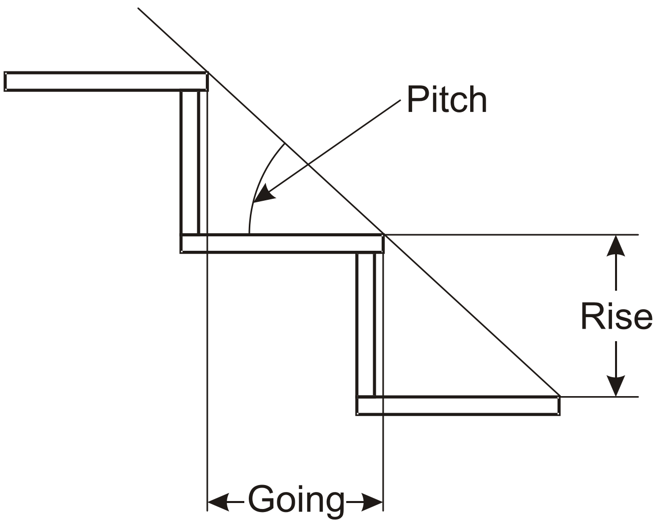


Figure 65: Schematic diagram of stair terminology

Stair descent is essentially a series of controlled falls, from one tread to the next. Increasing the vertical distance between each step makes the control of the fall more demanding, and is therefore more likely to lead to an uncontrolled fall. Equally, reducing the size of the step onto which the foot will land, also makes the misplacing of the foot more likely. The size of the going will have a significant influence on fall risk, with smaller goings presenting the highest risk of falls.

Consistency of dimensions within a flight of stairs allows the user to subconsciously adapt, placing their feet accordingly and negotiating the stair with little conscious thought. Where significant differences in rise or going are present between adjacent treads, the risk of falls is significantly increased. Variations in rise are more common at the very top or bottom of a flight, often where a prefabricated stair is connected to a landing above or where a floor covering has been added below after a stair has been installed. The effect of variation in going between adjacent treads will be more pronounced on treads with smaller goings.

With respect to the dimensions of goings, the Building Research Establishment (BRE) have published research highlighting the potential risks that can be associated with poor stair design including the effect of changing going dimensions (Roys & Wright 2003). Table 3 below shows the effect of going dimensions and variations between treads on the risk of a large overstep, where action should be considered if the average time between occurrences is 50 years or less (Roys & Wright 2003).

Risk on a 14-step light where there is no variation in going between steps				
Going	Average time between occurrences of large overstep			
	5 runs per day	25 runs per day	100 runs per day	2000 runs per day
225mm	**4 years**	**298 days**	**75 days**	**4 days**
250mm	**11 years**	**2 years**	**198 days**	**10 days**
275mm	145 years	**29 years**	**7 years**	**133 days**
300mm	>1000 years	>1000 years	>1000 years	73 years
325mm	>100,000 years	>1000 years	>1000 years	568 years
350mm	>100,000 years	>100,000 years	>100,000 years	>1000 years
375mm	>100,000 years	>100,000 years	>100,000 years	>1000 years
400mm	>100,000 years	>100,000 years	>100,000 years	>100,000 years

Risk on a 14-step flight where a single going is reduced by 10mm				
Going	Average time between occurrences of large overstep			
	5 runs per day	25 runs per day	100 runs per day	2000 runs per day
225mm	**2 Years**	**139 days**	**35 days**	**2 days**
250mm	**5 Years**	**340 days**	**85 days**	**4 days**
275mm	**50 years**	**10 years**	**53years**	**46 days**
300mm	>1000 years	>1000 years	323 years	**16 years**
325mm	>100,000 years	>1000 years	>1000 years	105 years
350mm	>100,000 years	>100,000 years	>100,000 years	>1000 years
375mm	>100,000 years	>100,000 years	>100,000 years	>1000 years
400mm	>100,000 years	>100,000 years	>100,000 years	>1000 years

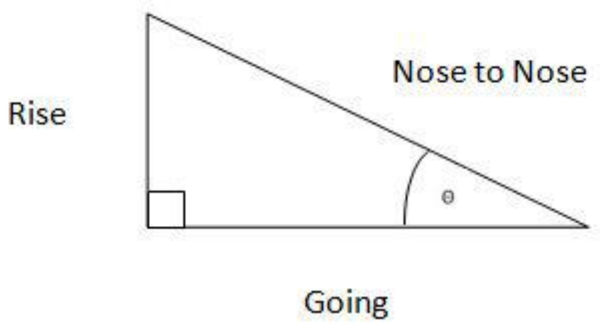
Table 3: Effect of going and variation between treads on the risk of a large overstep (Roys & Wright 2003)

It can be seen from the table above that a small change in the dimensions within a staircase can have a significant effect on the associated risks in their operation. However, there are also additional factors that affect staircase safety and measures can be installed to mitigate against them. For example, a clear highlight at the very edge of the tread (the nosing) makes it easier to distinguish precisely where the step ends and improves ability to place the foot correctly and therefore to safely negotiate the stair. The highlight should extend across the entire width of the tread, should be of a single colour to avoid confusing visual cues and should be of a colour that contrasts clearly with the material of the treads, the floor coverings at the top and bottom of the flight and on any landings. In addition to differences in colour, differences in the light reflectance value (LRV) can help to differentiate a nosing highlight from the tread below. The shape of the nosing is also important. A square nosing gives a clearer impression of where the very edge of the tread is and maximises the possible going of the tread when compared with a curved nosing with a large radius. However a radius of 6mm on the nosing is suggested to reduce the severity of injuries sustained during a stair fall.

Handrails serve three main functions: a guide for stair use, an aid to movement on stairs, and a method of preventing a fall. In order to suitably perform these functions, the handrail needs to be appropriately designed. Handrails should follow the pitch of the stair and be graspable and within easy reach over the full length of the stair. Research into the appropriate height for the handrail has led most standards to recommend a height of 900mm – 1000mm above the pitch line, measured from the nosing to the top of the handrail. Visual identification of a handrail is easier for stair users when the handrail contrasts with the surrounding environment, as discussed in relation to nosings above.

4.2.2. Survey Methodology: Physical Stair Measurements

In order to investigate a stair-fall accident, an onsite survey is required to establish the stair characteristics, determining the rises and goings while also examining if the handrails are appropriate. HSL normally undertake this survey using a calibrated digital inclinometer, steel rule and tape measure. The inclinometer is used to obtain the angle between adjacent nosings with direct reading of 0.1^{o} and the steel rule is used to measure the slope distance (SD) between the nosings of the steps to be measured. The methodology used is in line with the improved method highlighted by Johnson (Johnson 2006). The measurements for the rise and going for each step can be calculated using basic trigonometry relating to right-angled triangles that is shown in Figure 66.



$$Rise = \sin\theta \ \times Nose\ to\ Nose\ Measurement$$

$$Going = \ \cos\theta\ x\ Nose\ to\ Nose\ Measurement$$

Figure 66: Trigonometry for Stair Measurements

When undertaking a survey of a staircase it is important to use the improved method stated above, as opposed to the traditional method in which problems can arise. The traditional measurement technique consists of measuring the vertical height for the rise and then the horizontal distance for the going (Johnson 2006). The traditional measurements are performed using a steel rule and a straight edge as shown in Figure 67 (Johnson 2006).

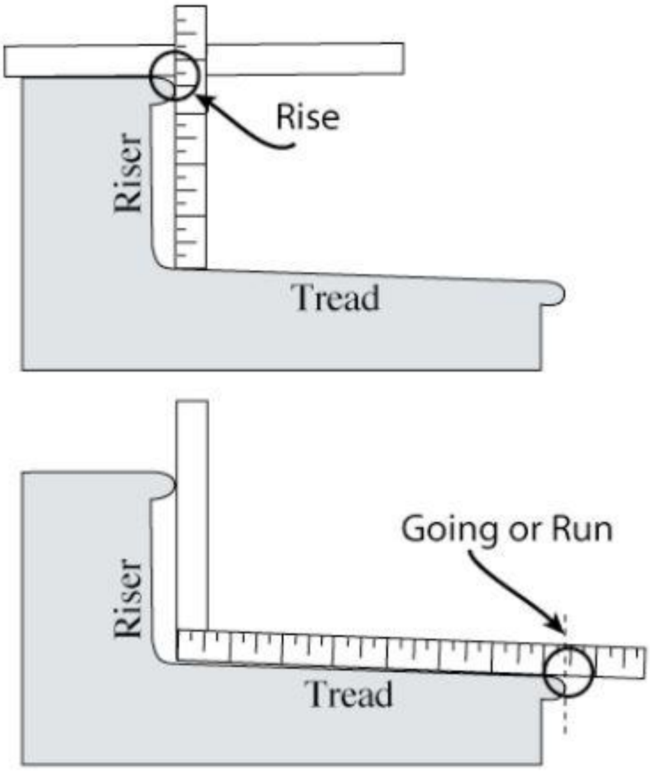


Figure 67: Traditional Method for Stair Measurement

Using the traditional method, a sloping tread can result in the measured rise and going not representing their actual values as illustrated in Figure 68 (Johnson 2006).

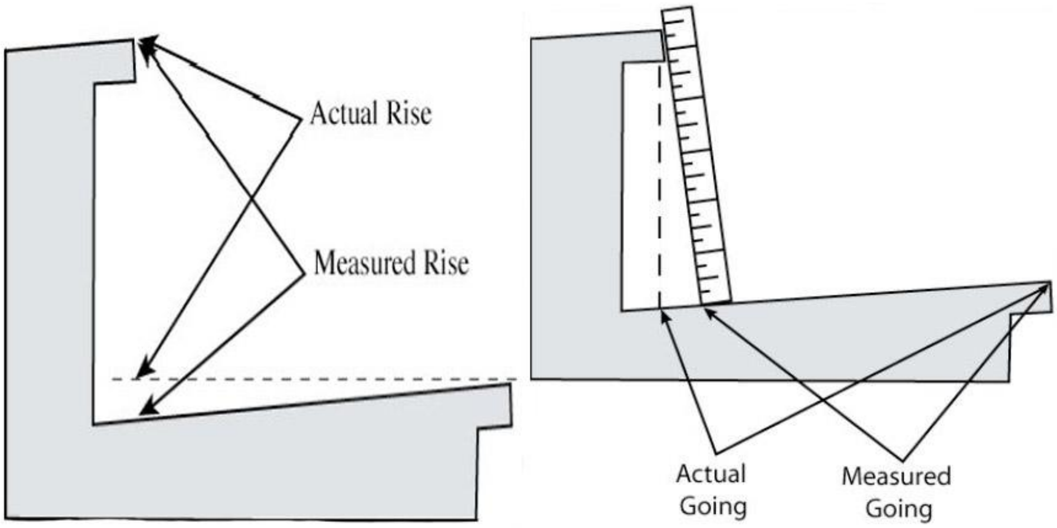


Figure 68: Traditional Method Errors

HSL measure the first rise using the traditional technique as it is not possible to calculate the first rise accurately using the improved technique.

In addition to obtaining the dimensions of the rise and goings of the stairs, measurements of the clear width of the stairs and the location and design of the handrails, also have to be taken. Handrails need to be appropriately designed if they are to be used successfully as an aid to negotiating the stair or to arrest a fall. Measurements of the handrail height are obtained by placing a tape measure on the nosing and extending vertically at two locations. The clearance between the handrail and the wall is measured with the tape measure and the perimeter of the handrail is measured by wrapping a string around the rail and comparing the length of string used with the calibrated rule.

4.2.3. Survey Methodology

There are a number of different processes that have to be undertaken when documenting an accident scene that have been discussed in the previous case studies therefore they will not be included in this section.

4.2.3.1. On Site Survey

When undertaking a survey for stair-fall investigations, it is important to ensure that the laser scanner is carefully levelled before a scan can commence. This can be achieved using the in built inclinometer (HDS6000: dual axis sensor and C10: dual axis compensator), which is essential for the precise measurement needed in this application. On many occasions a scene will require a number of scan set-up locations in order to record the environment in full (i.e. to overcome blind spots or to improve resolution), which are then later combined in software.

4.2.3.2. Data Processing

The two forms of registration (discussed previously in other case studies) can be used in conjunction with each other. Target registration can be used to constrain the scans and cloud to cloud registration used to "smooth" the result. This is the preferred form of registration and the one used by the authors in the case studies detailed below. However, as with all types of survey, sources of error require careful consideration, particularly since the survey could be used in evidence.

Determining the Position of Handrails

As previously stated, it is important for the accident investigator to obtain information in respect to the construction and suitability of handrails, with the conventional method of measurement discussed. This can also be achieved using a laser scanner using surface fitting algorithms such as the ones found within Leica cyclone. Laser scanning software allows the user to use the point cloud survey to assign "solid" 3D primitives to the record data to a high degree of accuracy. In many cases, handrails are cylindrical as in the Quay Case and therefore cylinders can be fitted to the point cloud to accurately model their location.

In certain cases, it may be important to obtain a profile of the handrail for assessment. This can be achieved by clipping the area of the point cloud that is required (showing only a selection of it) and showing it in profile, which can be evaluated to establish if it is fit for purpose. In addition, small sections can be taken at any location along the handrail, allowing the investigator to evaluate the handrail in full.

4.2.3.3. Taking Stair Measurements from Laser Scan Data

In order to obtain measurements for the rise and goings of stairs, there are a number of stages that have to be undertaken:

- Separation of Staircase from the Complete Survey
- Establishing a User Co-ordinate System (UCS)
- Taking Measurements and Presenting the Data

Separation of Staircase from the Complete Survey

When laser scanning a scene, the associated dataset can be considerable, particularly if a number of set up locations are required. Subsequently, the surveyed environment may include information that may be of relevance for the overall investigation process or context, but having seemingly no significance to the staircase itself. With this in mind, the staircase may be separated from the complete scene for further examination. It is important at this point to copy the dataset to preserve the original that may be required at a later date for other purposes and following this, the staircase can be extracted for further examination. In addition, as large point clouds require considerable computing power to display, by extracting the required data, it allows the computer to operate more efficiently and display the selected object in more detail.

Establishing a User Co-ordinate System (UCS)

A local co-ordinate system has to be established that is relative to the staircase itself and not referenced to the full surveyed environment (created from the initial orientation of the laser scanner). The local UCS can then be used later for taking measurements regarding the rise and goings of the stairs. Although this is only a transformation of the dataset (not affecting the geometry), this should only be performed on a working copy of the surveyed scene as the court may require an audit trial to the original data obtained.

The local UCS can be created in a number of ways using point cloud processing software. One of the steps can be selected and the "y axis" aligned to the tread of the step. The "x axis" is then determined at a 90 degree angle following the path of the stair string (an effective UCS can also be achieved by reversing this operation). Finally, the "z axis" will be directly vertical from the x-y plane.

The purpose of creating a UCS in this way, is to create a local co-ordinate system that is aligned with the stair itself and not determined by the orientation of the laser scanner from its first position. The UCS will then establish views which are directly proportional to the staircase, i.e. right or left views representing the stairs "side on". An example of the survey transformed and set to a UCS is shown Figure 69.

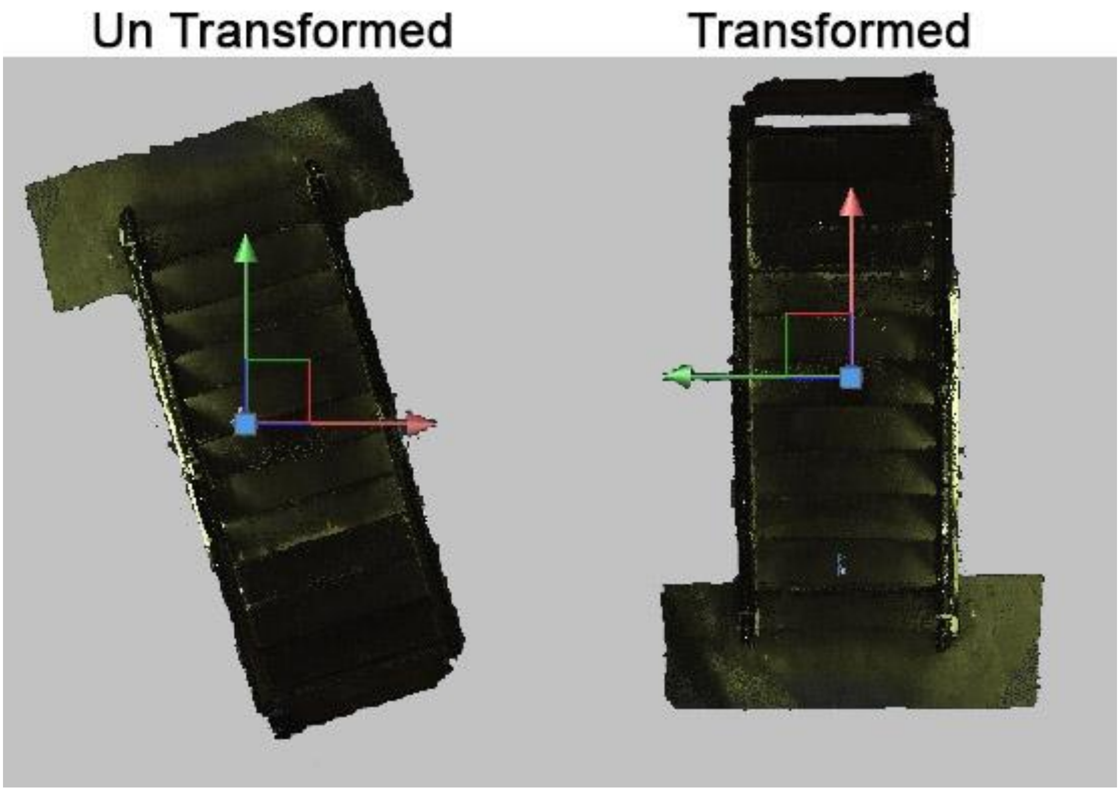
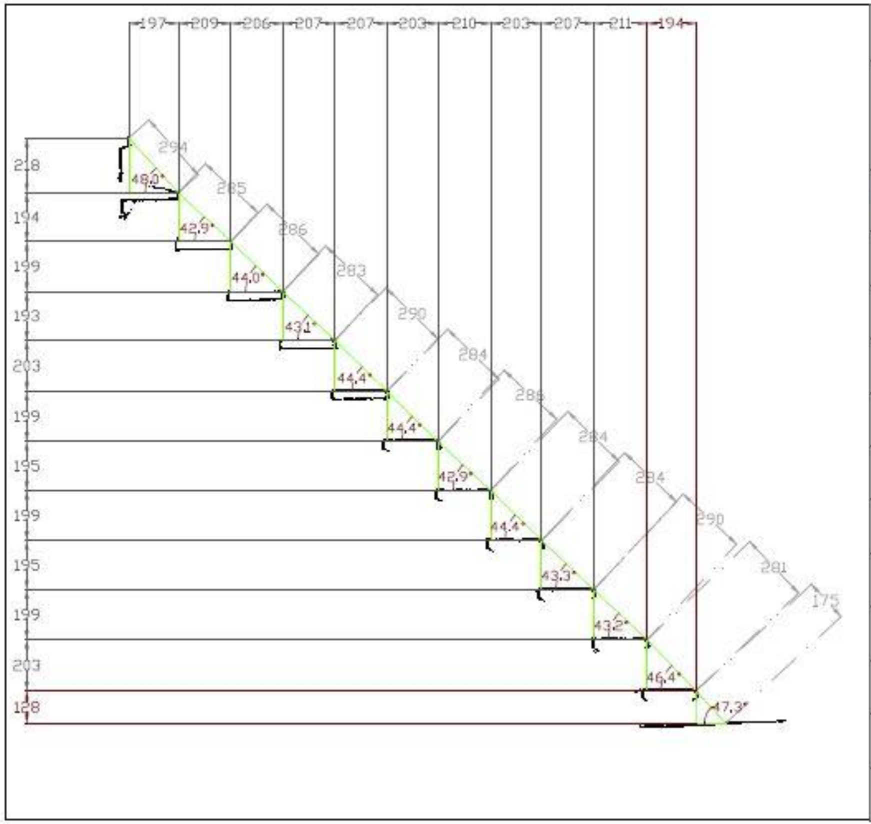


Figure 69: UCS Configuration

Taking Measurements and Presenting the Data

When a UCS has been set relative to the direction of the stairs, measurements can then be taken from the data. However, before this can be undertaken a section through the data has to be obtained relevant to where the measurements are required. For example, if the staircase has received a high amount of traffic, the centre of the stair could be worn and therefore it may be relevant to take sections and subsequent measurements from the centre and also the edges of the staircase. In addition, this methodology was chosen over that of fitting surfaces to the cloud, as surfaces would not represent the wear that may have occurred on the edge of the nosing. However, fitting surfaces would reduce the effect of noise that is often created when using a laser scanner. Therefore, in order to compensate for the mis-measurement that could occur by taking a reading from noise in the point cloud, this process is then repeated a number of times through a small section of data.

Once a section has been taken through the data using a CAD drafting package, the staircase can be viewed from the side and measurements for the angle and distance between adjacent nosings can be determined. As the placement for the point of measurement is subjective, this can be undertaken a number of times in order to obtain a spectrum of results and reduce the propagation of error, upon application of an arithmetic mean and standard derivation. The data can also be plotted and displayed to scale, an example of which is shown below in Figure 70.



Step Profile				
Stair No	Angle	Nose to Nose	Rise	Going
1(bot)	47.3º	175mm	128mm	-
2	46.4º	281mm	203mm	194mm
3	43.2º	290mm	199mm	211mm
4	43.3º	284mm	195mm	207mm
5	44.4º	284mm	199mm	203mm
6	42.9º	286mm	195mm	210mm
7	44.4º	284mm	199mm	203mm
8	44.4º	290mm	203mm	207mm
9	43.1º	283mm	193mm	207mm
10	44.0º	286mm	199mm	206mm
11	42.9º	285mm	194mm	209mm
12	48.0°	294mm	218mm	197mm

Figure 70: Presentation of Results

4.2.4. Case Study 1: Quay, Fatal Accident

4.2.4.1. Background of the Incident

An elderly lady died after she fell from quayside steps into the river below. She had been disembarking from a passenger ferry beside a quay, when the fall occurred. The authors were asked to examine the steps as part of the investigation process and were called as expert witnesses in the trial. The Health and Safety Laboratory (HSL) were contacted by the Health & Safety Executive (HSE) to undertake a stair-fall assessment. This included physical measurements of the dimensions to determine the relative rises and goings. In addition, a laser scan survey was carried out, using a Leica HDS6000 laser scanner and high definition camera assembly, to record the scene retrospectively of the incident. The survey was used to highlight the changes that were made to the steps to reduce any further risk associated with their use, following recommendations from HSL.

4.2.4.1. Results

The results of the physical measured survey are shown in Table 3, with the measurements taken from the edge of the stair on the nosing.

Stair Number	Angle (°)PS	Angle (°)LS	SD (mm)PS	SD (mm)LS	Rise. (mm)PS	Rise. (mm)LS	Going. (mm)PS	Going. (mm)LS
1 (Bot)	-	27.8	-	619	302	302	299	303
2	28.4	28.4	340	345	162	164	262	264
3	31.5	31.9	307	311	160	164	255	252
4	33.3	33.5	305	302	167	167	258	256
5	32.5	32.8	306	304	164	165	258	260
6	31.2	31.2	302	304	156	157	291	286
7	28.2	29.1	330	327	156	159	-	-
Min	28.2	27.8	302	302	156	157	255	252
Max	33.3	33.5	340	619	302	302	299	303
Mean	30.9	30.7	315	376	191	192	268	269

Physical Measured Survey	**PS**
Laser Scan Survey	**LS**

Table 3: Results of Physical Measured Survey and Laser Scan Survey

A comparison between the two surveys are shown in Table 4..

Stair Number	Angle Diff	Hyp Diff	Rise Diff	Going Diff
1	-0.9	3	-3	
2	0.0	-2	-1	5
3	-0.3	2	0	-2
4	-0.2	3	1	3
5	-0.4	-4	-4	3
6	0.0	-5	-2	-2
7			0	-4
Max	0.0	3	1	5
Min	-0.9	-5	-4	-4
Error + \-	1.0	5	4	5

Table 4: Difference Between the Two Surveys

It can be seen from the table that there are differences between the two sets of data with a maximum deviation of 5mm. There are a number of possible variables that may have had an effect on this. These are highlighted later.

4.2.5. Case Study 2: Cellar Stair, Fatal Accident

4.2.5.1. Background of the Incident

During 2012, a male publican died after falling on the stairs leading down to the beer cellar in his public house.

The authors were asked to examine the steps as part of the investigation process. HSL were contacted by the Environmental Health Department at the Local Authority to undertake a stair fall assessment. This included physical measurements of the dimensions to determine the relative rises and goings. In addition a laser scan survey was carried out, using a Leica C10, to record the scene of the incident.

The business was served with an Improvement Notice, which required a number of changes to reduce the risk of future stair-falls. The notice was complied with by way of installing a new flight of stairs and improved lighting in the area, at the company's cost.

4.2.5.2. Results

In this case study, the staircase was subject to wear in the centre due to heavy footfall. Owing to this, the measurements in this section were taken from a number of positions in order to evaluate the wear. In order to better understand the measurement locations, a schematic has been produced and is shown in Figure 71.

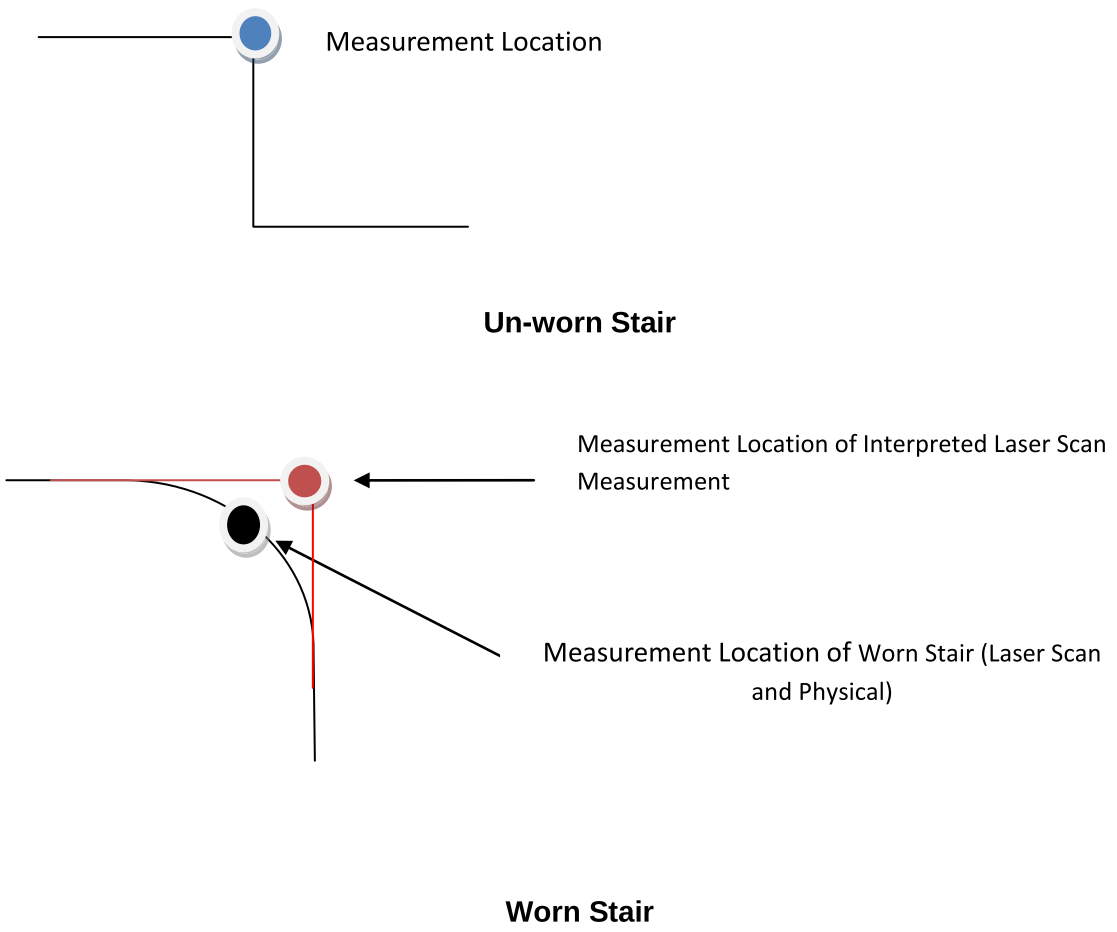


Figure 71: Schematic of Measurement Locations

There was considerable wear from heavy footfall to the centre of the stair. For this reason in this case study physical measurements were taken from the centre of the stair (black circle in Figure 71) and also next to the stair string to one side (blue circle in Figure 71). The measurements of the physical survey from the centre stair are shown in Table 5.

Stair Number	Angle (°)PS	Angle (°)LS	SD (mm)PS	SD (mm)LS	Rise (mm)PS	Rise (mm)LS	Going (mm)PS	Going (mm)LS
1 (Bot)		47.3		175	140	128	181	194
2	47.8	46.4	270	281	200	203	208	211
3	44.2	43.2	290	290	202	199	198	207
4	44.9	43.3	280	284	198	195	196	203
5	45.6	44.4	280	284	200	199	208	210
6	44.3	42.9	290	286	203	195	197	203
7	45.4	44.4	280	284	199	199	203	207
8	45.6	44.4	290	290	207	203	201	207
9	44	43.1	280	283	195	193	203	206
10	45.6	44	290	286	207	199	206	209
11	44.7	42.9	290	285	204	194	187	197
12	49.1	48	285	294	215	218		
Max	49.1	48	290	294	215	218	208	211
Min	44	42.9	270	175	140	128	181	194
Mean	45.6	44.5	284	277	198	194	199	205
Range					75	90	27	17

Physical Measured Survey	**PS**
Laser Scan Survey	**LS**

Table 5: Physical Measurements taken Centre Stair

Difference	Angle (°)	Hyp.(mm)	Rise (mm)	Going (mm)
1			12	-
2	1.4	-11	-3	-13
3	1.0	0	3	-3
4	1.6	-4	3	-9
5	1.2	-4	1	-7
6	1.4	4	-8	-2
7	1.0	-4	0	-6
8	1.2	0	4	-4
9	0.9	-3	2	-6
10	1.6	4	8	-3
11	1.8	5	10	-3
12	1.1	-9	-3	-10
Max	1.8	5	10	-2
Min	0.9	-11	-3	-13
Error Neg\Pos	1.8	11	10	13

Table 6: Comparison of Worn Centre Stair Measurements

A comparison of these two datasets is shown in Table 6 which shows discrepancies between the data, with differences of 10mm in the rises and 13mm in the goings. This is considerable, considering the narrow margin of error that triggers action within the building regulations governing stair design. There are a number of possible sources of error resulting in the variations that have to be considered. These are discussed later.

As the stairs were worn in the middle due to high footfall, measurements were taken on the edge of the stair string to compensate for this in both the physical and laser scan survey (blue circle in Figure 71). The results for the two surveys are shown in Table 7.

Stair Number	Angle (°)PS	Angle (°)Ls	SD (mm)PS	SD (mm)LS	Rise (mm)PS	Rise (mm)LS	Going (mm)PS	Going (mm)LS
1 (Bot)		49.4		172	136	131		112
2	47.4	45.8	284	287	209	206	192	200
3	44.5	43.9	289	286	203	198	206	206
4	45	43.9	284	284	201	197	201	205
5	46.3	45	280	280	202	198	193	198
6	43.9	42.7	295	294	205	199	213	216
7	45.5	44.3	283	284	202	198	198	203
8	44.9	43.5	288	288	203	198	204	209
9	45.6	44.7	283	283	202	199	196	201
10	45	43.5	287	290	203	200	203	210
11	45.4	43.7	285	281	203	194	200	203
12	48	47.1	293	299	218	219	196	204
Max	48	47.1	295	299	218	219	213	216
Min	43.9	42.7	280	172	136	131	192	112
Mean	45.6	44.8	286	277	199	195	200	197
Range					82	88	21	104

Physical Measured Survey	**PS**
Laser Scan Survey	**LS**

Table 7: Measurements taken at the Side of the Staircase

Difference	Angle (°)	SD (mm)	Rise (mm)	Going (mm)
1			-24	
2	-1.6	3	-9	14
3	-0.6	-3	3	-8
4	-1.1	0	4	-4
5	-1.3	0	-4	5
6	-1.2	-1	11	-14
7	-1.2	1	1	0
8	-1.4	0	6	-6
9	-0.9	0	-1	1
10	-1.5	3	7	-3
11	-1.7	-4	0	-6
12	-0.9	6	-14	23
Max	-0.6	6	11	23
Min	-1.7	-4	-24	-14
Error +\ -	2.6	6	24	23

Table 8: A Comparison between Measurements taken at the Side

A comparison between the two sets of measurements is shown in Table 8 with considerable differences between the datasets, including a maximum error of 24mm. In order to evaluate this error, it must firstly be classified..

One of the benefits of capturing a scene using a laser scanner, is the ability to examine the staircase any number of times and to apply different techniques. Working on the section through the laser scan at the centre of the staircase, an extrapolated value for an unworn nosing (red circle in Figure 71) was taken to compensate for wear and the results are shown in Table 9.

Nosing (to…)	**Angle** (°)	**SD** (mm)	**Rise (mm)**	**Going (mm)**
1	43.4	192	140	132
2	45.8	283	197	203
3	43	292	214	199
4	43.7	283	205	196
5	44.2	283	203	197
6	43.1	288	210	197
7	44.5	283	202	198
8	43.6	290	210	200
9	43.5	281	204	193
10	44.6	288	205	202
11	42.4	285	210	192
12	47.9	294	197	218
		Max	214	218
		Min	140	132
		Average	200	194
		Range	74	86

Table 9: Measurements Taken Compensating for Wear

The measurements were then compared to the physical measurements taken to one side (blue circle in Figure 71), as shown in Table 8 to identify a possible correlation.

Difference	**Angle** (°)	**SD (mm)**	**Rise (mm)**	**Going (mm)**
1	-	-	4	-
2	-1.6	-1	12	11
3	-1.5	3	11	-7
4	-1.3	-1	4	-5
5	-2.1	3	1	4
6	-0.8	-7	5	-16
7	-1	0	0	0
8	-1.3	2	7	-4
9	-2.1	-2	2	-5
10	-0.4	1	2	-1
11	-3	0	7	-8
12	-0.1	1	-21	22
Max	-0.1	3	11	22
Min	-3.0	-7	-21	-16
Error +/-	3.0	7	21	16

Table 10: Comparison between Measurements at the Side to Interpreted Wear

The comparison results are shown in Table 10, which identifies differences between these datasets. Further examination is required in order to establish whether or not, this is error or the result of inherent differences within the staircase. For example, there may be a dip in the centre of the stair, which has resulted in the difference shown.

4.2.6. Sources of Error

All forms of survey measurements are susceptible to some form of error.

4.2.6.1. Errors From Undertaking a Physical Survey

There are a number of sources of error that occur when undertaking a physical survey using the improved method described by Johnson.

Inclinometer Instrument Error

The inclinometer used is only accurate to 1 decimal place (dp) or 6 minutes of arc. This can therefore be a source of error through inaccuracy. For example, if the measured distance is 300mm between the noses and the angle recorded is 50.0 degrees:

$$Rise = 300 \times \sin 50.0 \qquad Going = 300 \times \cos 50.0$$

$$Rise = 229.8\,mm \qquad Going = 192.8\,mm$$

As the inclinometer is accurate to 6 minutes of arc, the angular measurement could lie between 49.95 and 50.04 degree, respective to 2dp. Therefore:

Lower

$$Rise = 300 \times \sin 49.95 \qquad Going = 300 \times \cos 49.95$$

$$Rise = 229.6\,mm \qquad Going = 193.0\,mm$$

Upper

$$Rise = 300 \times \sin 50.04 \qquad Going = 300 \times \cos 50.04$$

$$Rise = 229.9\,mm \qquad Going = 192.7\,mm$$

As shown above, owing to the measured distance being relatively small, there is a limited error as a result of using this equipment. If this equipment was used over a much larger distance, the effect would be greater. However, in practical terms utilising this method where the distances are relatively small (such as nosing to nosing) the error is mitigated.

Rule Misread and Booking Errors

Human error is the most common form of error that can occur when undertaking a survey using conventional means of measurement equipment such as tapes, rulers, chains etc. There are several ways to control this error e.g. taking rounds of measurements from either direction and using a false zero on the rule. A false zero is when the rule is positioned on a predefined value before the measurement is taken, for example 100mm (Uren & Price 2010). This compensates for any deviations within the rule at various stages.

Once a population of results (from repeat measurement) has been obtained, statistical analysis can be performed in order to establish which measurements may include significant error. In doing this, values that are possibly subject to error will be discarded. This has particular relevance to the case studies, as only one round of physical measurements were taken and the possibility of error cannot be ruled out.

Rule and Inclinometer Misplacement

This is again a form of human error that can occur from the misplacement of the instrument or rule, making the observed measurement incorrect e.g. if the rule was placed on a raised stone, the measurement would be an inaccurate representation of the object This can be controlled by taking a population of measurements and performing statistical analysis as discussed above.

Temperature

As the ruler used in the case studies was made of steel, this can be susceptible to temperature changes, either contracting or expanding. The ruler manufacturer will specify the operating temperatures in which the rule should be used and the correction which can be applied to the measurements to ensure accuracy. The formula for checking temperature variation is shown below

$$CF = C \; x \; L \; (T - To)$$

Where

$$CF = Correction\ Factor$$

$$C = Co\ Effecienct\ of\ Termal\ Expansion$$

$$L = Length$$

$$T = Temperature\ During\ Measurement$$

$$To = Standard\ Temperature\ (normally\ 20^{o}C)$$

Therefore for a temperature of 18°C

$$CF = 0.0000116\ X\ 0.3m\ (18 - 20)$$

$$CF = -0.00000696m$$

In relation to the above case studies, the effect of temperature would be negligible given the short distances that are obtained in stair measurements.

Sectional Measurement

When taking a section through the centre of a staircase, it is important to remain on a consistent bearing throughout, when comparing the datasets. This was controlled by measuring in from one stair string to ensure the measurement was consistent. However, if there is inaccuracy in this method, comparing the datasets may be complicated as the two sections must be taken from the same position. With reference to the two case studies this measurement wasn't recorded so ensuring the sections are the same isn't possible.

4.2.6.2. Sources of Error Using a Laser Scanner

There are a number of key sources of error when using a laser scanner. These are explained below with reference to the two case studies:

Errors in Registration

One form of error that requires considerable attention in relation to laser scanning is the registration process. The registration process as explained earlier, it is the method by which laser scan data is controlled and joined. When undertaking a survey using a laser scanner it is important to control the survey with adequate targets and also constrain adjoining surveys correctly.

Both surveys were undertaken using manufacturer approved targets and registered using both target and cloud to cloud techniques, to ensure accuracy. However as with all forms of survey an error was created when joining the clouds together.

Instrument Errors

There are a number of sources of instrumental error that can affect a laser scan survey, which can have implications for both distance and angular measurement.

Laser scanners obtain a measurement of distance in a number of ways. Some obtain the measurement by time of flight and others by phase distance.

Time of flight laser scan systems (such as the Leica C10 used in the cellar stair case study) measure the time between which the laser beam is emitted and returned, and convert this into a distance. Errors in these instruments occur from inaccuracies in the timing circuit used to measure the time (Cosarca et al. 2009).

Phase based systems (such as the Leica HDS6000 used in the Quay Incident) calculate distance by comparing the phase difference between the emitted beam and the one returned. Inaccuracies in this technology occur due to errors in the modulated wavelength and signal noise ratio (Cosarca et al. 2009).

In addition to errors in distance, angular errors can occur when obtaining the vertical and horizontal angles. Errors in the vertical angle occur when calculating the position of the rotating (or oscillating) mirror that is used to deflect the emitted beam. Errors in the horizontal angle can occur through errors within the electronic decoder that is used to calculate the angle.

There are a number of instrument errors that have to be considered which differ between different devices. This makes equipment selection essential for the task for which it is to be used. Reference should be made to the specification sheet of the laser scanner before undertaking the survey. In addition, the instrument should be calibrated and in good working order to reduce controllable error.

With reference to the above case studies the laser scanners selected were in calibration and suitable for the tasks required in reference to range and accuracy.

Surface Errors

There are a number of factors that can affect accuracy of measurement when recording a surface with a laser scanner. Since laser scanners use an infra red emitted laser beam, this can be subject to error. Infra red light is reflected differently dependent on the source material which is being recorded and thus, this can become problematic in environments with varying infrastructure. This error can be avoided if the objects are coated in the same material, but often this is impractical (Boehler & Marbs 2003).

The above points are particularly relevant to the case studies discussed above. There is considerably more error in the survey of the cellar stair case study as opposed to the quay case study. One of the contributing factors for this could have been that the cellar stairs were dark in colour, therefore resulting in surface error.

In addition, error can occur through edge effects. As a laser beam has a specific width, when recording the edge of a surface, the beam may be "split" between the reference object and the adjacent object. This can result in a number of incorrect points in the vicinity of surface edges (Boehler & Marbs 2003). This has particular reference in using laser scan technology to record staircases as stairs inherently include a number of edges.

Environmental Errors

Laser scanners can be affected by temperature. Consequently equipment manufacturers specify a operating range found in the datasheet of the instrument. The environment can also affect an instrument’s accuracy, as the speed of light can be affected by temperature and pressure variations. In addition, error has been reported when operating a laser scanner in the presence of dust or steam (Boehler & Marbs 2003). However, these sources of error are not relevant to the case studies discussed above as the equipment was operated without such interference and within specification.

One environmental error that needs to be considered is the effect of radiation. As laser scanners use Infra Red (IR) laser light for measurement, this can be subject to interference from illumination sources (Boehler & Marbs 2003). Sunlight can have considerable effects on the accuracy of a survey, for example, one of the case studies concerns steps located outside, so sunlight has to be considered.

Resolution

When using a laser scanner it is important to consider the density required of the survey. The instrument has a wide range of different resolutions in which it can capture data and the resolution used, depends on the task required. The density of a survey also has a direct correlation to the time required to complete the survey. The higher the density setting the longer the laser scanner takes to collect the information. This can result in scans taking longer if small objects or detailed object features are required as using a low density scan could result in these objects being missed (Boehler & Marbs 2003). In the above case studies high resolution scans were taken from a multitude of different locations to ensure this source of error was eliminated (and the full scene was recorded).

Interpretation

Undertaking a laser scan survey with the methodology described above can be subject to error through interpretation, as the placement of the point in which to start or end a measurement is subjective and therefore subject to error if misjudged. In order to reduce this, multiple sets of measurements can be taken to obtain a spread of results that can be compared mathematically using an arithmetic mean.

Setting of UCS

When establishing the UCS for the staircase, errors can occur if it is misaligned. If a UCS is set incorrectly when looking at a section of the stairs, it will be "twisted", and taking measurements with it would be unreliable and inaccurate. Assigning the UCS to the tread of a step that isn't parallel with the stair strings is easily done and has a negative effect on the accuracy of the survey. In addition, as the laser scanner inclinometer was used when undertaking the surveys, a UCS could be assigned by using the stair string and adopting the direction of gravity to set the Z axis.

4.2.6.3. Contributing Error

As there are a number of variables e.g. sources of error between the two surveys and the fact that the comparison has been performed retrospectively, the contributing error is hard to establish as a result. Further work is currently being undertaken by the author in order to quantify the specific error and therefore to assess the viability of using a laser scanner as part of a stair fall assessment in a controlled environment where surface and environmental errors are reduced .

4.2.7.Benefits of Using a Laser Scanner

There are a number of key benefits to using laser scan technology to evaluate construction of the stairs:

Obtaining the Bottom Step Angle

When undertaking a survey and taking measurements physically, it can be problematic obtaining the angle for the bottom step. This occurs because there is not another nosing for the inclinometer to be placed on, therefore the final rise is normally measured traditionally from the floor to the tip of the nosing. However, this can be a cause of error if the ground is uneven or sloping and so the measurement does not reflect the actual rise.

The bottom angle can be obtained from taking the measurement using laser scan data. A virtual nosing can be projected from the bottom step nosing at a difference equal to the average going of the flight. This can be used to calculate the first rise using Johnsons approved method stated previously.

Obtaining the Handrail in 3D

Having a 3D model of the handrail can be beneficial when assessing its suitability, as the cross section of the rail can be examined. An accurate measurement for the diameter for the whole rail can also be determined as explained previously.

In addition, the positions for the stanchions can be obtained at the base and top. This can be hard to obtain through conventional means if the stanchion is not upright. In addition, the layout of all handrails can be shown in 3D and their positions shown relative to all other objects in the scene in a way that is easy to understand.

Data Clarity

If a staircase has been found to have dimensional inconsistencies, alterations to the rises and goings may need to be made to make the stair safer. This is typically done by producing a 2D representation of the changes which a tradesman can use when making changes. The use of a 3D model can be of considerable benefit in the explanation of the changes, particularly if the required alterations are complex.

Repeatability of Measurements

In order to reduce propagation of error it is necessary to undertake measurements a number of times. If the environment has been laser scanned, repeat measurements can be taken quickly once the UCS has been obtained. This is considerably quicker than taking rounds of measurements in the field.

Multiple uses for the Data Obtained

As the dataset obtained using a laser scanner is very rich, it can be used for a multiple of different applications within the accident investigation process. Examples include recording the scene, testing hypotheses and allowing for incident reconstruction. In addition, if a scene that has already been laser scanned, the existing data can be used to evaluate the stair virtually, without sending an expert to the scene, which could have implications in terms of cost and safety.

Safety

Undertaking a physical survey, particularly on a stair where an incident has occurred, may put an expert at risk of falling. Most modern laser scanners have the ability to be operated remotely via an internet connection and have various ranges of non-contact measurement (in the extreme, up to 6km). Considering this, if the environment is captured using a laser scanner, and the evaluation of the staircase performed remotely, this will drastically reduce exposure to the hazard.

Education

Once laser scanned, the scene is recorded digitally and can be archived and referenced at any point in time, if required. One particular use for the data could be to educate people on the potential hazards and consequences of poor stair design and the implications this may have. A geometric and visually accurate 3D scene derived using laser scanning technology can be used to recreate and re-enact possible scenarios and demonstrate good practice, thereby, helping to prevent further accidents.

Multiple sections

By using a laser scanner to survey the stair and record the full environment, multiple sections can be created and used for stair measurements. This could provide the ability to compensate for deviations in the step profile between the stair strings. In performing multiple sections across the stair tread a range of results can be obtained, providing a greater number of readings to facilitate investigation. This also has additional benefits if one section through the stairs is damaged and others are not.

Calculation of Wear

Using the laser scan data, the rises and the goings can be extended virtually and the point in which they intersect, which represents the stair with 'no wear'. This is of particular importance if a survey is performed on stairs that have received a high footfall and the measurement is taken from the area of highest traffic.

Speed and Density of Data

A laser scanner provides a density of data in a short period of time, that is unprecedented by comparison to conventional survey techniques, creating a geometrically and visually accurate 3D environment (if digitally imagery is incorporated in the survey methodology). The associated dataset can then be used as a base to best fit surfaces upon, to create a virtual 3D model such as the one shown in Figure 72. Such models are useful to evaluate the incident and explain the environment to others in a way that is easy to comprehend.

Figure 72: An Example of a Model that has been Created Using Best Fit Surfaces

4.2.8. Limitations of Using a Laser Scanner

Adopting laser scanning technology for the use in the assessment of stair construction is not without its limitations:

Interpretation

When undertaking staircase measurements using a laser scanner, it is important to limit possible sources of error in the dataset. The point which is measured within the drafting package (where the curser is placed) is subjective and is at the discretion of the user. As the point cloud is made up of millions of points, it is hard to determine which is the exact point to record. Therefore, in order to reduce this possible source of error, multiple rounds of measurements should be taken, an arithmetic mean taken and standard deviation used to reduce any propagation of error.

Cost

Laser scanning technology is still relatively new, with the equipment and related software, expensive as a result. With this in mind, the use of laser scanners may not be appropriate for every incident. However, as the technology matures the costs related to its use will reduce, making it a more sustainable solution for accident investigation.

Errors using Laser Scanning Systems

There are a number of sources of error that are inherent in a laser scan survey that have been highlighted previously. The sources of error have to be controlled where possible, with the survey carried out in line with best practice. Therefore, taking multiple rounds of measurement, ensuring the equipment is in calibration and appropriate for the selected task is highly important. As there are limited tolerances in the deviation in stair design, governed by building regulations, it is essential to understand and reduce these variable sources of error highlighted previously.

4.2.9. Conclusions

The purpose of this paper was to explore the possibility of using a laser scanner for assessing key stair dimensions and it can be seen from the two case studies presented that measurements can be made using a laser scanner.

While incorporating this technology into a stair fall assessment can provide a wide range of benefits with regards to safety and the explanation of the environment to people other than the investigator, further work is required to assess the effect of the various sources of error that have been explored within this paper. With the lack of a population of measurements on the physical survey, it is hard to statistically assess the accuracy of the measured results from the laser scanner to categorically state that the laser scanner is responsible for most of the contributing error, although the authors believe this to be the case.

Due to the errors associated with laser scanners, for precise high accuracy surveys to narrow tolerances such as the measurements of rise and goings outlined in this paper, laser scanning may not be the best survey methodology available. For example, the use of conventional levelling may be used to obtain the measurements for the rise of a stair to a very high tolerance. However, the classification of the error from laser scanning must be established, in order to consider if the error is relative and therefore can be mitigated, through further research. The author plans to explore the use of different laser scanning systems that may be better suited to the task of stair measurement, such as high accuracy close range scanning equipment.

Laser scanners are impressive instruments to recreate an as-built virtual 3D environment that can be used in the explanation of the event, the contributing factors and in incident reconstruction. In addition, the recorded data can be used to address leading factors (through simulation of incidents in a geometrically accurate environment) and educate people in the implications of defective stair design. Therefore, deploying a laser scanner to survey accident scenes has considerable benefits that cannot be achieved through conventional means, where the data obtained can in addition, be used for a magnitude of different applications which are highlighted within this chapter.

In many cases, the justification for a survey using a laser scanner may not be warranted for every accident investigation (in the case of a low consequence incident) with regard to cost, availability of equipment and the time requirement for processing of the associated dataset obtained. As highlighted in this case study, stair falls are common (every 90 seconds), however high consequence events from these incidents are not compared to ratio of occurrence.

Therefore the laser scanner would not be deployed in every incident, the inclinometer and tape survey being of sufficient benefit, as this equipment is simple to use, portable, low cost, not requiring specialist software and data processing.

However, this methodology can only provide one outcome, being a simple 2D sectional profile of the staircase. In many cases, a 2D section would be all that is required and if a 3D survey of the scene is needed, utilising the laser scanner, the added benefit of using the survey for another purpose such as stair assessment, is merely another use of the rich dataset obtained.

4.3. The Integration of Laser Scanning and 3D Modelling in the Industrial Accident Investigation Process

Abstract

Industry is committed in reducing accident numbers and improving safety; however, repetitive incidents still occur. Effective accident investigation provides a deeper understanding of the events surrounding an incident. A key part of the investigation process is to accurately record the accident scene, in order to help explain the incident circumstances and situation to people not associated with the incident. For a number of years, techniques used by accident investigators to record data have been the same where investigators are tasked to represent three-dimensional (3D) accident scenes using two-dimensional information.

Over a number of years, there have been considerable innovations in accident survey instrumentation and software. This paper explores the benefits that can be derived by using laser scanning data with regard to the accident investigation process, with discussion on accuracy, time, witness verification and reduction in human error. In addition, further uses for 3D data will be discussed in respect to training and proactive risk assessment.

One of the principal benefits that can be derived from laser scanning data is the ability to navigate around the accident scene virtually. This allows the investigator to stop at different viewpoints; therefore, providing a clearer understanding of objects and their reference to others. In order to demonstrate the potential of 3D surveying in relation to accident investigations, the author undertook a fatal accident investigation using laser scanning technology. Based on this case study, there are a number of benefits that laser scanning techniques provide over conventional survey methods when investigating an accident.

4.3.1. Introduction

Within the UK, falls from height pose a significant risk to workers accounting for a substantial proportion of reported injuries under RIDDOR (Reporting of Injuries, Diseases and Dangerous Occurrences Regulations). RIDDOR statistics show that in 2012/13 falls from height contributed to 31% of all fatal accidents at work, where 46 people were fatally injured from a fall (HSE 2013c). The graph shown in Figure 73 illustrates the number of fatal injuries resulting from an accident in reference to the cause.

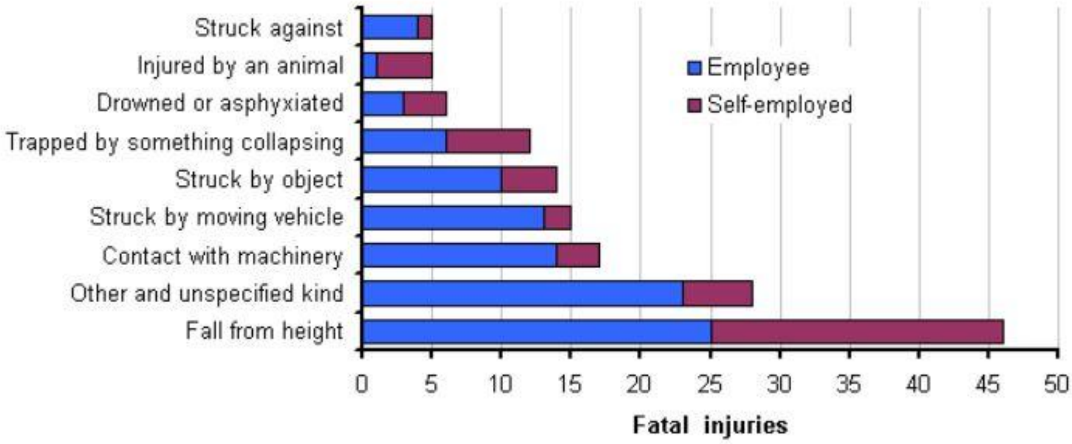


Figure 73: Fatal Injuries Against Causes (HSE 2013c)

It can be seen in Figure 73, that the number of fatalities occurring, as a result of a fall from height, far exceeds any other cause of death in 2012/13. In addition to fatal injuries, there were 2835 major injuries as a result of a fall from height (HSE 2013c). This demonstrates that falls from height pose a significant risk to people at work. With this in mind, these work activities have to be controlled in order to mitigate the risks involved while working at height.

There are a number of laws that are relevant to working at height which have been established in order to clarify the roles of companies and help ensure safe operating procedures, these are the (HSE 2012b):

- Health and Safety at Work Act 1974
- Work at Height Regulations 2005
- Management of Health and Safety at Work Regulations 1999
- Construction (Design and Management) Regulations 2007
- Lifting Operations and Lifting Equipment Regulations 1998
- Provision and Use of Work Equipment Regulations 1998

In the UK, the Health and Safety Executive's (HSE) role is to ensure that companies and individuals comply with legislation regarding matters of Health and Safety. Considering the risks and associated regulations governing falls from height, HSE enforcement within this sector is substantial. Between 2012/13, more than one in ten offences prosecuted by the HSE were under the Work and Height Regulations 2005 (WAH2005), with HSE, prosecuting 97 times under WAH2005, where 83 of these convictions resulted in a fine of over ten thousand pounds (HSE 2013c).

Through an improved focus and drive towards safety, the number of fatal injuries suffered from people at work has fallen, however the percentage of fatal injuries due to falls from height has remained the same (HSE 2013c). These statistics are alarming and more needs to be done in order to address the situation.

4.3.2. Case Study: Fall From Height Resulting in a Fatal Accident

The following dataset was obtained following a fatal accident investigation, concerning a contractor who fell from height and unfortunately died from his injuries some weeks later. As the information involving the case is of a sensitive nature, specific details about the incident have been redacted.

When an incident occurs, it is important to record the area for reference at a later date and explain the scene to people unconnected to the event itself. The author was asked to survey the scene and produce a record of the environment that could be used in the investigation process. This was of particular importance in order to help in the explanation and recreation of the events surrounding the incident, as a number of fundamental changes had occurred at the location. In addition, a virtual 3D model was created to test theories of the investigation team, in order to establish if hypotheses were plausible in a geometrically accurate representation of the scene. This section will discuss the methodology of data gathering and recreation of the scene, with discussion on the benefits that were obtained by incorporating a 3D survey into this particular accident investigation process.

4.3.2.1. Methodology

There are a number of processes that have to be undertaken in order to survey and recreate a scene following an industrial accident.

Data Gathering

Firstly, the accident investigator must brief the surveyor on the key aspects of the case and what is considered to be of importance to the investigation team. In the above case, it was key to record the footprint of the building, the fall area and obtain the dimensions of the roof from which the person fell. Following this, the 3D recorded scene can be used in order to recreate the event itself and test the various hypotheses that may be established by the investigators.

Laser Scanning

Using a laser scanner, a survey was taken of the scene retrospectively in order to recreate the incident scene and to better understand the event itself. An open traverse was performed around the building using targets within each scan position that were used to constrain the survey later in the registration process. A plan view of the data and of the location of the instrument set ups is shown in Figure 74.

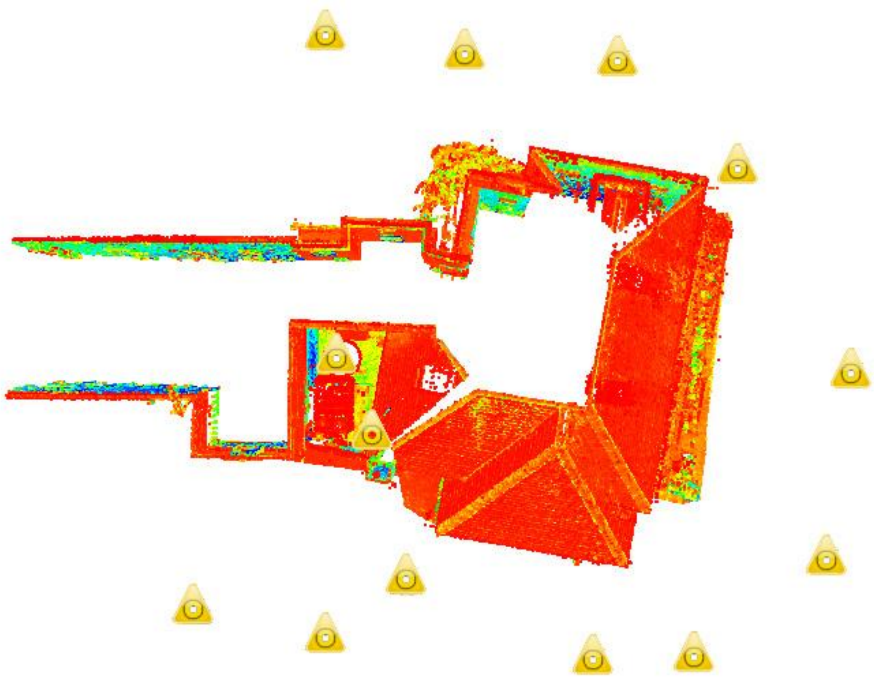


Figure 74: Plan View of Laser Scan Data with Instrument Locations

Photographs were also taken from the laser scan set up positions which were later overlaid in order to create a geometric and visually accurate 3D environment. The photo textured point cloud of the elevation is shown in Figure 75.

Figure 75: Photo Textured Point Cloud

Laser scanners are line of sight instruments, because of this they suffer from blinding. Blinding occurs when an object obscures the view of another object behind it. Thus, the point cloud will not be able to gather data of the obscured object unless it is moved to a position where it can be observed. With this in mind, it can be seen in Figure 74 and Figure 75 that minimal data has been gained of the roof itself. This is because the survey was taken from ground level, as the scaffold which had previously surrounded the building was no longer there and it was not possible to gain access to the roof in order to capture it with the laser scanner. This problem was anticipated and a solution was established using an aerial mounted camera.

Go Pro Camera and Gyrocopter

As the roof was of major significance to the investigation team, a method of capturing it had to be determined. In order to achieve this, a gyrocopter with a mounted camera was used. The camera was set to take photographs at a given time interval while the gyrocopter was flown over the building. Figure 76 shows an image of the gyrocopter operating within the accident scene.

Figure 76: Gyrocopter with Aerial Mounted Camper

In this system, the camera’s position is fixed. Therefore, two separate flights were made with the camera set at different angles. Firstly, the gyrocopter was flown with the camera positioned at 45 degrees to capture the scene and context of the whole environment. Secondly, to gather data of the roof the camera was positioned pointing down in order to obtain photographs of the roof. Examples from both flights are shown in Figure 77.

As a Go Pro camera has a fisheye lens, the images are subject to lens distortion. This makes the images good as a visual reference and illustration of the roof conditions, with a number of images from different angles and viewpoints that may be essential when explaining the event to others. However, due to the lens distortion measurements cannot be taken from these images, therefore a solution was sought to obtain a visually and geometrically accurate image of the roof.

Figure 77: Photographs from the Gyrocopter Flights

Ortho-rectified Aerial Photography

Aerial photography can be subject to a number of errors, being derived from the sensor system or the recorded terrain. These errors have to be considered and corrected before measurements are taken from the photograph (Mercer et al. 2000). This process is known as ortho-rectification. There are a number of companies that supply images to order that have been corrected and can be used for this application. In this case the author obtained a image from the Channel Coastal Observatory (CCO) taken in 2013 and represented the roof in the same condition at the time of the incident. The image obtained is shown in Figure 78.

Figure 78: Ortho-Rectified Aerial Photograph (Channel Coastal Observatory 2013)

The photograph is to scale and therefore measurements could be taken directly from the image to obtain measurements for the roof layout. In addition, these measurements were then compared to the laser scan traverse as a second level of accuracy. As the aerial image was taken showing the roof in the condition as at the time of the incident, it also provided a deeper insight into the area prior to the incident and explaining the scene to others. The aerial image was also used in the creation of the 3D model that is discussed later in this paper.

Investigation Photography

There was limited photographic information of the scene in its condition directly after the incident. When the investigation was undertaken the scaffold had been dismantled and the only documented information about the condition were four photographs taken by the workers on site. Two of which are shown below in Figure 79.

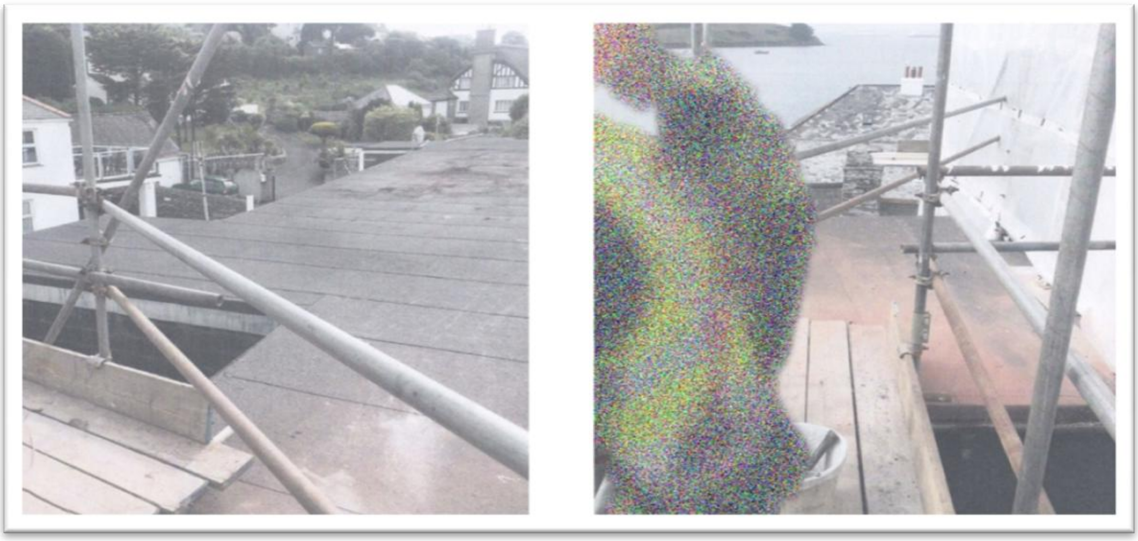


Figure 79: Photographs Taken at the Time of the Incident (Speake 2013)

As these photographs were the only illustrations of the location of the scaffold, these were used in order to take measurements and construct a 3D model of the scaffold in its location. Although these photographs are not ortho-rectified, measurements were taken on the same reference planes and compared to known measurements within the laser scan data, along with the regulations governing scaffold construction in UK legislation to aid in modelling the scaffold virtually.

4.3.2.1. Data Processing

Much of the captured data can be used directly by the investigation team as is the case with all photography. However, in order to use the laser scan data first the point clouds must be processed.

Laser Scan Data

Firstly, the photographs must be "mapped" to the point cloud. This is done by selecting common points within the photograph and the scan data. Using these selection points, the photographs can then be projected onto the point cloud and real world colours achieved. By colouring the point cloud in this way, it makes the virtual environment easier to understand to a non technical person or someone unconnected to the event. Figure 80 illustrates the difference between "raw" point cloud data with intensity along with a photo textured point cloud.

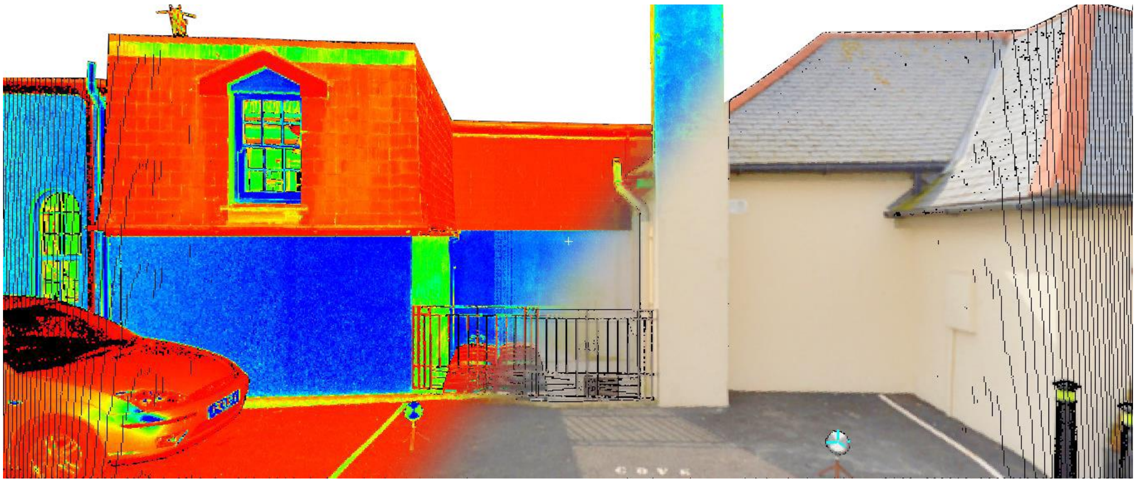


Figure 80: Blend Between a Intensity Mapped Point Cloud and a Photo Mapped Point Cloud

A number of targets were placed around the building which remained static between the two laser scan positions. These targets were then used in the registration process in order to constrain the scans together. In addition, common points in the point clouds were also used to add redundancy and further constraints between the scan locations.

Once the point cloud data has been colour mapped and the full scene is obtained and processed, the data can be used for a multitude of different purposes within the investigation process. This includes using the point cloud data to take measurements, which may be of use for the investigation team. In addition, the registered model is used in order to observe the relationships between everything in the scene and observing them within a virtual 3D space.

As the survey was undertaken retrospectively of the scaffold being removed, it was hard to establish the location of the structure within the scene. In addition, point cloud data by its very nature is made up of millions of 3D data points, which provides a overview of the scene and from a distance is visually complete. However, as the user begins to zoom into a specific area, the data points can become visually sparse. This can be because of a number of factors, but the most common is the hardware capability required to display all the recorded points owing to the density of the data collected. Considering these issues, both laser scan data and photographs were used to produce a virtual "solid" 3D model of the scene. A solid 3D model aids in bringing all the sources of data capture together in a way that is easy to understand.

Creation of 3D Model

In order to produce a 3D model, the point cloud is used as a base to accurately create geometry. This was the methodology used in the above case study to recreate the building's structure, which was recorded in the laser scan survey. Following this, the model was textured using photographs and a virtual lighting system added. A rendered image of the building is shown in Figure 81.

Figure 81: Rendered Image of 3D Model of the Building

When creating 3D models for an accident scene reconstruction, it is imperative that the model maintains its integrity to the laser scan survey and there are many programs that can be used in order to perform a validation of accuracy. Figure 82 shows the result of a deviation analysis of the mesh model with the laser scan data.

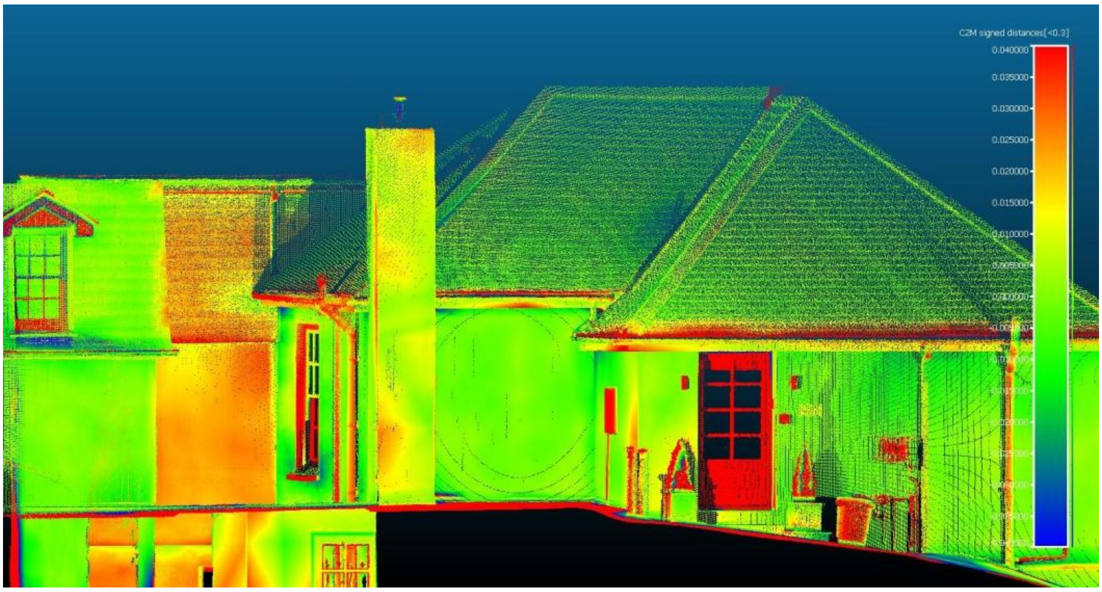


Figure 82: Deviation Analysis Results

As previously stated, a laser scanner is a line of sight instrument and therefore the roof was not collected within the survey. Therefore, the ortho-rectified aerial photography was incorporated into the laser scan data footprint, to provide a accurate representation of the roof. A rendered image showing the roof modelled to the edge of the laser scan data also incorporating measurements from the ortho-rectified aerial photograph and textured with a photograph from the gyrocopter flight, is shown in Figure 83.

Figure 83: Rendered Image of the Building and Roof

In addition to the building, the scaffold was of great importance to the investigation team, in order to test hypotheses and statements given by persons involved in the incident. This was achieved by taking the limited photographs of the scaffold in position, and taking approximate measurements from them.

Using known sizes of objects within the image, the measurements for others were derived. Having the additional benefit of the laser scan data to obtain other measurements for the doorway and footprint was essential to maintain the accuracy of this process. Once some fundamental measurements were obtained, the scaffold could be modelled in 3D and placed into the scene. A rendered image of the scene with the scaffold infrastructure added is shown in Figure 84.

Figure 84: Rendered Image of Complete Scene

Once the scene had been modelled, it was then possible to observe the accident from any number of different camera angles virtually, many of which would not have been possible to do on site without specialist equipment and reconstructing the scaffold, such as images directly above the scene. An example of the roof taken directly above is shown in Figure 85.

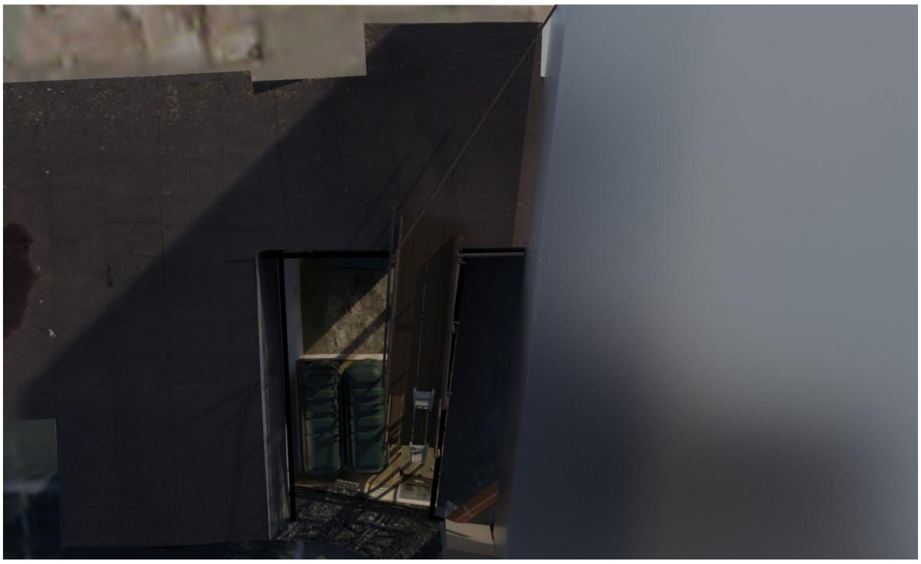


Figure 85: Rendered Image from Above

The completed scene can be used in the investigation process with further benefits derived from the data in addition to visual representation.

Production of 2D Plans

Although the data captured by a laser scanner is in 3D, sometimes 2D representations of the scene are required in order to display the scene and provide dimensions. Firstly, as the laser scan data in this particular case was recorded on a local scale and not geo-referenced to a co-ordinate system, a User Co-ordinate System (UCS) was created. This was aligned with the front wall of the building, parallel with the wall where the accident occurred. The UCS was formed in order so that the plan and the elevation of the incident area would be aligned allowing it to be observed in the correct orientation. An elevation plan of the fall area is shown in Figure 86.

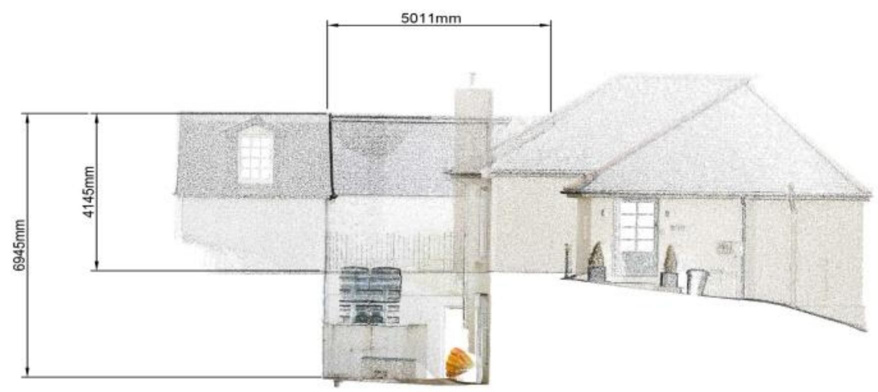


Figure 86: Elevation Plan of Fall Area

In addition, in order to produce a topographic plan of the building, a section was taken through the point cloud to create a footprint of the building. The plan of the scene in shown in Figure 87.

Figure 87: Topographic Plan of the Incident Scene

The production of scaled drawings can aid in the discussions of the scene on paper without the use of a computer or visual display. In addition, measurements can be clearly represented in a way that is easy to understand.

4.3.3. Benefits to the Investigation

There were a number of key benefits that were highlighted by undertaking laser scan survey and modelling the scene in 3D:

Explanation of the Event to People Un-connected to the Event

Understanding an accident scene is essential in order to gain a deeper understanding of the events surrounding an incident. With this in mind, the methodology expressed in this paper provided a comprehensive reconstruction of the accident scene. The completed model allows people to understand the location and interaction of all objects within the recorded scene. In addition, as the scene is recorded virtually, it gives the ability to observe the scene from any number of possible locations, many of which would not be possible to view at the incident scene without specialist equipment.

Witness Account

In this particular case, there were a number of witness accounts that were made in the course of the investigation, that had to be tested to determine if they were plausible given the environment. Having a geometric and visually accurate reconstruction of the scene was essential in order to demonstrate inconsistencies in the statements of witnesses, challenging the position of scaffolding and also the areas in which materials were loaded. The sizes of the materials were known and modelled in 3D and they were then positioned in the locations as suggested by witnesses. With this information being reproduced in a visual format, the witnesses were then questioned again relating to their recollection of the locations and positioning of said materials. By incorporating this methodology, the investigation team were able to better understand the event and the circumstances surrounding the incident and perhaps more importantly challenge the accounts given by witnesses.

Testing of Hypotheses

During an investigation, the team need to test a number of possible hypotheses of what may have occurred before, during and after the event itself. This aids in understanding what factors may have had an influence on the incident occurring. In this case study, there was a particular focus on the area in which materials were being loaded and the placement of the materials in relation to the workers and equipment. Using the 3D model, the scene was explored further in order to establish or disregard possible hypotheses formed by the investigation team and circumstances relating to the event. In other cases where a 3D survey hasn't been undertaken, the ability to visualise this can be problematic, this being of particular significance in this case as access to the roof was restricted. Therefore, the ability to check the locations of the materials and their interaction with other objects would have been awkward without additional expense re-constructing the scaffold and false roof.

Safety

The methods described in this paper were non contact forms of data capture and therefore improved safety benefits could be obtained. Laser scanners operate using Electromagnetic Distance Measurement (EDM), which allows the surveyor and the investigation team to operate the equipment from a safe distance when recording the scene. In addition, aerial photography was captured using a gyrocopter which again allowed the investigation team to record the scene without the necessity to work at height. This was of key importance as access to the roof was restricted and gaining access would have required the use of a work platform and or Mobile Elevated Work Platform (MEWP).

Limited Intrusion to House Owner

As the survey was taken retrospectively from the time of the incident and the conditions in the scene had changed, with the scaffold structure removed, it was important to the investigation team to understand the location of the scaffold at the time of the incident. This could have been done in two ways. Either the scaffold could be constructed on site or virtually, as discussed in this paper. If the investigation team decided to re-construct the scaffold, this could be very intrusive to the house owner, resulting in a number of possible complications, such as the expense and also the time taken to construct the scaffold may have become issues. Therefore, the ability to construct the scene virtually is a great benefit, as the survey time taken on site was limited and could be taken from a distance with little inconvenience to the home owner.

Representation of the Roof

As the accident occurred on the roof and there was no access available, a methodology had to be considered that would allow the scene to be captured in its entirety from the ground. The methodology discussed in this paper allowed for this and provided the investigation team with the information required. In addition, having the scene recorded in 3D allowed the investigation team to observe the roof from angles that would not be possible on site. Having this ability was greatly beneficial in order to observe the locations of materials in relation to the other objects in the scene from varying camera positions.

Scene Revisits

In the course of an industrial accident investigation, the team may deem it necessary to visit the scene a number of times in order capture additional information or to evaluate\ test various hypotheses. This can be significant with regard to the expenses of travelling time on site, the intrusive nature of the visits, scheduling issues between the investigation team and the house owner in order for access to be provided and other factors such as the weather. By incorporating the methodology stated in this paper, the scene can be captured in very high detail and observed virtually at any time throughout the investigation.

Data Clarity

Understanding an accident scene is essential in order to investigate the accident efficiently. Creating a virtual model of the scene can be highly beneficial, in being able to observe the scene in its entirety or have the ability to remove certain items that may provide additional clarification. In this investigation with the scaffolding removed, it was hard to envisage the scene from all angles other than the ones captured in the limited photography that was provided to the investigators. This situations can become paramount if the investigation team has to explain to the scene to non technical people, for example in gathering witness statements or in a courtroom environment with the scene being explained to a jury. Using a fly through animation, stopping at key locations within the scene, can provide an essential tool in this process especially in the initial introduction of the scene to a court. The model can then be referenced at any point during court proceedings in order to provide context to witness statements, emphasise a particular point or demonstrate hypotheses.

Enabling Incident Reconstruction

Given the richness of the data set, once an accurate 3D model has been created, it can be used for a multitude of different applications, one of which is reconstructing the incident. In the above case, the location of where the deceased fell was known. Therefore, using this information, a person was modelled virtually and the fall trajectory path was created from witness account and possible hypotheses. The fall was then recreated in order to demonstrate possible incident scenarios, i.e. where the deceased may have been standing prior to the fall. It is important however to restrict interpretation of the data and only operate on the facts, particularly if the case may be tried in a courtroom.

Hindsight

On many occasions when undertaking an investigation, it may become apparent at a later stage that something unrecorded at the initial site investigation may have relevance to the case. If conventional surveying methodology was used then there is no way to reconcile this, as the points were recorded subjectively and the scene may have subsequently changed.

As a laser scanner and an aerial mounted camera are largely indiscriminate in data collection, the information initially gathered, which may at first be unused or disregarded by the investigators, may then later become essential to the investigation team. With this in mind, the data collected should be stored in its entirety and information extracted from the dataset without affecting the original. This is also of importance for evidence management and continuity. In this case study, the focus was on the area in which the deceased fell and the location of the materials loaded on the roof. Further into the investigation, focus was then on the entirety of the perimeter scaffolding and the potential fall risk from every elevation. As this data had been captured it was readily available without the need for further site investigations and thus readily available to the investigation team.

4.3.4.Conclusion

By adopting this methodology throughout the investigation, it provided a wide number of benefits that have been discussed previously in this paper. This was of particular importance in this case as the scene had changed from the time of the initial incident. This had a number of implications for the investigation team in the understanding of the event itself and possible scenarios that may have occurred within the environment. Constructing a scaffold in situ would not have been plausible as there would be a number of implications, considerable expense and intrusion to the home owner.

Therefore by incorporating a laser scan survey, the investigation team was provided with additional information and the locations of particular objects within a 3D scene were able to be modelled. This means that interview questions could be targeted by the investigator, used to challenge some of the statements made, while being able to visually display the scene to the interviewee. In addition, the model can be shared with experts in the field to help explain the surrounding environment, rather than just showing a number of 2D photographs or other illustrations that may be hard to comprehend.

Over recent years there have been considerable advancements in the geospatial industry, both in hardware and software applications. This has caused an influx of possible applications of the data, being considered for a wide range of different fields, one of which being the accident investigation process. However, it is particularly important in any incident that the data is handled with caution and that accuracy is maintained. Focus must be placed on maintaining the integrity of the data throughout the process from capture to the final deliverables.

This is achieved through using a surveying point cloud processing software such as Leica Cyclone, which gives the user full control of the dataset and the ability to monitor the accuracy of the processes undertaken. In addition, Cyclone provides statistics on the registration adjustment that has been undertaken when the laser scan positions have been joined together, which can be printed to form a audit trail for possible use in legal proceedings.

These advantages not apparent in some software applications that could be considered as "hobbyist" such as Autodesk 123D Catch, where photographs from various locations can be uploaded and the software creates a 3D model for the user automatically. This can be an issue from two counts, in respect to the accuracy of the model and also the the information of a potentially sensitive nature being shared over the internet.

Alternative software is available such as Visual SFM that allows the user to perform the registration of the data themselves, although the process is still largely automatic and the details of the registration adjustment limited. The author is not stating that the models created by Visual SFM or Autodesk 123D Catch are always inaccurate. However, caution should be placed with regard to the subsequent model and it is important to perform analysis on the data in order to ensure its accuracy, for example, to compare the geometry of the model to that of known measurements.

An accurate point cloud will form the basis of any subsequent mesh model that is created, so it is important to maintain the accuracy of the laser scan data as it will affect the whole process if it is not controlled. As described in this PhD study, there are numerous ways that can be used to create solid models, either through the use of complex meshing software (3D Reshaper, MeshLab or Geomagic) or modelling directly from the point cloud data in 3DS Max, for example. The created solid model can then be compared to the original survey dataset, as illustrated in this paper through the use of Cloud Compare for example. The deviation analysis of the mesh model and survey data is an important step to undertake, as the accuracy of the mesh model can then be verified.

Although, it is important for the model to appear aesthetically pleasing and easy to understand, possibly by using software that is associated with the film and gaming industry (such as 3DS Max), ultimately the audience must be observing a representation that is accurate and not one that has been made for visual merit only (unless that is its only purpose). In that case, modelling the scene approximately from photographs or video may have been sufficient and wouldn't justify the resources required in incorporating a 3D survey. If the purpose of the survey is to record the scene accurately in high detail, which can then be used for a scientific or engineering purpose, then adopting the methodology expressed in this paper with regard to accident investigation can be highly beneficial to the investigation team.

In many cases in which the author has been involved, there is a requirement from the investigation team to show the environment in a larger context. Therefore, some of the contextual elements of the model may not require the same stringent survey and modelling methodologies and a balance has to be established relating the size and complexity of the model and the information it is intended to display.

5.0 Chapter 5: Applications of Laser Scanning and 3D Modelling within the Mining Industry

This chapter is presented in a number of case studies written in the style of academic papers

Case Study One: The Benefits of Laser Scanning and 3D Modelling in Accident Investigations: In a Mining Context

Work was undertaken in order to evaluate the use of laser scanning and 3D modelling following an accident in a mine. Although the case study was staged, the author has also been involved in the investigation of the mining fatalities both domestically and abroad, but these case studies are under legal restriction and could not be used within this PhD. Therefore, a staged incident is presented in order to express some of the findings of the other restricted cases

Adapted from;

Published in Mining Technology ISBN 1743-2863

Eyre, M., Foster, P., Jobling-Purser, J., & Coggan, J. (2015). The Benefits of Laser Scanning and 3D Modelling in Accident Investigation: In a Mining Context. *Mining Technology*, 11. doi:10.1179/1743286315Y.0000000004

And presented at ICSMIRI London 2014

Eyre M, Foster, P, & Jobling Purser J. The Benefits of Laser Scanning and 3D Modelling in Accident Investigations: In a Mining Context. *Proceedings of ICSMIRI, 35th International Conference of Safety Mines Research Institutes, P463-P475. ISBN:1-86125-174-2*

5.1. The Benefits of Laser Scanning and 3D Modelling in Accident Investigation: In a Mining Context

Abstract

The mining industry is committed to operating safely and reducing accident numbers. However mining is considered to be inherently dangerous due to unknowns. With this in mind, understanding accidents is essential in order to learn from them and to develop robust Health and Safety Management Systems and proactive Risk Assessments.

Effective accident investigation and training is essential in order to accomplish this, while providing a record of the incident to help explain the situation to people unconnected to the event. Over a number of years there have been considerable innovations in survey instrumentation and software used to record data. However, the final deliverable data has remained the same, with surveyors tasked to represent a 3D environment using 2D deliverables.

This section explores the benefits which can be obtained using 3D data capture and visual representation, with regard to accident investigation, with discussion on accuracy, time, witness verification and reduction in human error.

Additionally, the use of 3D data to reconstruct a complex environment for use in training and proactive risk assessment will be explored.

5.1.1. Introduction

5.1.1.1. The Problem

Within the mining industry, fatalities have been on a steady decline in many countries for a number of years. Data gathered by the US Department of Labor, Mine Safety and Health Administration, show that there were 70 fatalities in 2002, compared to 36 in 2012 (US Department of Labor 2013). Additionally, statistics gathered from the UK Health and Safety Executive show, that there were 54 fatalities in 1981, compared to 10 in 2011, in the extractive and utility industries (HSE 2012c). The same story is demonstrated in South Africa, where there were 774 fatal accidents in 1984, compared to 168 in 2008 (Chamber of Mines South Affica 2009).

Although the mining industry is committed to reducing accident rates through improving safer working practices and robust health and safety management systems, accidents are still occurring. With safety being the number one priority in mining, civil, commercial and industrial settings and with possible accidents being varied and complex (MacNeill 2008), it is imperative that any breach of safety resulting in an accident or loss of life is investigated thoroughly. . Undertaking an accident investigation provides clarity and fosters a deeper understanding of the risks that are associated with the workplace (HSE 2004), identifying both immediate and underlying causes.

5.1.1.2. Why we Investigate Accidents

Every incident indicates that there is a certain degree of failure in a safety system. One of the ways in which these failures can be identified is through accident investigation. Appropriate incident investigation ensures that (Du Pont 1990):

- The causes of the incident are identified and that with this information an understanding of the development of the event can be determined.
- The results of the investigation can be applied to the safety model in order to prevent re-occurrence.
- The findings are well communicated throughout the organisation or wider industry where there is potential for similar incidents.
- Training and standards within the organisation are improved in order to prevent recurrence.
- Employee misunderstandings or concerns are identified and can be addressed.

Gathering information is the first stage in the investigation process, after emergency response has been undertaken and the site has been made safe and secure. The information can be in the form of safety documentation relating to the incident, statements from witnesses or physical information recorded within the incident scene. There may be a lack of information and many uncertainties, but the investigator must keep an open mind in order to establish what has happened. Not all information gathered may have a direct relation to the cause of an accident. However, this information may provide greater insight into the hazards and risks associated with the workplace (HSE, 2004).

5.1.2. Surveying of Accidents

In most accident investigations, it is necessary for the scene to be recorded. Depending on the complexity or severity of an accident, this could range from a sketch of the environment and the locations of objects, to a detailed plan prepared from measurements taken by a qualified surveyor. In road traffic collisions and in the mining industry, the latter is common practice. The surveyor should provide sufficient geospatial information in order to allow investigators to determine the factors that may have had an influence on the event (Mine surveyor.net 2010). It is an important note, that a surveyor should be used in the recording of accidents to ensure the integrity of the measured data and that the equipment used is to a sufficient standard. The use of conventional surveying techniques in relation to the accident investigation process is shown in Figure 88.

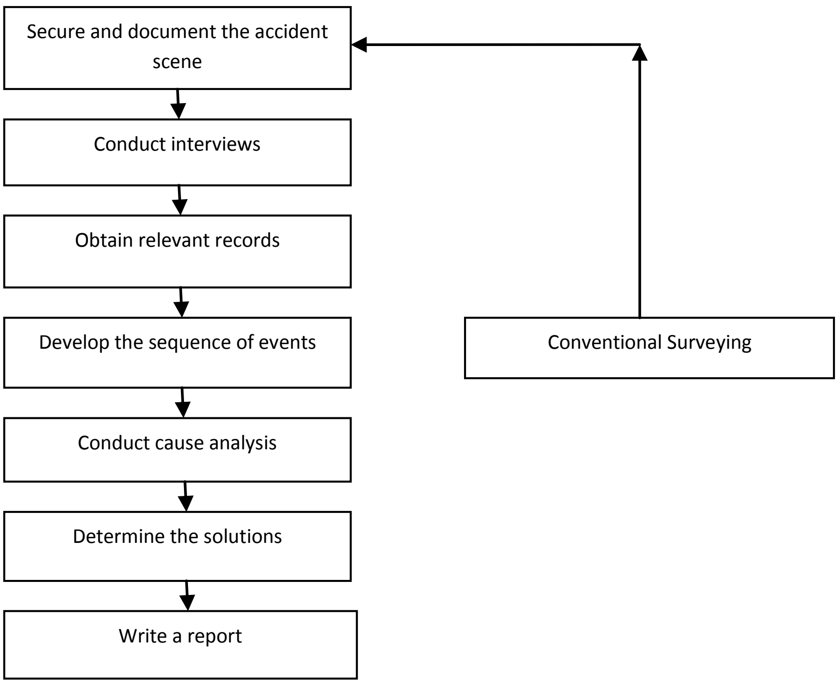


Figure 88: The integration of surveying within the accident investigation process

In addition, the survey can aid the development of risk assessments and safe operating procedures that relate to the geospatial factors which have contributed to previous accidents (Minesurveyor.net 2010).

When conducting an accident investigation survey, it is crucial to consider what information may be regarded as important by the accident investigator and also what may be useful for future reference (HSE 2004). As a result of the surveyor's opinion of what might be contributory factors in the incident, errors may arise with details of the accident site being wrongly recorded or otherwise missed out.

Errors can occur owing to a number of factors, the major factor being time. As soon as the accident occurs the scene begins to deteriorate and there can be pressure to finish the investigation process (Helmricks 2010), which may result in a rushed survey and influence further error. Other errors can occur as a result of discrete data collection using conventional surveying, e.g. if a surveyor was to record a vehicle, a measurement shot would be taken at the end of each axle and at each corner of the vehicle (Helmricks 2010) and from this the car would be drawn. This method could create error e.g. if the car had a dent, this would not be represented and it may be significant. Thus, information is missed.

Upon arrival at an accident scene, the surveyor should undertake four key activities. Firstly, the surveyor needs to be briefed by the accident investigator about what has happened and the nature of the incident. Then a rapid reconnaissance of the site should be undertaken, a rough sketch made and finally, a control survey should be established from which a detail survey can be undertaken (Helmricks 2010).

The following information should be recorded when undertaking a survey in a mining accident and also in road traffic collisions (Mine surveyor.net 2010):

- Accurate positioning of the scene and the topography of the surrounding area
- Signage which is related to the accident
- Features on the roads or surroundings
- Objects or features that may have contributed to the accident

- Orientations, appropriate scaling and information necessary for investigators

It can be seen from the literature review of survey methodology and deliverable data over the last two centuries that little has changed in order to explain the circumstances surrounding accidents. This has largely been based on the instrumentation that has been available to surveyors, the equipment has largely been linear based in terms of measurement with theodolites used for angular measurements. This has restricted the possibility of enhancing the survey deliverables, due to subjective, discrete point collection from equipment available. However, recent developments in survey equipment such as laser scanning technology allow diverse data capture in 3D and could have a profound effect on accident investigation.

5.1.2.1. Current Practices and Problems in Mine Accident Investigation

A survey is used to help explain the scene to people unconnected to the event, and a plan will often be the first item required by the mine inspector investigating an incident. In addition to the plan for a number of years in the mining industry, photographs have been used in order to complement the record of the accident scene.

In the mining industry, typically, the surveying methods used to produce accident plans are offset tape measurements and the use of a total station for single point mapping methodology. However, this surveying methodology has drawbacks that include (Foster et al. 2013):

- The process is time consuming.
- The process can cause the incident site to be disturbed.
- Human error may result in some key details missed.
- Complex structures or uneven surfaces are interpreted using single discrete points.
- The accident scene may still be unsafe putting the surveyor in danger.

In addition to the methodology stated above in opencast operations the use of GPS mapping can be incorporated. This survey methodology greatly increases the speed of data collection over tape measurements. However, the data collection is still discrete and provides limited detail.

5.1.3. 3D Surveying an Accident Scene with Laser Scanners

3D surveying of an accident scene begins in the traditional way with the surveyor producing a quick sketch of the accident area outlining the relative positions of the objects in the scene recorded. It is important to do this early as the scene may change or deteriorate.

Following this, the laser scanner set up positions should be decided in order to obtain detail of the whole area to be referenced. Multiple set up positions are required to survey the whole of a scene which are then joined together through the registration process (discussed previously).

There have been a number of papers published on the accuracies of data acquisition, target setup and registration notably (Becerik-Gerber et al. 2011), with laser scanning accuracy comparable to the accuracies achieved by total stations.

5.1.4. Case Study: Staged Electrocution

In order to demonstrate the potential of 3D surveying in relation to accident investigation, a staged fatal injury was created by the authors in a working mine in 2012.

The staged accident was an electrocution to a maintenance worker who had been tasked to replace the metal cage doors on the entrance to a switch gear chamber. Through initial inspection, it was apparent that there were a number of elements that could have had an influence on the accident.

Illustrations of various deliverable data from a staged accident scenario are shown in Figures 89-93.

The data provides an accurate record of the scene in terms of angular and distance measurement. In terms of accident investigation, this provides an accurate 3D environment in which measurements between elements can be taken and the scene can be virtually revisited any number of times.

Whilst undertaking the survey, digital photographs were taken at the same position from which the laser is emitted by the scanner. This allows the point cloud to be accurately overlaid with the photographs (as shown in Figure 89) which provides geometric realism in which measurements can be taken. In addition, using photographs can aid in the explanation of the scene to persons unrelated to the event.

Figure 89: Laser scan data with photographic overlay

Photographs were taken from key locations in the accident area in order to provide additional information, an example of which is shown in Figure 90. Photographs provide an extra level of integrity to the survey, while conforming to conventional survey practices.

Figure 90: Photograph from set location

Using the point cloud and photographs, a highly accurate 3D model can be produced, an example of which is shown in Figure 91. The model not only provides additional clarity to the scene, but also the combination of all the above can be made into a video format, which can help to navigate a jury around the scene stopping at key areas of interest. However, in practice the face of an individual would not be shown and would be considered as inadmissable within a court.

Figure 91: 3D model of staged accident

In addition, a 3D model can be used to reconstruct the accident and may help to illustrate the sequence of events prior to the incident, by producing an animation of the events as they unfolded. Also, it can be used to put together a training aid to assist with accident prevention, by producing an accurate virtual environment that could be used in a simulator training suite. The process involved creating a solid 3D model of the scene can be time consuming , so with this in mind, 3D models may only be appropriate in cases that require further analysis. Data collection is the first stage, followed by extensive post processing work using a variety of different software applications in order the preserve the data's integrity and produce a final model.

Once a 3D model has been created, sections can be removed such as the roof of the accident area to demonstrate the location of elements within the scene. This is demonstrated in Figure 92.

Figure 92: 3D model with roof removed

Although the data is captured in 3D, it can be used to produce 2D deliverables in the form of plans and sections. Therefore, conventional deliverables are retained if the need for 2D plans arises as they can be extracted from the dataset.

The 2D deliverable produced from point cloud data is a precise representation of the scene and not an interpretation. An example of a 2D plan is shown in Figure 93.

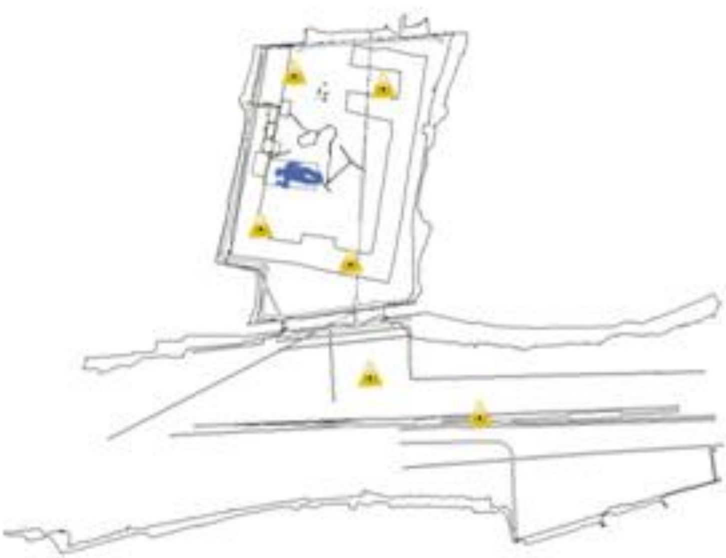


Figure 93: 2D plan created from point cloud data

5.1.5. Benefits of Laser Scanning in Accident Investigation

Based on the staged case study, there are a number of benefits that laser scanning provides over conventional survey methods within an accident scene:

- 3D data collection\ data clarity
- indiscriminate data collection\ reduction in human error
- surveying of complex structures or unnatural environments\ large density of data collected
- speed of data collection
- witness statement verification/ first person view points
- safety
- conventional deliverables retained
- enables incident reconstruction

3D Data Collection\ Data Clarity

This can be most beneficial in the explanation of an environment to people or persons that were unconnected to the event. 3D data allows the observer to see a realistic and spatial view of the full scene, rather than a singular planner view in plan or section.

In addition, the data can be used to create a highly accurate 3D model that can be used in reconstruction of an accident scene to assist in reducing the probability of re-occurrence. This is done by using the laser scan data as a reference to model around to produce a virtual reconstruction.

This has considerable benefits when applied to a mining accident where it is hard for non mining people to comprehend the environment in which people operate within the extractive industry.

Indiscriminate Data Collection\ Reduction in Human Error

It is hard to distinguish what is relevant within an accident scene. Data collection using conventional survey methods is subjective and is influenced by the surveyor's judgement as to what points need to be recorded. By comparison, a laser scanner will record virtually, a full dome 360^{o} point of view from the scanner's location, which is free from bias given that the equipment is indiscriminate in the points it records. Indiscriminate data collection is also useful, since some data may be picked up which seems irrelevant, but which may become crucial later in the investigation.

Surveying of Complex Structures or Unnatural Environments\ Large Density of Data Captured

Using a conventional surveying instrument, a surveyor records self selected, discrete points. In order to record a complex surface a surveyor would have to record every material change in an object's surface, which could take a very considerable amount of time e.g., a surveyor using a total station may be able to capture 500 points in 4 hours (Van der Merwe & Andersen 2012).

However, a laser scanner can record a vast amount of data, offering up to a million points a second with minimal point spacing, therefore as long as blinding is taken into consideration, a highly accurate representation of a complex structure can be produced. In this case study, 7 set up locations were recorded on a high resolution setting, with the total number of points being in access of 31 million. In addition, the equipment selected undertook each laser scan in 3.5 minutes. After completion of the laser scan, a camera rig was placed on the tripod and photographs were taken at each location. This provided a true RGB and geometrically accurate scene.

In the mining industry the geometry of the excavation is complex as much of the environment is within its "raw" form and not finished. Therefore, in certain accidents e.g. where a collapse has occurred, the investigation team may feel it appropriate to understand the source and location of the material in which has fallen.

Speed of Data Collection

An accident survey must be efficient and effective. Modern laser scanners can perform a high resolution full dome scan in approximately 4 minutes depending on the make and model, resulting in time savings of up to 50% for data collection in road traffic collisions (Essex Police 2013). In the mining industry there may be pressures can be placed upon the investigation team to allow production to continue.

Witness Statement Verification/ First Person Viewpoints

A witness may retain information that is relevant to an investigation. However, a witness "who has a vested interest in the results of the investigation may offer a biased testimony" (US Department of Labor 1990). In this case study, , this was not necessary to demonstrate this, as the "worker" was alone at the time of the incident and not operating any equipment.

Although in other cases, where appropriate, by positioning a camera at the location of a witness, within an accurate 3D surveyed environment, it is possible to show what would have been seen. This can then be used to assess the reliability of the witness account. In addition the same methodology can be used in order to establish what the driver of a vehicle could see e.g., to determine "blind spot" locations, which can be essential in mining vehicle collisions where equipment restricts visibility.

Safety

Accident scenes can sometimes be unsafe areas in which to operate e.g. if a fall of ground or land slip has occurred. Some modern laser scanners offer a large range e.g. the VZ-6000 laser scanner developed by Riegl offers a range of 6km (Riegl 2012). Large range capability is useful for unsafe environments as most modern laser scanners can be operated remotely via an internet connection. Once set up in position, the location of the laser scanner can be used to limit the surveyor’s exposure to a hazard. Devices are also available that can carry a laser scanner to its scanning location.

Conventional Deliverables Retained

Although the data is captured in 3D, it can easily be reprocessed to produce 2D representations of the accident scene, as there are certain circumstances in which the data has to be represented in a 2D form. This may be a personal preference of the person observing the data or if a plan is required to be shown within a formal incident report.

Enables Incident Reconstruction

When the data is collected using a laser scanner the data can be used as a base to make accurate 3D models. Using this model, the accident can be reconstructed and different scenarios can be staged and tested within a virtual space, establishing full incident reconstruction. This can be particularly useful to establish the reach of machinery in relation to the surveyed environment for example.

The use of laser scanning in accident investigation will change the way in which surveying will be incorporated within the investigation process. This is demonstrated in Figure 94.

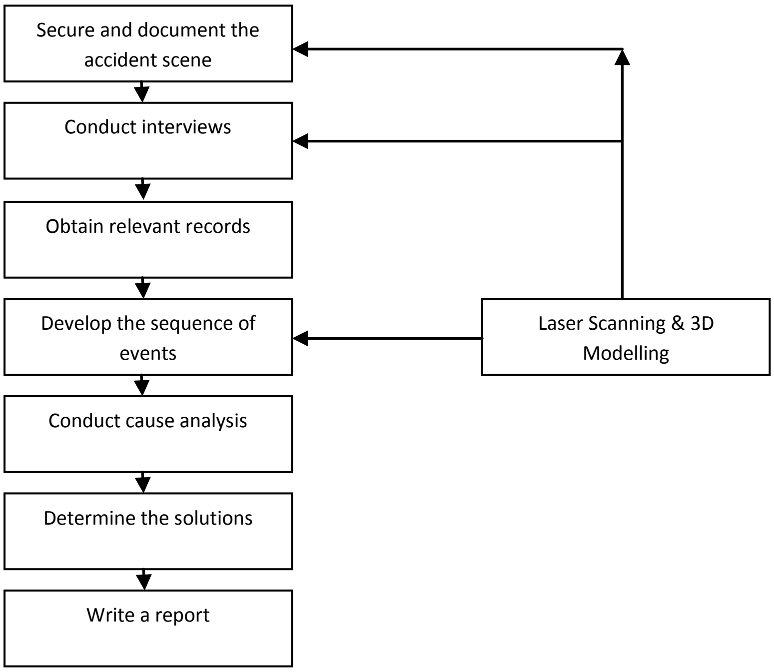


Figure 94: The integration laser scanning in the accident investigation process

Rather than just recording the scene, the data collected using a laser scanner is rich and can therefore be used for a number of different applications within the accident investigation process. Additionally, once captured the data is stored and can provide the possibility of information being extracted for a different use in the future e.g., an accident on the highway may have an influence on road design.

5.1.6. Conclusions

Mining environments are unnatural, manmade developments that pose considerable risks to an operation and hazards are in abundance. Although, many of the hazards found within the mining industry are similar to those in other industries, there are certain specific hazards which the mining industry needs to address.

These make the industry prone to incidents and when they occur they can be catastrophic in respect to their consequence. Therefore, there is considerable scope to improve investigation methodologies in an attempt to prevent future similar events and this could be achieved using a laser scanner to better understand the event.

The un-natural environment of a mining operation poses complications with regard to the survey process to accurately record the scene of an incident. The complex geometry of a mine site may be difficult to accurately represent using conventional single point measuring methodologies. Conventional surveying of complex scenes is also time consuming and human error can sometimes be a problem.

However, if a laser scanner is used to record the scene, it will capture all the information of a complex structure (if blinding is considered), quickly with limited human interaction. This can be of considerable benefit if a fall of ground has occurred with laser scanning being implemented in a number of ways in the surveying process, providing benefits both common and mining specific. The common benefits have largely been highlighted within this research in previous case studies, therefore benefits relating to the mining industry will be discussed below.

Firstly, the laser scan model can be used to establish where the material has fallen from, which might not be immediately apparent. This can be achieved by modelling the destination object, translating the material within the virtual model and examining where the location of source may have been, by matching the complex geometry together. In addition, if periodic laser scans (prior to the incident) have been taken of the same area, Cloud Compare software can be used to evaluate the two point clouds in order to highlight areas of change.

Secondly, in a fall of ground, it will be necessary to establish the location of bolting systems or geotechnical controls, in order to see if the work has been undertaken to the proposed design and is fit for purpose. A laser scan survey can have a number of benefits over a conventional survey in this respect. Using conventional means, human error may be a contributing factor and the surveyor may have not seen a bolt(s) and therefore it will be un-recorded.

However, as a laser scanner is largely indiscriminate in terms of data capture, human error can be reduced. In addition, the recorded bolting system can be plotted in 3D and the spacing between the bolts can be examined to a high degree of accuracy, by placing a circle of set diameter on the location of each bolt to ensure the circles intersect.

Thirdly, where a fall of ground has occurred, there will obviously be significant safety implications when the surveyor is tasked to record the scene. With this in mind, the instrument can be operated remotely via internet link to ensure the safety of personnel. In addition, the time taken to record the scene can be shorter, thus reducing the exposure time in the hazardous area.

Finally, the ability to observe the model from aspects that are otherwise unachievable in the real world, for example from within the rock mass, given that different viewpoints, can help to better understand the event and the surrounding factors in a way that is easily understood. In addition, this can be utilised when explaining the incident to people from a non technical or mining background who may may find the unique environments hard to envisage.

The findings of an investigation must be implemented in order to ensure the prevention of similar events. This process can be enhanced when using laser scanning methodologies over conventional means of data capture. Considering a vehicle collision in an underground mine as an example, if a laser scan survey had been undertaken a number of benefits may be obtained as detailed below.

Firstly, if the laser scanner is positioned in the cab of the vehicle at the same level as the driver's eye, this can simulate the drivers Field of View (FoV). The information obtained can be used in a number of ways, such as, if the laser scan identifies that there are obstructions to the driver's FoV. For example, the vehicle in question may have a guard obscuring the FoV, which could have a direct effect on equipment design and selection employed by the mining operation. In addition, the guard could be easily interchangeable and therefore a solution could be to retro manufacture a different guard to improve the driver's visibility.

Secondly, it could be found though the evaluation of the point cloud data and subsequent 3D model that a junction within the mine presents a significant problem to the driver's FoV. Therefore, a solution can be designed in 3D by removing some of the hanging wall for instance, to create additional visibility. This can be tested virtually using the modelled equipment and excavation geometry in order to scrutinise the result before it is implemented in the real world. Additionally, this also can have an effect on the future developments in that mine and be applied to other operations, thus having a wider impact.

Finally, the dataset can be used proactively as a training aid to highlight potential problems that drivers may encounter within the operation, providing clarity, while showing the 3D model in a environment in which the operator is familiar.

To conclude, in order to prevent accidents we need to understand them and laser scanning has the ability to bring the scene alive, allowing the investigation to identify immediate and underlying failures, which may have been unidentifiable using conventional means.

6.0. Chapter 6: Conclusions

This chapter will discuss overall conclusions for the whole PhD study. In order to make this comprehensive, the author has split this chapter into the sections discussed in this thesis.

6.1. Fire Applications

The role of the UK Fire and Rescue Service (FRS) is to preserve life and reduce the damaging effects of the events (fire and extrication of trapped people) for which they are responsible. In many cases, FRS personnel have to operate in potentially unsafe environments and it is paramount for commanding officers of scenes to ensure the safety of their team. This is achieved through effective decision making and risk assessment. Fire by its very nature is destructive and can have profound effects on materials that it comes into contact with. Although many buildings are designed to withstand fire, there is a finite amount that materials can endure before they become unstable and succumb.

When tacking a fire, obtaining information on the fire's state is essential, including the properties of burning materials and also the time elapsed since ignition occurred. In addition, if the response time to a scene has been slow, the commanding officer must consider this and assess its implications, before sending personnel into a building to bring the fire under control. This then creates a high stakes environment, where the officers have to make quick and effective decisions under the extreme pressure of the situation. Currently, the service is heavily dependent on training and the experience of the operational team. However, if a laser scanner was deployed to aid in monitoring the structural stability of the environment, some of the pressure could be alleviated. This in turn could then lead to improvements in the safety of FRS personnel and the efficiency of the fire fighting strategy deployed.

Following a fire, it is important to understand how it was caused and progressed throughout a structure. This is essential in order to understand how the building performed when exposed to the fire in order to address if there are any improvements that could be made in order to prevent recurrence. In the UK, the Building Research Establishment (BRE) develops standards that are encompassed in building regulations and determine how future developments should be constructed. This research is paramount, in order to ensure the implications of a fire are mitigated, safe evacuations of a building are made, while the safety of FRS personnel operating on scene is maintained. In certain cases, it may be deemed that a comprehensive fire investigation should be undertaken to establish how the fire occurred and if it was a result of negligence or arson. Given this, it is important to record the scene for future reference and to aid in a deeper understanding of the incident.

The UK FRS are also responsible for extricating trapped person(s) from vehicles following a RTC. This operation has to be undertaken with great care in order to prevent further injury to the causality. Modern vehicles are safer due to, in many cases, advanced technological safety systems designed to alleviate the consequences of a collision. However, many of these systems can become a hindrance to FRS personnel when performing extrication. In addition, as there are many different makes and models of vehicles available, the location of the safety devices can vary greatly.

Given this, there is considerable scope for the FRS service to establish a system that can assist their crews, such as the one discussed (AR) in this PhD. This system would allow the incident commander to direct the personnel using enhanced information, thus improving both the safety of all parties involved and speed of the process, which could have wide ranging benefits, from injury statistics to road closure times.

Ultimately, the use of the technology discussed within this thesis, is governed by budget constraints that are imposed on the FRS by central government. Therefore, the justification for large investment may not be available, especially since in the UK, there are currently many cuts being made to frontline public services giving little remaining budget for experimental projects. However, as the technology matures and equipment costs inevitably subside, the FRS may look at incorporating the technology using the methods explored in this thesis. With reference to the laser scanning of post fire environments, currently there are several private companies that offer this service, generally acting on behalf of insurance companies to help establish liability and the volume of damaged goods. Also, if the fire involves a loss of life or is suspected to be arson, criminal proceedings may be brought and the use of a laser scanner could be beneficial, with its associated costs being allocated to the police and crown prosecution service.

6.2. Industrial Accidents

In order to prevent future incidents, an investigation team needs to scrutinise the accident in order to fully understand the events that may have contributed to the outcome. In many cases, accidents can be complex multi causal events, which makes them hard to envisage.

When an accident occurs, it is important to document it as soon as possible as the scene is in an immediate state of decay. Therefore, an accident investigator must take photos, video and begin to gather geospatial information to provide future reference of the scene and of the key details that he/she may feel contributed to the event itself. This process can be fraught in complex scenes, where key items could easily be missed if the investigator didn't deem them to be relevant initially, but later after further analysis, found them to be contributing factors. As a laser scanner is largely indiscriminate in terms of data collection, reductions in this sort of human error can be obtained since the scene can be recorded in an unprecedented level of detail. The data can also then be used for a magnitude of different applications within the accident investigation process. However, it will not become a replacement for the process itself, it will only complement it, as the essential purpose of an accident investigation is to find the root cause of the incident and then establish solutions to prevent reoccurrence, which cannot be achieved using laser scan data alone.

Thus, a laser scan survey can be used to visually display a sequence of events that lead to the incident and of their plausibility in a geometrically accurate environment. Following this, the investigator will conduct a cause analysis where a laser scanner has little relevance, other than to check the accuracy of witness statements that may carry weight in the case. However, when determining a solution, various engineering based controls could be modelled and tested in order to evaluate their effectiveness to prevent the incident occurring again. In addition, the accident can then be presented as a visual aid to address leading indicators by educating people through training on the implications of not adopting the controls highlighted in the investigation, while presenting them in a real world application that is easy to understand.

From the author's experience of working with the UK HSE, accident investigators have considerable knowledge in respect of safety, investigation techniques and the law. However, they are not surveyors and require assistance to operate surveying equipment and to produce the deliverable data needed for the investigation. Much of the surveying work has been undertaken by external contractors until fairly recently, when the Health and Safety Laboratory (HSL) began to develop the skill in house. However, further research is required in order to evaluate the use of 3D data and begin to explore the numerous benefits that could be achieved. This may become a lengthy process as the judicial system is always slower to adapt to new technology as confidence in the results is required to ensure the reliability of the evidence presented.

6.3. Mining Applications

The mining industry is essential to provide the raw materials to manufacture many of the products used in the modern world. However, the industry is considered by some as unsafe and destructive to the environment.

Mining has many of the hazards found in an industrial environment, but also others which are specific to the industry, such as heavy machinery, explosives, confined spaces and many geotechnical issues. Although many of these hazards can be found individually in other industries, mining companies have to try and control all of them in their operations. In addition, due to the scale of many mining operations hazards are in abundance, which makes the industry predominately dangerous and a large number of incidents occur yearly. Hence safety and accident investigation is paramount.

The use of 3D data can be a major tool for the industry within the accident investigation process and although many of the benefits can be considered generic to that of an industrial incident, there are a number of specific advantages. For example, when an accident has occurred due to a fall of ground, the implications can be extensive, with the environment sometimes unsafe for investigators to operate in. Most modern laser scanners can be operated remotely via an internet link, which is advantageous when operating in high risk environments. Various companies have begun to capitalise on this and automated vehicles have been developed to carry laser scanners into areas deemed unsafe for personnel. These have been adopted by the mining industries following some high profile incidents, some to limited success. In addition, the author has been presented with data which has been collected remotely by a robot following a fall of ground. Unfortunately, this work has been legally restricted and couldn't be used in this thesis. However, with reference to this work, the data was highly beneficial to the investigation team as without adopting this methodology, the only information available would have been from a distance and from one side only, which would have been of limited use. The robot was obtained and fitted with a number of mounted video cameras and also a 360 degree high resolution digital camera system. In addition, the robot was fitted with a laser scanner operated remotely to gather geospatial data and using all these data sources, a 3D reconstruction of the incident was created. The information collected far exceeded the level of detail that could have been obtained using conventional means. It provided the investigation team with various pieces of information including the size\volume of the material that failed and the location of bolting systems used to strengthen the ground. This, of course was all gathered while not endangering human life.

Although there are a number of benefits that can be obtained using 3D data, the mining industry is slow to implement the technology. There are a number of possible reasons for this, for example, to embrace the technology, mining companies will have to make considerable investment in the equipment and software required to produce the deliverables needed. Secondly, the industry would need considerable training to incorporate the methodologies into the "day to day" operation of the mine. Finally, there is a global skills shortage of mining industry professionals and an aging workforce. The author believes that in order for the industry to implement the technology, it needs to be focused on educating mining graduates in the use of this technology and of the benefits that can be obtained. This will then provide the industry with a source of trained labour and reduce the substantial outlay that is currently required. However, in order for this to happen, the mining companies must encourage the development of the technology for their operations through research budgets or external consultants.

6.4 Synergy Across Case Studies

The following section has been drawn from the analysis and conclusions of the multiple case studies explored in order to highlight common themes emerging throughout the different industries.

When an incident occurs particularly one of a high consequence, there is pressure placed upon the investigation team to establish the cause. In addition, along with the problem of scene decay, there can be a perceived pressure for the investigation to complete quickly and restore services. This creates a high pressure situation in which the surveyor has one opportunity to record an incident obtaining all the information on which the investigation could later rely. Therefore, as with any time pressured process there are implications in relation to human error and of particular relevance is the miss-recording of incident scenes. Having the technology available that can capture data quickly which far surpasses conventional means is key, with the additional benefit of reducing human error owing to the instrument being largely indiscriminate in terms of data collection.

In addition in many cases, scenes can present considerable danger and the time taken to record a scene can pose significant problems in relation to safety. In certain cases, this can result in the investigation being delayed or limited, in relation to the data that can be recorded. Laser scanning can provide benefits in this area, as modern instruments can be operated remotely and the speed of data collection is unmatched with regard to conventional surveying means.

When incidents occur, this can result in the creation of complex geometry, in respect of two objects colliding or just the recording of the human forms of those involved. Therefore, the ability to record objects using conventional means is problematic, with the created models not accurately reflecting the reference object. Laser scanning therefore has significant benefits again in this area and has been detailed within this PhD study. With models created by laser scanners providing a more accurate representation, subsequent analyses become more reliable (for example in respect of virtual testing of hypotheses, witness verification and the reconstruction of events).

Obviously, the cost of the equipment and the complexity of creating models are considerable factors, resulting in laser scanning not being suited to every incident and therefore being used largely for high consequence events. In addition, it is easy for the user to get "too involved" with the incident resulting in personal interpretation becoming a negative factor, therefore this needs to be controlled as discussed in this PhD study.

6.5. Conclusions in Respect to the Aims of the Study

In order to evaluate the use of laser scanning and 3D modelling in the accident investigation process, a number of aims were defined at the start of the project in order to constrain the study and provide clarity. The author believes these have been met and will discuss in this section, how this has been achieved:

<u>Identify suitable industrial applications of the technology in relation to the management of accident scenes</u>

Firstly, a review of the current literature and applications in which laser scanning has been applied, was undertaken. This highlighted that there is limited literature in respect of laser scanning as a method to record accident scenes, although, there have been significant research contributions in using computer generated models in the accident investigation process and subsequent legal proceedings.

In addition, the author noted that the technology had been applied to RTCs in a commercial sense and is beginning to gain pace and acceptance across the industry. Following this, the author believed there was considerable scope to develop processes in laser scanning and 3D applications, in respect of other industries such as mining, the management of fire scenes, industrial accidents and also RTCs.

<u>To review and develop skills in a wide range of software applications used to process point cloud data, produce mesh models and subsequent visualisation of findings critical for this projects development</u>

It quickly became apparent that due to the nature of this study, that developing skills and exploring links between software applications would be essential. Therefore, from an early stage, the author began researching and studying the software applications required to produce the final deliverable data required by investigation teams.

This was achieved initially by considering the current software applications used by the industrial partner 3DMSI Ltd and exploring how they could be incorporated to create final deliverable data required, in the context of accident investigation. It was understood that software relating to the management of point cloud data (Leica Cyclone) and conventional CAD drafting programs

(AutoCAD, AutoCAD Civil 3D and Microstation) remained similar across most industries, however additional packages (3DS Max and meshing software) would have to be used, in order to create mesh models and allow for video production and the animation of subsequent models. In addition, photo editing, normal mapping and video creation software also had to be examined in order to create realistic 3D models and subsequent animations, largely performed in the adobe suite.

In the early stages of the project, a direct connection between Leica Cyclone and 3DS Max was not available to the author, where models had to be created using complex meshing software and then incorporated into 3DS Max. However, as the project progressed, the industry realised that there would be a significant benefit in providing users with this connection, achieved through a plugin for 3DS Max, using a subsidiary software application. This has provided substantial benefits, with the user being able to produce models directly from the point cloud data, within one software application.

While the processing methods devised by the author and used within this PhD, have become the intellectual property of the author and the sponsor company, some of the various software applications used within this PhD are listed below, in which the author is now proficient:

- Leica Cyclone
- AutoCAD
- AutoCAD Civil 3D
- Autodesk Recap
- Autodesk 123D Catch
- Visual SFM
- MeshLab
- 3D Reshaper
- Topogun
- Adobe Photoshop
- Adobe Premiere Pro
- Adobe After Effects
- Reconstruct Me

Investigate the integration of laser scanning and the subsequent presentation of geospatial data to the widest range of associated stakeholders for:

- *The development of commercial applications*
- *The display of evidence in legal proceedings*
- *The improvement of survey methodology employed in accident investigations.*

This has been achieved by making contact with a number of companies and governmental bodies responsible for the management of accident scenes. This was undertaken after a number of skills had been obtained in various software packages. Following this, the author used industry contacts to establish meetings with the FRS, HSE, HSL, Mining HSE, the Police, mining companies and independent investigation companies to demonstrate where possible laser scanning techniques and 3D methodologies could be used in "live" incidents. This led to some of the production of some of the case studies detailed in the thesis.

However, for obvious reasons relating to the sensitive nature of certain incidents, a large proportion of this work was unable to be published and in such cases, the author used staged accidents with the discussion focusing on some of the findings of the restricted cases. Some of the work undertaken may, in time, be available for publication and the author plans to publish this information if this occurs.

Evaluate the use of laser scanning technology to capture geospatial data of a scene and to investigate the benefits and limitations associated with its deployment, in terms of accident reconstruction and data gathering

And

Develop accident reconstructions of a number of case studies throughout the project

This thesis draws on information from a wide range of industries and applications in which laser scanning and 3D modelling has been applied, by the author. This has provided the author with access to the significant amounts of data which has been used. The author has been able to provide specific conclusions in each section separately, providing clear divisions between the case studies. Finally, the industry has then been evaluated as a whole, in the final chapter, and trends thereby established between the industries. The structure of the thesis has also provided the opportunity for the author to publish data as the PhD progressed, which was considered important in a quickly developing technological industry.

6.6. Suggestions for Further Work

Advancement in laser scanning technology has been phenomenal and, although still in its infancy, new and innovative applications are continually being developed. The geospatial industry has warmly embraced the technology, providing deliverable data that previously could only be imagined, making the real world virtual. As a result the use of the laser scan data as a form of survey is ever evolving, with new and innovative applications being explored in order to obtain a competitive edge over industry rivals.

This means there are exciting times ahead in the industry and improvements in the equipment will ultimately result in laser scanners being the equipment of choice for many survey applications.

This rapid development of instrumentation and computing software results in considerable scope for research within this area. Where laser scanning can be considered as a "solution looking for a problem" and research can focus on exploring the vast number of applications to which it can be applied.

In respect to accident investigation, confidence in the data and its application is beginning to grow, providing investigation teams with a form of data that they have not been exposed to before. This, in turn, leads to considerable advancement in the technology. Paradoxically, with equipment being easier to use, this in itself may be a source of concern, as care should be taken to ensure the integrity of the datasets produced and that the data is fit for purpose. Continuing research is essential, used to understand and experiment with developing technologies in order to classify and limit possible sources of error that may be encountered.

In addition, laser scanning and 3D modelling datasets are vast with one case containing considerable amounts of files, which all needs to stored and correctly referenced for retrieval. To this end, new methods of storage and database systems need to be established to ensure secure storage of potentially sensitive data relating to an accident. Research within consumer electronics needs to be tailored to data storage and accessibility to a world where information is in abundance across all industries.

ReferencesAckland, P., 2012. *A Guide for Commericial Kitchen Fires-Prevention and Investigation: A Collaboration of Experts* Volume 1. P. Ackland, ed., Summerland BC: Phillip Ackland Holdings Ltd.

Andrew, M.S., 2013. Chemical Roulette. *OSA Magazine*, pp.45–47.

Baker, A., 2002. *The Iron, Steel and Coal Industry of North Staffordshire* first., Inwell Press.

BBC, 2012a. Fire Destroys Best Western Hotel in Falmouth. *News Cornwall*. Available at: http://www.bbc.co.uk/news/uk-england-cornwall-17897467 [Accessed November 25, 2013].

BBC, 2012b. Shirley Towers Inquest: Firefighters died in tower block. Available at: http://www.bbc.co.uk/news/uk-england-hampshire-18457212.

BBC, 2013. Timeline: Warwickshire firefighter deaths. Available at: http://www.bbc.co.uk/news/uk-england-coventry-warwickshire-16651345.

Becerik-Gerber, B. et al., 2011. Assessment of target types and layouts in 3D laser scanning for registration accuracy. *Automation in Construction*, 20(5), pp.649–658. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0926580510002165 [Accessed August 19, 2013].

Birch, R., 2013. Prosecution after Exeter Quay ferry death. *Express and Echo*, p.1. Available at: http://www.exeterexpressandecho.co.uk/Prosecution-Exeter-Quay-ferry-death/story-17872578-detail/story.html.

Boehler, W. & Marbs, A., 2003. *Investigating Laser Scanner Accuracy*. Mainz, University of Applied Sciences. Available at: http://archive.cyark.orarchive.cyark.org/temp/i3mainzresults300305.pdf.

Borys, D., 2000. See the Wood from the Trees: A Systems Approach to OH&S Management. In *OHSMS Proceedings of the First National Conference*. pp. 152–172.

BRC Global Standards, 2012. *Understanding Root Cause Analysis*, Available at: http://www.brcglobalstandards.com/Portals/0/Books/Rootcause/rootcause.html.

BRE, 2013. Fire Safety Engineering. *Fire Safety Engineering*. Available at: http://www.bre.co.uk/page.jsp?id=1855 [Accessed January 7, 2014].

BRE, 2009. Lakanal House Fire Inquest. Available at: http://www.cila.co.uk/files/KN5222 - Lakanal Case Study.pdf [Accessed November 8, 2013].

Brooke, D. et al., 2010. *International Review of Surveillance and Control of Workplace Exposures: NOHSAC Technical Report 5*, Wellington, NZ.

Available at: http://www.dol.govt.nz/publications/nohsac/pdfs/technical-report-05.pdf.

Broughton, J., 2003. The benefits of improved car secondary safety. *Accident; analysis and prevention*, 35(4), pp.527–35. Available at: http://www.ncbi.nlm.nih.gov/pubmed/12729816.

BSi, 2010. *British Standard BS5395-1:2010 : Stairs. Code of Practice for Design of Stairs with Straight Flights and Winders*, BSi.

Buys, J.R. & Clark, J.L., 1995. *Events and Causal Factors Analysis*, Idaho Falls, Idaho. Available at: https://www.frcc.com/Training/Shared Documents/Cause Analysis Training Materials/Reference Material/E and CF Charting.pdf.

Calland, V., 2005. Extrication of the Seriously Injured Road Crash Victim. *Emergency Medicine Journal*, 22(April), pp.817–821. Available at: http://emj.bmj.com/content/22/11/817.full.

Canadian Centre for Occupational Health and Safety, 2006. Hazard Control. Available at: http://www.ccohs.ca/oshanswers/hsprograms/hazard_control.html [Accessed July 27, 2014].

Caulfield, B., 2009. Topic 3: Angle Measurement. *Lecture 6*, p.34. Available at: http://www.tcd.ie/civileng/Staff/Brian.Caulfield/3A1/3A1 Lecture 6.pdf [Accessed August 4, 2014].

Chamber of Mines South Affica, 2009. *Annual Report 2009*,

Channel Coastal Observatory, 2013. Ortho-Recified Photograph.

Collins, 2014. Accident: Defintion. Available at: http://www.collinsdictionary.com/dictionary/english/accident.

Cosarca, C., Jocea, A. & Savu, A., 2009. Analysis of error sources in Terrestrial Laser Scanning. *Journal of Geodesy and Cadastre*, 11, pp.115–124. Available at: http://www.uab.ro/reviste_recunoscute/revcad/revcad_2009/11.cosarca_jocea_savu.pdf.

CyArk, 2001. History. *CyArk History*. Available at: http://archive.cyark.org/history [Accessed August 8, 1983].

DeHaan, J., 2002. *Kirk’s Fire Investigation* Fifth., New Jersey: Pearson Education, Inc. Upper Saddle River, New Jersey.

Delemont, O. & Martin, J.-C., 2007. Application of Computational Fluid Dynamics modelling in the process of forensic fire investigation: Problem and solutions. *Forensic Science International*, 167(2-3), pp.127–135.

Department for Communities and Local Goverment, 2005. *The Economic Cost of Fire: estimates for 2003*,

Department for Communities and Local Goverment, 2011. *The economic cost of fire: estimates for 2008*, UK. Available at: http://webarchive.nationalarchives.gov.uk/20121108165934/http://www.communities.gov.uk/documents/corporate/pdf/1838338.pdf.

Department for Transport, 2012. *Reported Road Casualties in Great Britain 2012 Annual Report*, Available at: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/245383/rrcgb2012-00.pdf.

Department for Transport, 2013. Vehicle Licensing Statistics VEH0101. , pp.1–3. Available at: https://www.google.co.uk/url?sa=t&rct=j&q=&esrc=s&source=web&cd=2&ved=0CCkQFjAB&url=https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/9291/veh0101.xls&ei=oH0EVNu9Cary7Abtt4A4&usg=AFQjCNE_uw7zCWybzlsUdCNNvzFrmdV-EA&bvm=bv.74115972,d.ZGU&cad=rja.

Derbyshire Fire and Rescue Service, 2011. *RTC*, Learning and Development and Corporate Communications.

Dunbar, I., 2013. Ian Dunbar’s Weblog. *Ian Dunbar’s Weblog*. Available at: http://blog.holmatro.com/blogs/9-the-team-approach.html [Accessed June 17, 2013].

East Glenville Fire Department, 2009. Glossary of Firefighting Terms. Available at: http://www.eastglenvillefd.com/_mgxroot/page_10845.html [Accessed November 12, 2013].

Easydrive, 2013. Total Station Robotics. Available at: http://www.ieasydrive.com/total_stations.htm [Accessed October 17, 2013].

Essex Police, 2013. 3D laser scanner. Available at: http://www.essexpcc.com/news_features/features_archive/2013/january/3d_laser_scanner.aspx [Accessed February 7, 2013].

Evans, A.J. et al., 2001. A New Vision for Engineering Geodesy. In *IAG 2001 Scientific Assembly 2-8 September*. Budapest, p. 6.

Evergreen Valley College, 2012. SG-149 3D Laser Scanning for Land Surveying. *Module 1: Introduction*. Available at: http://faculty.evc.edu/z.yu/nsf2/Curriculum modules/Module 1.pdf [Accessed August 4, 2014].

Eyre, M. et al., 2015. The Benefits of Laser Scanning and 3D Modelling in Accident Investigation: In a Mining Context. *Mining Technology*, p.11.

Eyre, M., Foster, P. & Speake, G., 2014. Surveying the Scene. *SHP Magazine*, p.P4. Available at: http://www.shponline.co.uk/features/cpd-articles/features/full/surveying-the-scene.

Farina, P. et al., 2012. Recent Advances of High Precision Radr for Monitoring Slopes in Large Open Pit Mines. In *Australian Centre for Geomechanics: Newsletter*. Australian Centre for Geomechanics, pp. 22–25.

Faucheux, M., 2011. The History of Global Positioning System (GPS). *Bright Hub*, p.1. Available at: http://www.brighthub.com/electronics/gps/articles/108097.aspx [Accessed August 5, 2014].

Ferjencik, M. & Kuracina, R., 2008. MORT WorkSheet or how to make MORT analysis easy. *Journal of hazardous materials*, 151(1), pp.143–54. Available at: http://www.ncbi.nlm.nih.gov/pubmed/17606323 [Accessed July 29, 2014].

Ferry, T.S., 1998. *Modern Accident Investigation an Analysis* Second., John Wiley & Sons Inc. Available at: http://books.google.co.uk/books?id=NJVvvIGBsmQC&printsec=frontcover#v=onepage&q&f=false.

Fire and Rescue Services Act, 2004. Fire and Rescue Services Act. , p.55. Available at: http://www.esfrs.org/document/pdf/fa/membersArea/ukpga_20040021_en.pdf.

Fire Investigations UK, 2012a. Fire Development. Available at: http://www.fireinvestigationsuk.com/services/fire-developement/ [Accessed November 7, 2013].

Fire Investigations UK, 2012b. Origin and Casuse. Available at: http://www.fireinvestigationsuk.com/services/origin-and-cause/ [Accessed November 7, 2013].

Fire Safety Advice Centre, 2011. Fire Investigation. Available at: http://www.firesafe.org.uk/fire-investigation/ [Accessed November 6, 2013].

Foster, P. et al., 2013. Accident scene reconstruction in underground mining operations. *Position IT*, 96(April/ May), pp.30–34.

Foster, P.J., 2011. CSM122 Health, Safety and Environmental Management Course Notes. , p.10.

Fuld, H., 2012. Layar Just Brought Augmented Reality to the Mainstream but Can it Revive Print ? *Inneractive*. Available at: http://blog.inner-active.com/2012/06/layar-just-brought-augmented-reality-to-the-mainstream-can-print-be-saved/ [Accessed June 20, 2013].

Geigle Safety Group, 2013. *Effective Accident Investigation: OSHAcademy Course 702 Study Guide*, Beaverton, Oregon. Available at: http://www.oshatrain.org/courses/studyguides/702studyguide.pdf.

Germain, A. & Rowan, R., 1997. *Safety, Health and Environmental Management*, AEI And Associates.

Guidotti, T.L. & Clough, V.M., 1992. Occupational Health Concerns of Firefighting. *Annual Review of Public Health*, (13), pp.151–171. Available at: http://www.annualreviews.org/doi/pdf/10.1146/annurev.pu.13.050192.001055.

Hall, K., 2012. How 3D Printing Impacts Manufacturing. *ComputerWeekly.com*. Available at: http://www.computerweekly.com/feature/How-3D-printing-impacts-manufacturing [Accessed December 17, 2013].

Hardy, S., 2012. Falmouth Beach Hotel Fire: Caused by Workman. *ITV Westcountry*. Available at: http://www.itv.com/news/westcountry/2012-05-01/falmouth-beach-hotel-fire-caused-by-workman/ [Accessed November 25, 2013].

Harris, R.J., 1973. Answering questions containing marked and unmarked adjectives and ad-verbs. *Journal of Experimental Psychology*, 97, pp.399–401.

Helmricks, D.R., 2010. Motor Vehicle Accident Forensic Survey. In *FIG Congress 2010: Facing Challenges- Buolding Capacity*. Sydney, Austrailia, pp. 11–16. Available at: http://www.fig.net/pub/fig2010/papers/fs03c%5Cfs03c_helmricks_4669.pdf.

Hiremagalur, J. et al., 2007. Creating Standards and Specifications for the Use of Laser Scanning in Caltrans Projects. *Leica White Paper*, p.115. Available at: http://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:Creating+Standards+and+Specifications+for+the+Use+of+Laser+Scanning+in+Caltrans+Projects#0.

Höglund, R. & Large, P., 2003. *Direct Reflex EDM Technology for the Surveyor and Civil Engineer Direct Reflex EDM Technology for the Surveyor and Civil Engineer*, Available at: http://www.amerisurv.com/PDF/Direct_Reflex_EDM_Technology_White_Paper.pdf.

Hoover, R., 2011. 3D Laser Scanner History. *eHow*. Available at: http://www.ehow.com/facts_7625254_3d-laser-scanner-history.html [Accessed August 8, 2014].

HSE, 2013a. Approval of a Proposed Prosecution. Available at: http://www.hse.gov.uk/enforce/enforcementguide/investigation/approving-approval.htm [Accessed January 20, 2014].

HSE, 2013b. *Enforcement Management Model (EMM) Operational Version 3.1*, UK. Available at: http://www.hse.gov.uk/enforce/emm.pdf.

HSE, 2009. *Enforcement policy statement*, UK. Available at: http://www.hse.gov.uk/pubns/hse41.pdf.

HSE, 1993. *Extensive Fall of Roof at Bilsthorpe Colliery* HSE, ed., Suffolk: Sudbury, Suffolk : HSE Books, 1994.

HSE, 2012a. Fatal injuries to employees, the self-employed and members of the public, by main industry, 1981 - 2011/12p. Available at: http://www.hse.gov.uk/statistics/history/histinj.xls.

HSE, 2012b. *Health and safety in roof work*, UK: HSE. Available at: http://www.hse.gov.uk/pubns/priced/hsg33.pdf.

HSE, 2011a. Health and Safety Management Lecturing Resource for Quarrying Related Degree Courses: Accident Aetiology. , pp.1–19. Available at: www.hse.gov.uk/quarries/education/documents/topic3.doc.

HSE, 2004. *Investigating accidents and incidents*, London: HSE.

HSE, 2011b. Leadership and Worker Involvement Toolkit. *Management of Risk when Planning Work: The Right Priorities*. Available at: http://www.hse.gov.uk/construction/lwit/assets/downloads/hierarchy-risk-controls.pdf [Accessed July 27, 2104].

HSE, 1999. *Reducing Error and Influencing Behaviour*, Available at: http://www.hse.gov.uk/pubns/priced/hsg48.pdf.

HSE, 2013c. *Slips & trips and falls from height in Great Britain , 2013*, Available at: http://www.hse.gov.uk/statistics/causinj/slips-trips-and-falls.pdf.

HSE, 2012c. *Statistics on fatal injuries in the workplace 2012/13*,

HSE, 2013d. The Expert. *Enforcement Guide*. Available at: http://www.hse.gov.uk/enforce/enforcementguide/investigation/expert-role.htm [Accessed December 18, 2013].

Hurn, J.A., 1989. *GPS: A Guide to the Next Utility*, Trimble Navigation Limited.

Hydro Tasmania, 2010. *Incident Management- Investigation Methodology Guide*, Available at: http://www.google.co.uk/url?sa=t&rct=j&q=&esrc=s&source=web&cd=4&ved=0CDoQFjAD&url=http://www.hydro.com.au/system/files/contractor-ohs/Safe-Systems/Incident_management_investigation_guide.doc&ei=3t7YU4usCYWk0QWrxIGQBA&usg=AFQjCNGxs3c_XlIaqZfWitUfZT5TSmbrTg&bvm=bv.71778758,d.d2k.

Hyett, A.J., 2004. Innovative Digital Instrumentation for Geotechnical Monitoring Systems. In *2nd International Symposium on Mining Technologies of*

Narrow-Vein Deposiits. Canadian Institute of Mining Metalurgy and Petroleum, pp. 1–8. Available at: http://www.yieldpoint.com/pdf/moc_sud_hyett.pdf.

Inglobe Technologies, 2013. Inglobe Technologies. *May 23th 2013 - Inglobe Technologies to present the new ARmedia 3D Tracker at AWE 2013 in Silicon Valley*. Available at: http://www.inglobetechnologies.com/en/news/fullnews.php?id=40 [Accessed June 13, 2013].

Johnson, D.A., 2006. An improved method for measuring stairways. *IEA*.

Kaplan, E. & Hegarty, C., 2005. *Understanding GPS: Princples and Applications* Second Rev., Artech House.

Kennie, T.J.M. & Petrie, G., 2009. *Engineering Surveying Technology* ED Edition., CRC Press.

Khoo, V.H.S., Tor, Y.K. & Ong, G., 2010. Monitoring of High Rise Building using Real-Time Differential GPS Monitoring of High Rise Building using Real-Time Differential GPS. In *FIG Congress 2010 Facing Challenges- Building the Capaciity*. Sydney, Austrailia: International Feberation of Surveyors, pp. 11–16. Available at: http://www.fig.net/pub/fig2010/papers/ts02d%5Cts02d_khoo_tor_et_al_3976.pdf.

Kingston, J. et al., 2008. *3CA: Investigators Manual*, Delft, Netherlands. Available at: http://www.nri.eu.com/NRI5.pdf.

Kingston, J. et al., 2007. *Events and Conditional Factors Analysis Manual*, Delft, The Netherlands: Noordwijk Risk Initiative Foundation. Available at: http://www.nri.eu.com/NRI4.pdf.

Kingston, J. et al., 2009. *NRI MORT User ' s Manual For use with the Management Oversight & Risk Tree analytical logic diagram* Second Edi., The Noordwijk Risk Initiative Foundation. Available at: http://www.nri.eu.com/NRI1.pdf.

Krug, E.G., Sharma, G.K. & Lozano, R., 2000. The Global Burden of Injuries. *American Journal of Public Health*, 90(4), pp.523–526.

Leary, M. Lou, 2000. *Fire and Arson Scene Evidence: A Guide for Public Safety Personnel*, Washington DC. Available at: http://www.crime-scene-investigator.net/fireandarsonsceneevidenceNIJ.pdf.

Lee, D., 2010. Causation Theory. Available at: http://www.es3global.com/risk-history.php [Accessed January 23, 2012].

Lee, M., 2009a. Fireground Tacktics: Offensive vs. Defensive. *Fire Rescue 1.com*. Available at: http://www.firerescue1.com/fire-attack/articles/499269-Fireground-Tactics-Offensive-vs-Defensive/ [Accessed November 12, 2013].

Lee, M., 2009b. Fireground Tacktics: Pre-Fire Planning. *Fire-Rescue 1.com*. Available at: http://www.firerescue1.com/Columnists/Michael-Lee/articles/454801-Fireground-Tactics-Pre-Fire-Planning/ [Accessed November 13, 2013].

Lee, M., 2009c. Fireground Tactics: Planning Your Attack. *Fire Rescue 1.com*. Available at: http://www.firerescue1.com/Columnists/Michael-Lee/articles/486141-Fireground-Tactics-Planning-Your-Attack/ [Accessed November 12, 2013].

Leica Geosystems, 2014. Leica ScanStation P20. *ScanStation P20*. Available at: http://hds.leica-geosystems.com/en/Leica-ScanStation-P20_101869.htm [Accessed August 8, 2014].

Leigh, C., 1962. *Explosion at Tower Colliery, Glamorganshire: report on the causes of, and circumstances attending, the explosion which occurred at Tower Colliery, Glamorganshire, on 12th April, 1962*, London : HMSO, 1962.

Livingston, A.D., Jackson, G. & Priestley, K., 2001. *Root Causes Analysis: Literature Review*, Birchwood, Warrington: Her Majesty's Stationery Office. Available at: http://www.hse.gov.uk/research/crr_pdf/2001/crr01325.pdf.

Loftus, E.F., 1975. Reconstructing memory : The incredible eyewitness. *Jurimetrics Journal*, 15(3), pp.188–193.

Lumsdon, J., 2010. The Minnie Pit Halmerend. Available at: http://northstaffsminers.btck.co.uk/TheMinniePitHalmerend [Accessed February 8, 2013].

MacNeill, P., 2008. *International Mining Fatality Database Project Report Overview of the project undertaken at the NSW Department of Primary Industries*, Available at: http://www.dpi.nsw.gov.au/__data/assets/pdf_file/0009/182484/International-Mining-Fatality-Database-project-report.pdf.

McNeese, B., 2005. Analyzing Cause and Effect Diagrams. *SPC for Excel*, p.1. Available at: http://www.spcforexcel.com/knowledge/root-cause-analysis/analyzing-cause-and-effect-diagrams [Accessed October 1, 2014].

Mercer, J.B. et al., 2000. ORTHORECTIFICATION OF SATELLITE IMAGES USING EXTERNAL DEMS FROM IFSAR. In *Intermap Technologies Corp, Commission II, Working Group II/2*. Calgary, pp. 1–6. Available at: http://www.ipi.uni-hannover.de/fileadmin/institut/pdf/mercer.pdf.

Van der Merwe, J.W. & Andersen, D.C., 2012. Applications and Benefits of 3D Laser Scanning for the Mining Industry. In *The Southern African Institute of Mining and Metallurgy Platinum 2012*. Sun City, South Africa: SAIMM, pp. 501–518.

Mine surveyor.net, 2010. Accident Investigation Surveys. Available at: http://www.minesurveyor.net/gsaccident.php [Accessed February 1, 2013].

Ministry of Justice, 2013. *The Criminal Procedure Rules Part 33*, UK: Ministry of Justice. Available at: http://www.justice.gov.uk/courts/procedure-rules/criminal/docs/2012/crim-proc-rules-2013-part-33.pdf.

Munson, S., 1999. *Assessment of Accident Investigation Methods: For Wildland Firefighting Incidents By Case Study Method*. University of Montana. Available at: http://www.iprr.org/proj/munpaper.html.

NASA, 2000. NASA Procedures and Guidelines for Mishap Reporting, Investigating and Recordkeeping. *NASA Procedures and Guidelines*, p.1. Available at: http://nodis3.gsfc.nasa.gov/displayCA.cfm?Internal_ID=N_PR_8621_0001_&page_name=AppdxI33 [Accessed July 28, 2014].

National Fire Protection Association, 2004. *NFPA_921.pdf* 2004th ed., Qui: National Fire Protection Association. Available at: http://www.sierragal.com/252_stuff/NFPA_921.pdf.

National Ocean Service, 2012. Micrometer Scale. *NOAA Celebrates 200 Years*. Available at: celebrating200years.noaa.gov/theodolites/micrometer.html [Accessed August 4, 2014].

Nationwide Mutual Insurance Company, 2013. *RS 1007: Accident Investigation*, Harleysville. Available at: http://www.harleysvillegroup.com/losc/trs/rs/rs1007.pdf.

Nelson, L., 2012. Root Cause Analysis (RCA) and the Corrective Action/ Preventative Action (CAPA) Process. *Us Department of Energy*, p.47. Available at: http://www.asqlongisland.org/seminars/2010_11_05_CAPA_LloydNelsonRootCauseAnalysis.pdf [Accessed July 30, 2014].

NOAA, 2012. AGA Geodimeters, Models 4D and 4L. *NOAA Celerbates 200 Years*. Available at: http://celebrating200years.noaa.gov/distance_tools/geodimeters_4d_4l.html [Accessed August 4, 2014].

NQA, 2009. *Guide to Implementing a Health and Safety Management System*, Dunstable, Bedfordshire.

Nystrom, E.C., 2014. *Seeing Underground- Maps, Models and Mining Engineering in America* 1st ed., Reno: University of Nevada.

OSHAcademy, 2006. Event and Causal Factor Charting. Available at: http://www.oshatrain.org/notes/2hnotes12.html [Accessed July 27, 2014].

Pace, S. et al., 1995. *The Global Positioning System: Assessing National Policies*, San Monica, CA: Rand. Available at: http://www.rand.org/content/dam/rand/pubs/monograph_reports/2007/MR614.pdf.

Parkinson, B.W., 1994. GPS Eyewitness: The Early Years. In *GPS World*. p. 42. Available at: http://www.cs.cmu.edu/~sensing-sensors/readings/GPS_History-MR614.appb.pdf.

Pienaar, A., 2012. A Practical Study of the Movement and Surveying Radar in Mining. In *Australian Centre for Geomechanics: Newsletter*. Australian Centre for Geomechanics, pp. 16–19.

Du Pont, 1990. Safety Management Training Incident Invesatigation Seminar: Training Booklet.

Price, W., 1983. The Global Positioning System. *Land and Minerals Surveying*, pp.42–58.

Quintero, M.S. et al., 2008. *3D Risk Mapping: Theory and practice on Terrestrial Laser Scanning* Version 4., Leonardo da Vinci (EU) - Community Vocational Training Action Programme. Available at: https://lirias.kuleuven.be/bitstream/123456789/201130/2/Leonardo_Tutorial_Final_vers5_ENGLISH.pdf.

Rasmussen, J., 1990. Mental Models and the Control of Action in Complex Environments. In D. Ackermann & M. J. Tauber, eds. *Mental Models and Human Computer Interaction 1*. Amsterdam, pp. 41–69.

Read, J. & Stacey, P., 2009. *Guidelines for Open Pit Slope Design*, Collingwood, Aus: CSIRO.

Reason, J., 1997. *Managing the Risks of Organizational Accidents*, Ashgate Publishing Limited; illustrated edition edition.

Reeve, I., 2010. *A Reduction in Fatal Casualties- who, why and what does this mean ?*, Wokingham, Berkshire.

Riegl, 2014. LMS-Z420i. *Product: LMS-Z420i*. Available at: http://www.riegl.com/products/terrestrial-scanning/produktdetail/product/scanner/4/ [Accessed August 8, 2014].

Riegl, 2012. Riegl VZ-6000. Available at: http://www.riegl.com/nc/products/terrestrial-scanning/produktdetail/product/scanner/33/ [Accessed February 4, 2013].

Rikhardsson, P.M., 2004. Accounting for the cost of occupational accidents. *Corporate Social Responsibility and Environmental Management*, 11(2), pp.63–70. Available at: http://doi.wiley.com/10.1002/csr.52 [Accessed August 19, 2013].

Rochester Insitutue of Technology, 2010. Incident Investigation Process and Exercise. *Incident Investigation Process and Exercise*, p.10. Available at: https://www.rit.edu/~w-outrea/training/Module3/M3_IncidInvesProcess_wExer.pdf [Accessed September 29, 2012].

Roed-Larsen, S. et al., 2004. Accident investigation practices in Europe--main responses from a recent study of accidents in industry and transport. *Journal of hazardous materials*, 111(1-3), pp.7–12. Available at: http://www.sciencedirect.com/science/article/pii/S0304389404000809 [Accessed July 26, 2014].

Roys, M. & Wright, M., 2003. BRE NOSINGS.pdf. , p.5.

Sandercock, P.M.L., 2008. Fire investigation and ignitable liquid residue analysis--a review: 2001-2007. *Forensic science international*, 176(2-3), pp.93–110. Available at: http://www.ncbi.nlm.nih.gov/pubmed/17949931 [Accessed January 7, 2014].

Santonio Fire Department, 2009. Glossary of Fire Department Terms. Available at: http://www.sanantonio.gov/safd/PDFs/Media/GlossaryFireTerms.pdf [Accessed November 12, 2013].

Santos-Reyes, J. et al., 2009. Applying MORT to the analysis of the “Tláhuac” incident. *Reliability Engineering & System Safety*, 94(10), pp.1547–1556. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0951832009000635 [Accessed July 29, 2014].

Sawyer, A., 1886. *Accidents in Mines* Simpkin Marshall and CO, ed., London: Allbut and Daniel, Percy Street Printing Works.

Schofield, D., 2009. Animating Evidence : Computer Game Technology in the Courtroom. *Journal of Information Law and Technollogy*, 2009(May), pp.1–21.

Schofield, D. & Goodwin, L., 2007. Using Graphical Technology to Present Evidence. In M. S, ed. *Electronic Evidence: Disclosure, Discovery and Admissibility*. London, pp. 101–121.

Shen, T.-S., Huang, Y.-H. & Chien, S.-W., 2008. Using fire dynamic simulation (FDS) to reconstruct an arson fire scene. *Building and Environment*, 43(6), pp.1036–1045. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0360132306003908 [Accessed January 7, 2014].

Solar, S., 2008. *Firefighter Safety and the Modern Vehicle*, Available at: http://ceas.uc.edu/content/dam/aero/docs/fire/Papers/FirefighterSafety-ModernVehicle.pdf.

Sondalini, M., 2011. Understanding How to Use the 5-Whys for Root Cause Analysis. *Lifetime Reliability solutions*, p.9. Available at: http://www.lifetime-reliability.com/tutorials/lean-management-methods/How_to_Use_the_5-Whys_for_Root_Cause_Analysis.pdf [Accessed July 29, 2014].

Speake, G., 2013. Photographs taken after the incident, provided to the investigation team.

Staiger, R., 2011. 10 Years of Terrestrial Laser Scanning- Technology, Systems and Applications. In *FIG Working Week: Bridging the Gap Between Cultures*. Marrakech, Morocco, p. 13.

Staley, B.G. & Foster, P.J., 1996. Investigating Accident and Incidents Effectively. *Mining Technology*, 78(895), pp.67–70.

Stratasys, 2013. Object 1000. *Full Scale Prototypes With Flawless Precision*. Available at: http://www.stratasys.com/3D-Printers/design-series/precision/objet1000 [Accessed December 17, 2013].

Sturman, B. & Wright, A., 2008. The History of Tellurometer. In *Intergrating the Generations: FIG Working Week ,14-19 June*. Stokholm, Sweden: FIG, p. 11. Available at: https://www.fig.net/pub/fig2008/papers/hs01/hs01_03_sturman_wright_2833.pdf.

Surveyors Historical Society, 1994. The Great Theodolite. *Backsights Magazine*, p.14. Available at: http://ndla.no/en/node/66397.

Taylor, G., Easter, K. & Hegney, R., 2004. *Enhancing Occupational Safety and Health*, Butterworth- Heinemann.

Taylor, M.C., Lynam, D.A. & Baruya, A., 2000. *The Effects of Drivers' Speed and Frequency of Road Accidents. Berkshire*,

The Fire Brigades Union, 2008. *In the line of duty: Firefighter deaths in the UK since 1978*, Surry, UK. Available at: http://www.firetactics.com/fbu_fatalities_report.pdf.

The Helpful Engineer, 2011. Measuring Cracks With Tell Tales. *The Helpful Engineer*. Available at: http://thehelpfulengineer.com/index.php/2011/05/measuring-cracks-with-tell-tales/ [Accessed November 13, 2013].

The Institution of Engineering and Technology, 2012. *Accident Investigation: Health and Safety Briefing No 60*, Available at: http://www.google.co.uk/url?sa=t&rct=j&q=&esrc=s&source=web&cd=11&ved=0CFMQFjAK&url=http://www.theiet.org/factfiles/health/hsb60-page.cfm?type=pdf&ei=ih_VU-DIN_CZ0QWRyICwCg&usg=AFQjCNH0qfSnD_9o86hENFmkniQq1PSVaQ&bvm=bv.71778758,d.d2k.

Tiller, R., 1990. Surveying Instruments Today and Tomorrow. *Land and Minerals Surveying*, pp.29–33.

Top Car, 2013. Top Car Rating. *Top Car Rating*. Available at: http://www.topcarrating.com/topspeed.ph [Accessed June 14, 2013].

Transportation Reseach Board, 2012. *Rockfall Characterization and Control* A. K. Turner & R. L. Schuster, eds., Washington DC: Transportation Reseach Board.

Uren, J. & Price, B., 2010. *Surveying for Engineers* Fifth Edit., Palgrave and Macmillan.

US Department of Labor, 1990. *Accident Investigation*, Available at: http://www.labtrain.noaa.gov/osha600/refer/menu16a.pdf.

US Department of Labor, 2013. Mine Safety and Health Administration Fatality Statistics. Available at: http://www.msha.gov/stats/charts/allstates.pdf [Accessed February 14, 2013].

Wallis, D.A., 2005. History of Angle Measurement. In *FIG Working Week: From Pharaohs to Geoinformatics*. Cairo, Egypt, p. 17. Available at: https://www.fig.net/pub/cairo/papers/wshs_01/wshs01_02_wallis.pdf.

Watson, L., 2001. The Platinum Ten. , p.3. Available at: http://www.resqmed.com/GoldenHourPlatinum10.pdf.

Wells, G.L. & Loftus, E.F., 2003. Eyewitness memory for people and events. *Handbook of Psychology*, Part Three, pp.149–159. Available at: http://onlinelibrary.wiley.com/doi/10.1002/0471264385.wei1109/abstract?systemMessage=Wiley+Online+Library+will+be+disrupted+on+11th+July+2015+at+10%3A00-16%3A00+BST+%2F+05%3A00-11%3A00+EDT+%2F+17%3A00-23%3A00++SGT++for+essential+maintenance.++Apologies+for+the+inconvenience&userIsAuthenticated=false&deniedAccessCustomisedMessage=.

Wirstad, J., 1988. On Knowledge Structures for Process Operators. In *Tasks, Errors and Mental Models*. Bristol PA: Taylor and Franics Inc, pp. 50–69.

Zmijewski, C., 2013. Preserving Evidence with 3D Laser Scanning. *Claims Journal*. Available at: http://www.claimsjournal.com/magazines/special-report/2013/09/30/237308.htm [Accessed December 9, 2013].

Zoller and Frohlich, 2012. *How We Build Reality*, Available at: http://www.zf-laser.com/fileadmin/editor/Broschueren/Z_F_IMAGER_5010_E_FINAL_kompr.pdf.