Non-invasive imaging

Peeking through the curtain

Exploitation of the "memory" properties of scattered light allows for single-shot imaging through thin opaque layers including biological tissue.

A simple glance at your own hand is enough to tell you that your body is opaque. While it's true that skin and flesh do absorb visible light the chief reason that you can't see through your hand at all is that biological tissue is a very strong scatterer and is highly effective at scrambling any signal that tries to pass through. As a consequence non-invasive *in-vivo* optical imaging is usually limited to superficial investigation[1]. Now, writing in *Nature Photonics* Katz and co-workers[2] report a single-shot imaging technique that is able to retrieve the shape of an object hidden behind a strongly scattering layer.

The interaction of light with matter is actually a very complex topic but in some cases a simplified picture can carry us a long way. When thinking about light propagating through a disordered medium such as biological tissue it is intuitively useful to picture a collection of balls (light) that need to traverse a pinball machine (the medium) crowded with bumpers and kickers (scatterers made from local inhomogenities). If there are just a few bumpers, most of the balls will be able to cross the machine, interact with any object on the other side, and come back to you. Measuring how many balls come back from each direction you can then reconstruct the shape of the object, and this is exactly what our eyes do continuously when we look around through air. If there are plenty of bumpers, but a few lucky balls still manage to avoid all of them and pass through unscattered, it is still possible to form an image. What you need to do is to select those lucky few to form your image and discard all the others that have been scattered[3]. Another option you have is to measure how the pinball machine scatters the balls and compensate for it if the situation is not too complex[4].

However, once the number of bumpers in the machine increases the problem become more and more complicated and difficult to address. At a certain point there are no more balls that can traverse the machine unscattered, and any ball you throw in will be bounced around in a seemingly random and completely unpredictable way, making any form of compensation impossible. Of course the presence or the absence of an object behind our pinball machine will still have a small effect on how many balls we get back and from which direction they come. So you can measure carefully all the balls you get and try to infer the position of the object[5] but this approach is limited in its capabilities.

This simplified picture has its limits however, and our pinball analogy cannot carry us further. So it is time to abandon it and realize that light is actually a wave, and thus coherent light will not only scatter but will also interfere, forming complex fringe patterns which complicates the situation yet further. Yet every cloud has a silver lining and in this case it is the fact that interference carries phase information thus allowing us (at least in principle) to fully characterize the disorder and compensate for it despite its complexity[6].

The trick used by Katz and colleagues[2] has its roots in astronomy, where a turbulent atmosphere acts as a scattering medium and blurs any picture taken from the ground. One of the consequences of wave scattering is that the light emerging from a disordered medium is in the form of a complex and seemingly random speckle pattern. This is often considered a hindrance by people trying to use laser light for displays and imaging, because it introduces unwanted artefacts, but it has a few surprising properties that can be exploited to unravel disorder. One of the more counter-intuitive of these properties is the "optical memory effect"[7] (also known as "intrinsic isoplanatism"), i.e. the fact that, despite all the scrambling, some memory of the appearance of a light pattern on one side of the scattering medium, is retained on the other side. More specifically: if the light coming from a point source produces a given speckle pattern, the light coming from a point source at a small distance d from the first one produces exactly the same speckle pattern, just shifted by d. So, in a sense, some memory on the directionality of light is preserved. As a consequence, information about the shape of an object hidden behind a scattering layer, is actually encoded inside the apparently random speckle pattern created by the scattered light. Decoding this information requires some complex mathematical machinery, but can be done to obtain the original shape of the hidden object[8,9].

When doing ground-based astronomy, we usually want to image the stars through a distorting atmosphere. And since stars are, by their own nature, light sources that do not require any external illumination, this method works in a straightforward manner, yielding diffraction limited images of celestial objects through even the most turbulent atmosphere. But so far all the applications related to microscopy have required complex illumination and long scans[10,11].

Katz and coworkers[2] have found a simple and elegant solution to the problem by treating objects hidden behind a scattering screen like they were stars. They hide an object (actually a screen with a object-shaped hole) behind a scattering screen that can range from frosted glass, to a layer of zinc oxide paint to a thin (~300µm) slice of chicken breast, and then consider each point of the object to be a point source. The light from each of those points will cross the screen, get scattered and form the very same speckle pattern, just shifted with respect to each other. The resulting seemingly random light intensity pattern, can be captured and has the property that its autocorrelation is the same as the object autocorrelation[8,10]. This autocorrelation can now be numerically inverted and the shape of the hidden object retrieved with very high resolution. The result is a single-shot measurement technique that just requires milliseconds to be completed and only very simple equipment: a good quality camera and a computer. As an added bonus they realized that exactly the same principles can be exploited to image an object positioned around a corner, and thus out of direct sight, just looking at the light coming from the object and scattered from the wall. It turns out that the procedure to do so is simple enough that can be implemented using a smartphone camera.

Of course this method comes, just like every other imaging technique, with his own baggage of limitations and problems yet to solve, chiefly the limited field of view. In fact, the memory effect is valid only in a relatively small range[7], and there is currently no known way to extend it. Furthermore this method only works to look through a scattering layer. If the object is hidden deeply in a scattering medium the memory effect range will be effectively zero, making any imaging impossible. A more delicate point are the phase retrieval algorithms required to "decode" the information about the hidden object[9]. Despite the fact that variants of these algorithms are known since almost 40 years, obtaining the desired answer without getting stuck at false point is still more an art than a science, making this kind of methods less reliable than we would like them to be. Additionally the authors worked using a hole in a black screen as their object, thus avoiding stray light problems and increasing the signal to noise ratio. This is a sensible choice when the goal is to demonstrate a new method, but this simplified geometry is unlikely to work as-it-is in a real microscopy experiment.

The dream of a truly non-invasive imaging technique that is capable to see deeply hidden objects is still a dream. But we are making big steps in that direction, and I wouldn't be surprised if major breakthroughs are forthcoming.

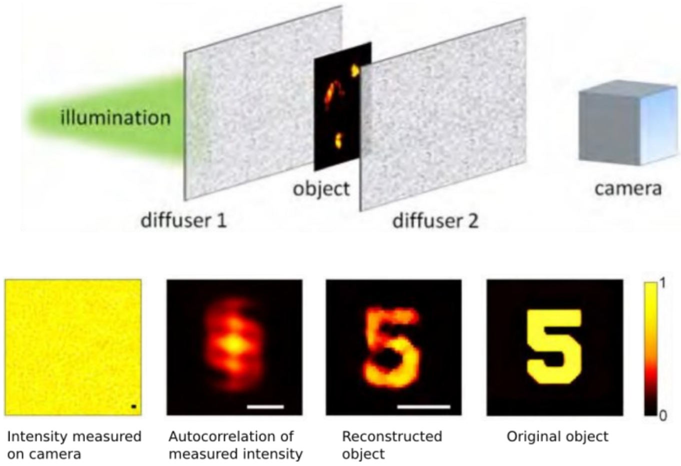

Figure 1: (adapted from xxx) an object enclosed between two scattering screens is illuminated by monochromatic light. The light passes through the first scattering screen, getting scrambled, and illuminate the object. In this case the object is a simple pattern carved in an otherwise black screen so, when illuminated from the back, it behaves like an extended source. The light from the object then passes through the front diffuser, get scrambled again and then can be detected by a simple camera. The light measured this way looks like an almost flat intensity pattern with some small, and seemingly random, fluctuations on top. The informations about the object can be retrieved by autocorrelating the measured intensity[8,10] and then numerically extracting the shape of the original object[9].

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2. xxx

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