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NAVIGATING THE FUTURE: STRATEGIC MANAGEMENT OF A MOBILE AQUACULTURE SYSTEM WITH RECEDING-HORIZON CONTROL

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ABSTRACT

The New Zealand-based Whakapōhewa ki ahumoana Reimagining Aquaculture project (funded by the Ministry for Business, Innovation and Employment Endeavour Fund) lead by Plant & Food Research, is designing a mobile aquaculture system for finfish, towed by an autonomous vessel, powered by renewable energy sources.

This work presents the vessel management strategy for this mobile aquaculture solution, inspired by receding-horizon control, which uses available weather forecasts to minimize the energy consumption by the autonomous vessel while maintaining an optimal flow speed through the fish enclosure such that the optimal biological conditions (e.g. swim speed) for the fish can be maintained. The simulations performed for a generalized salmonid fish species cultured in Tasman Bay, New Zealand show that the food storage capacity of the autonomous vessel is consistently a limiting factor at low swim speeds ($\leq 0.4\,\mathrm{m\,s^{-1}}$), while energy capacity limits at higher swim speeds. The simulations highlight how such a strategy allows the system to successfully shelter from storms and by virtue of going further from its "safe haven" can maintain optimal conditions for the fish through the enclosure. We anticipate this work to be a starting point for more sophisticated management strategies considering engineering criteria, species specific requirements, and environmental parameters such as temperature and water quality that impact fish welfare explicitly.

1. INTRODUCTION

Globally, demand for seafood is increasing and is expected to increase substantially over the coming years. With capture fisheries stable, or in decline, finfish aquaculture is essential to meet this increasing demand. As space is limited in sheltered areas, sustained growth in finfish aquaculture requires moving into areas not currently used for aquaculture. These may be more wave and current exposed and will require improved understanding and mitigation strategies for impacts to the marine environment [1]. It follows that new, sustainable, and more innovative systems are necessary to ensure safe, profitable, and sustainable production. One potential innovation is mobile aquaculture facilities that are not permanently stationed, but rather able to relocate by using autonomous systems to tow fish enclosures. Such a system could move to areas with optimal conditions for the fish, such as temperature and water quality. Mobility can also mitigate negative impacts related to waste from fixed aquaculture systems for finfish.

The New Zealand-based Whakapōhewa ki ahumoana Reimagining Aquaculture project (funded by the Ministry for Business, Innovation and Employment Endeavour Fund) lead by Plant & Food Research [2], is designing such a mobile aquaculture system for finfish, towed by an autonomous vessel, powered by renewable energy sources. The project includes the design of vessel management systems that balance logistical factors, such as food and energy availability, with fish welfare and environmental conditions.

Such a system, operating in the open ocean with no crew and minimal intervention, requires a strategic approach to route planning, enabling consideration of the dynamic marine environment and incorporating real-time weather considerations. Long-term deployments of autonomous surface vessels (ASVs), for applications similar to this, make use of management strategies based on advanced navigation algorithms which dynamically adjust to changing weather patterns [3, 4]. These vary in complexity and level of autonomy. The simplest approaches, treats the route planning as a static decision problem to be completed prior to any missions and relies on accurate and up-to-date weather forecasts at the time of planning [3–5]. This preemptive route planning

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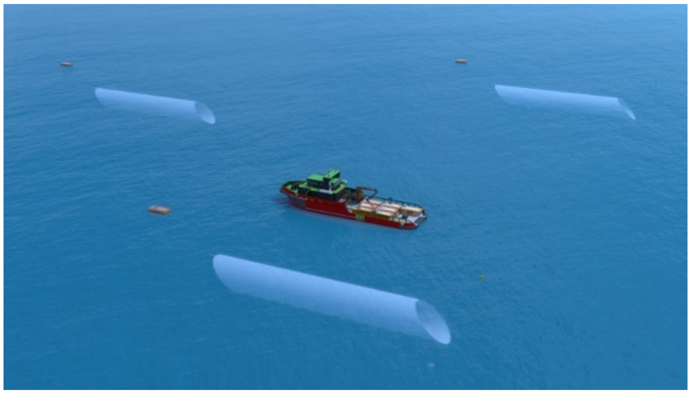

FIGURE 1: ILLUSTRATION OF THE REIMAGINING AQUACULTURE CONCEPT

strategy aims to optimize vessel performance based on anticipated weather conditions, by dynamically adjusting the speed and heading of the vessel. As this is done ahead of the mission, it does not account for any changes in the weather system or forecasts.

Dynamic route planning methods are more complex methods, which consider the forecast as it updates during the mission and uses that information to dynamically update the route of the system towards objectives such as maximizing fuel efficiency, vessel stability, or safety. There are several *dynamic route planning methods*, including the use of machine learning algorithms to predict and anticipate the impact of changing weather patterns on vessel dynamics. By improving decision-making accuracy in response to evolving environmental conditions, machine learning can enhance the ASV's adaptability [3–5].

Fuzzy logic control systems provide another alternative, capable of considering the uncertainty associated with weather forecasts. Fuzzy logic allows the ASV to make decisions based on a range of possible scenarios, improving adaptability. Sensor networks beyond the ASV can also be integrated, enabling the system to consider the environmental parameters and weather in a wider area, thereby enabling better consideration of developing weather conditions [6, 7]. To date, fuzzy logic control is generally used for obstacle and collision avoidance rather than higher level route planning [8].

Finally, human-in-the-loop systems represent an approach where human operators collaborate with the system, particularly in challenging weather conditions. These semi-autonomous systems combine human expertise with autonomous capabilities to ensure safe navigation. The choice of strategy often depends on factors such as the vessel's specific mission, the level of autonomy desired, and the nature of the anticipated weather challenges [9, 10].

Within the dynamic route planning methods, *receding-horizon control*, also known as model predictive control, allows ASVs to continuously reassess and adapt their planned routes and control actions based on a rolling prediction horizon [11–13]. Implementations of receding-horizon have been shown to successfully optimize the economic dispatch of a battery management system while considering the impact of weather forecasts [14, 15]. Given this success, a similar approach is considered here for the management of this mobile aquaculture system. In the context of weather-aware management, this means incorporating live meteorological data, such as wind speed, wave height, and current velocity, into the decision-making process. This enables the ASVs to optimize their routes in real-time, considering economic, engineering, or fish welfare based criteria.

These adaptive strategies extend beyond simple route adjustments. ASVs equipped with receding-horizon-control can dynamically alter their speed and heading, responding to the immediate weather conditions they encounter. For instance, in the presence of rough seas or adverse wind patterns, the vessel may autonomously adjust its course or reduce speed to ensure both operational efficiency and fish safety. Similarly, the approach could target spatial areas with preferential conditions for fish welfare, avoid pollution events or adverse temperatures.

In the present work, we present the vessel management strategy for a mobile aquaculture system for a generalized salmonid finfish, towed by an autonomous vessel. Inspired by receding-horizon control, the management strategy uses available weather forecasts to optimize the path of the mobile aquaculture system such that the optimal swim speed for the fish is maintained at all times. The paper presents simulation results for a grow-out operation conducted in Tasman Bay, New Zealand.

2. APPROACH

For the present work, it is assumed that the mobile aquaculture installation has two key locations identified a priori, the *safe haven location* – a sheltered site where the system can return to in the event of storms or when it needs to be resupplied with either feed for the fish or energy for its propulsion system, and a *target location* – an offshore location where the system aims to operate. In fair weather, the system will therefore try to remain as close as possible to the target location while in adverse conditions, or if supplies are running low it will attempt to remain as close as possible to the safe haven location. In future work, the optimum location could be set dynamically to target optimal conditions.

The methodology outlined below implements a recursive receding-horizon inspired strategy. Under this strategy, at each time-step, the ASV selects its optimal heading and speed for that time-step such that the system is as close as possible to the target location over the entire receding-horizon (i.e. six hours) while maintaining an optimal swim speed for the fish. To evaluate the entire horizon, the same algorithm is recursively called for progressively shorter horizons, hence receding, for all the possible positions at each future time-step given its current heading, speed, position, and limits on how rapidly it can change heading. The wave and current forecasts are therefore used to compute the fuel consumption of the ASV required to maintain the desired swim speed for the fish.

A flowchart of the procedure at each time-step is given in Figure 2. At each time-step, t, the method is aware of its current position, its target position (i.e. either the offshore location or the safe haven location that it would like to remain close to), its current food reserves (f_t), its current energy reserves (e_t), the food consumption required to return to safe haven (f_{haven}), and the energy consumption required to return to safe haven (e_{haven}). If the food or energy is at the required thresholds necessary to

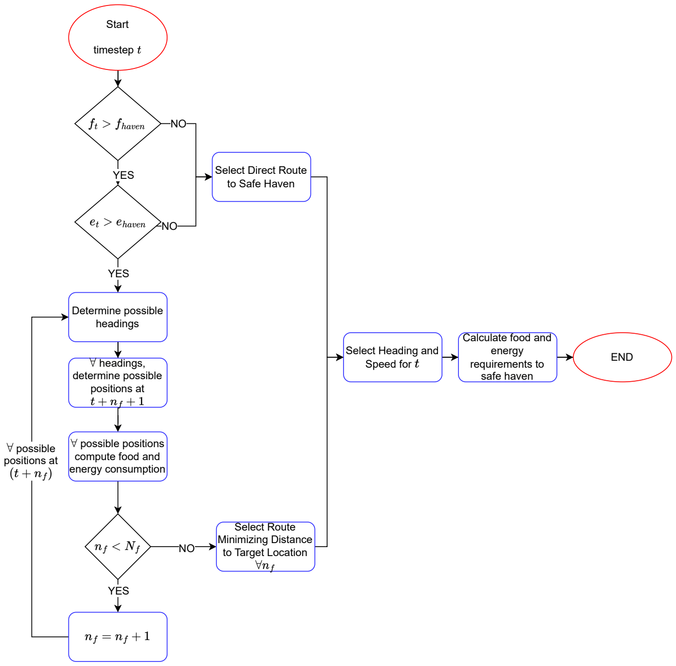

FIGURE 2: OVERVIEW OF THE RECURSIVE RECEDING-HORIZON PATH PLANNING APPROACH.

return safe haven, then the system identifies the optimum route back to the safe haven location and takes an immediate step along this route. Note, a safety factor can be set for the food and energy, to ensure that the system does not run out of food before returning to the safe haven. If the system has surplus food and energy, then it steps through each time-step from the present, t, until N_f future time-steps. For each time-step $t + n_f$ the system determines the possible headings that can be taken, limited by maximum rate of heading change defined by the turning radius of the ASV. For each of these headings, informed by the spatial forecast, the system then identifies the necessary vessel speed required to maintain the optimal swim speed of the fish, and the associated energy consumption to maintain this speed and heading for one time-step. By undertaking this analysis recursively, at each n_f future time-steps, all possible positions are considered and evaluated allowing each of the available routing options to be evaluated.

Once each route is evaluated considering N_f future time-steps, the system selects the route that minimizes the total distance between the ASV and the target location over the $t+N_f$ time-steps. It then takes the first step as identified in this route, proceeds to the next time-step and repeats the entire process. In this way, even though it considers N_f future time-steps when making a decision, it is only committed for the next time-step and is able to dynamically adjust as the weather and any associated forecasts update.

In the present work, this route optimization approach is presented for several possible optimal fish swim speeds demonstrating how different fish swim speeds can be successfully targeted. Optimal swim speeds were defined herein as the physiologically optimum swimming velocity of fishes, determined by the speed at which the metabolic cost of transport is smallest (i.e. U_{opt}), and coincides with theoretically optimum growth [16, 17]. Which in the case of Atlantic salmon *Salmo salar* represents speeds between $0.5\,\mathrm{m\,s^{-1}}$ to $0.6\,\mathrm{m\,s^{-1}}$ across a range of body lengths [18]. However, it is important to note here that different species of fish have different optimal swim speeds depending on their age and body length [19–21].

3. CASE STUDY

Site

The mobile aquaculture system under development through this project has been tested in Tasman Bay at the north end of New Zealand's South Island. The real-world aquaculture system, currently in development, has undertaken prototype testing, and design iteration here. Given the relative isolation and oceanic exposure of the region, Tasman Bay would represent a exemplary site for such a solution.

In order to demonstrate the capabilities of the proposed management strategy, a scenario is considered within Tasman Bay whereby, the system seeks to maintain the fish near either the offshore locations P2 or P3 (see Figure 3) and uses the more sheltered, inshore site labeled P1 as a safe haven and resupply location.

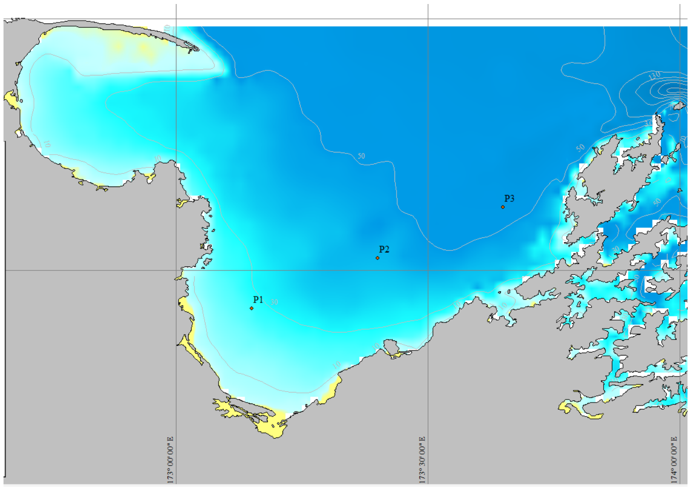

FIGURE 3: BATHYMETRY OF TASMAN BAY [22]. LOCATIONS P1, P2, AND P3 ARE HIGHLIGHTED REPRESENTING POINTS OF INTEREST WITHIN THE BAY WHICH HAVE INCREASING LEVELS OF WAVE AND CURRENT EXPOSURE. DARKER COLORS DENOTE DEEPER WATER.

TABLE 1: COORDINATES OF THE THREE LOCATIONS OF INTEREST IN TASMAN BAY

Site	Longitude (E)	Latitude (S)	Depth [m]
P1	173.150	41.075	22
P2	173.400	40.975	43
P3	173.650	40.875	53

This area is covered by detailed metocean models [22], providing a hindcast of estimated currents across the region and spectral wave conditions (see Table 2 for a summary of the conditions). Initial analysis identified that wave conditions were

TABLE 2: SUMMARY OF METOCEAN CONDITIONS AT THE THREE LOCATIONS OF INTEREST

		P1		P2		P3	
		H_s [m]	U [m s^{-1}]	H_s [m]	U [m s^{-1}]	H_s [m]	U [m s^{-1}]
January	**Min**	0.09	0.00	0.15	0.00	0.13	0.00
	Max	2.00	0.83	3.11	0.99	3.28	1.12
April	**Min**	0.06	0.00	0.11	0.00	0.12	0.00
	Max	1.85	0.79	2.55	0.97	2.61	1.08
July	**Min**	0.12	0.00	0.27	0.00	0.23	0.00
	Max	1.70	0.85	2.91	1.15	3.30	1.25
October	**Min**	0.04	0.00	0.09	0.00	0.09	0.00
	Max	2.02	0.78	3.09	0.91	3.38	1.08

most consistently represented with dynamic fits to Torsethaugen spectra [23, 24].

Mobile Aquaculture System

The mobile aquaculture system is still in development, and values used in this study are not necessarily indicative of a final design. Here, a design for the harvest of up to 30,000 salmon (150.000 kg harvest biomass, starting biomass of 12.000 kg) was assumed. This enclosure is a 10.000 m^3 cylindrical enclosure of 14 m diameter and 65 m length. A separate piece of work has designed a theoretical ASV to tow this system that is 30 m in length between perpendiculars. The combined system has sufficient capacity for 12.000 kg of feed, and 64 MW h of energy capacity for the propulsion system.

The case study undertaken here demonstrates the management strategy for the mobile aquaculture system while maintaining different optimal swim speeds, and the impact that this has on operations. For the purpose of this work, the food consumption was assumed constant at 200 kg d^{-1}, representing a biomass (fish-size) dependent ration between 0.15 %/d to 1.6 %/d.

In order to accurately model the system movement and energy consumption, at each time-step, the drift and resistance forces of the vessel and towed enclosure are computed based on the desired speed of the system as well as the environmental conditions. This calculation is based on pre-run computational fluid dynamics (CFD) simulations of the system (combined autonomous vessel and net) which populate a series of look-up tables defining the loads on the system for different seastates. These are combined with efficiency curves of the vessel's propulsion system to compute the power consumed by the system to maintain the target fish swim speed (i.e. the towed system's speed through water). Details of these CFD simulations are outside the scope of the present study. To accurately compute the drift and resistance forces, the wave and current conditions in addition to the towed system's speed through water need to be known.

Input Data

The simulation of the system and route optimization process requires as input the details of the fish enclosure and the ASV along with the drift and resistance forces that the propulsion system must overcome. For the present work, this was provided by the vessel designers in the form of parametric lookup tables defining the drift and resistance forces as a function of the wave parameters (H_s, T_p) and system velocity relative to the currents.

For the purposes of this study, hindcast metocean data is used in place of a forecast, providing spatial data at each time-step for waves and currents. The wave hindcast provided by Oceanum [25] is a 5 km SWAN model for New Zealand forced by ERA5 global reanalysis data. The currents, also extracted for the year 2000 are provided by a 3D ROMS model forced by CFSR and CFSv2 global reanalysis data. This nested model provides data at 3.5 km resolution for the Central New Zealand domain that includes Tasman Bay.

System Objectives

In order to demonstrate the capabilities of this weather forecast informed receding-horizon route optimization, simulations were run separately starting in four different seasons (summer, autumn, spring, winter), two different target locations (P2/P3), and six different fish swim speeds (0.0 m s^{-1} to 1.2 m s^{-1}).

4. RESULTS

A total of 48 simulations were run to demonstrate the capabilities of this receding-horizon management strategy. Figures 4 to 7 show the tracks of the system, starting from P1 and then traveling to the respective target locations. For all the plots, regardless of the desired swim speed or target location, it can be seen that the system travels to the desired target, and then makes figure-of-eight patterns around the site, maintaining the desired swim speed enabling it to use the forecast and any ambient currents to reduce the requirements on the propulsion system and allows the system to retreat to P1 to avoid adverse conditions (see Figure 4). Interestingly, as the swim speed increases, the extent of the figures-of-eight increases leading to greater distances covered away from the target location. Importantly throughout, this process, the desired swim speed is maintained - 0.6 m s^{-1} for Figures 4 and 5 and 1.0 m s^{-1} for Figures 6 and 7.

Figure 8 shows the endurance of the system (i.e. the time after being resupplied with food and energy at P1 that the system runs out of either food or energy) as a function of the target swim speed for the fish. Though the food consumption is unaffected by the fish swim speed, the energy consumed by the propulsion system is. From Figure 8 it can be seen that when the optimal swim speed exceeds 0.4 m s^{-1} the endurance drops from 303 h, representing

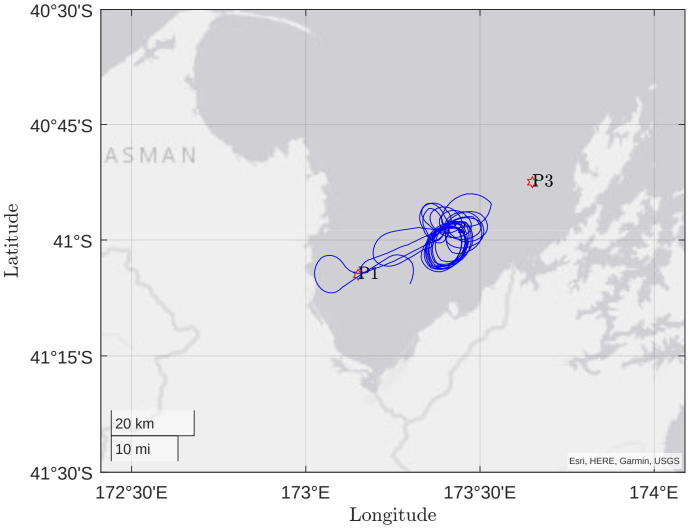

FIGURE 4: ILLUSTRATIVE TRACK OF THE SYSTEM FOR AN APRIL DEPLOYMENT WITH A TARGET SWIM SPEED OF 0.6 $\mathrm{m\,s^{-1}}$. TARGET LOCATION P2.

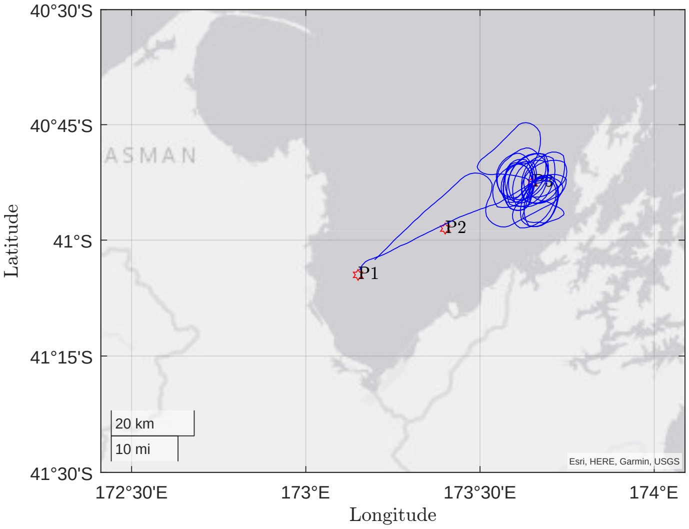

FIGURE 5: ILLUSTRATIVE TRACK OF THE SYSTEM FOR AN APRIL DEPLOYMENT WITH A TARGET SWIM SPEED OF 0.6 $\mathrm{m\,s^{-1}}$. TARGET LOCATION P3.

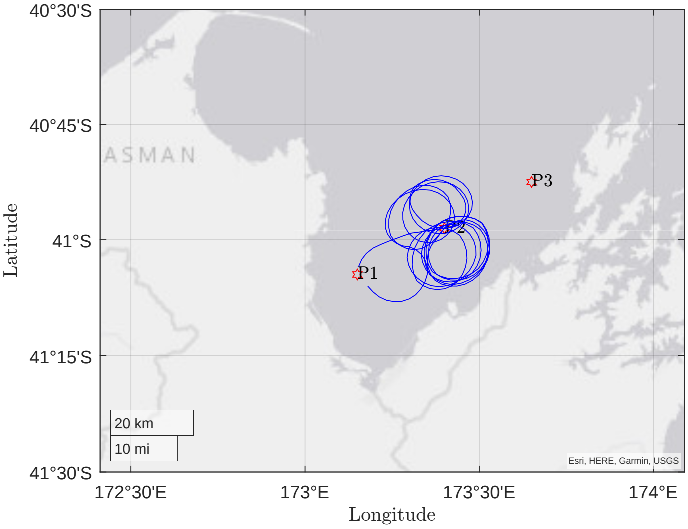

FIGURE 6: ILLUSTRATIVE TRACK OF THE SYSTEM FOR AN OCTOBER DEPLOYMENT WITH A TARGET SWIM SPEED OF 1.0 $\mathrm{m\,s^{-1}}$. TARGET LOCATION P2.

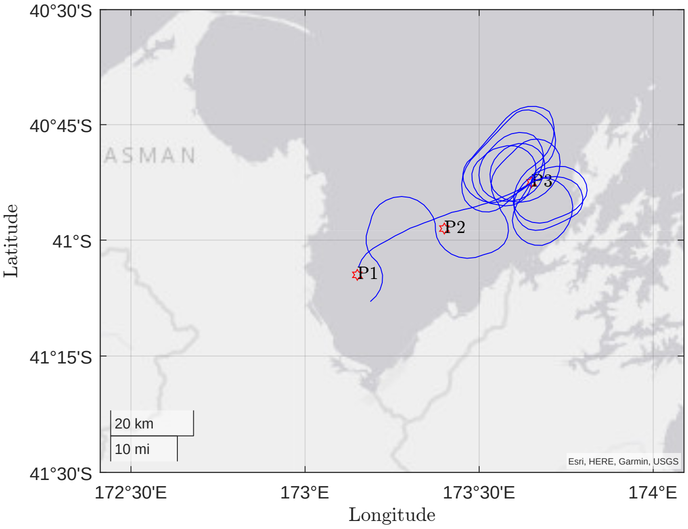

FIGURE 7: ILLUSTRATIVE TRACK OF THE SYSTEM FOR AN OCTOBER DEPLOYMENT WITH A TARGET SWIM SPEED OF 1.0 $\mathrm{m\,s^{-1}}$. TARGET LOCATION P3.

the transition from when food supply limits the endurance to when energy becomes the limiting factor.

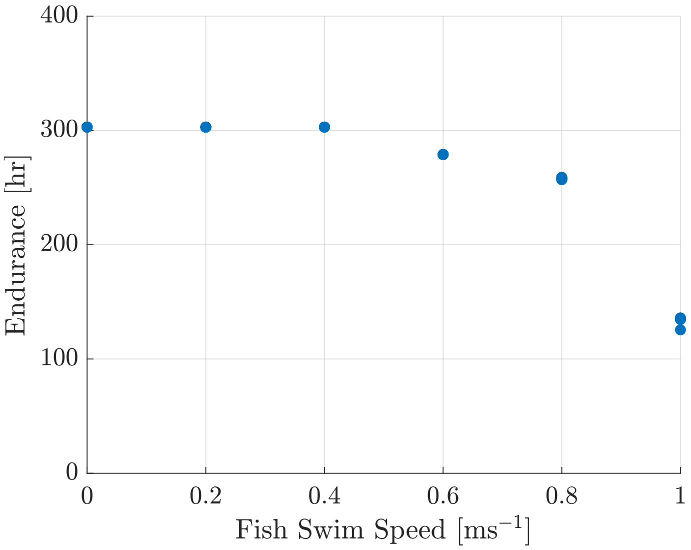

FIGURE 8: SYSTEM ENDURANCE (I.E. TIME BEFORE RUNNING OUT OF ENERGY OR FOOD) VERSUS THE DESIRED FISH SWIM SPEED.

Finally, Figures 9 and 10 show the temperature variation experienced by the fish during the simulation. Comparing the same month (i.e. season), shows that the target location, either P2 or P3, has limited impact on the experienced temperature. Though not shown here, similar behavior is seen for varying optimal swim speeds, with the temperature experienced by the fish governed by the season more than anything else.

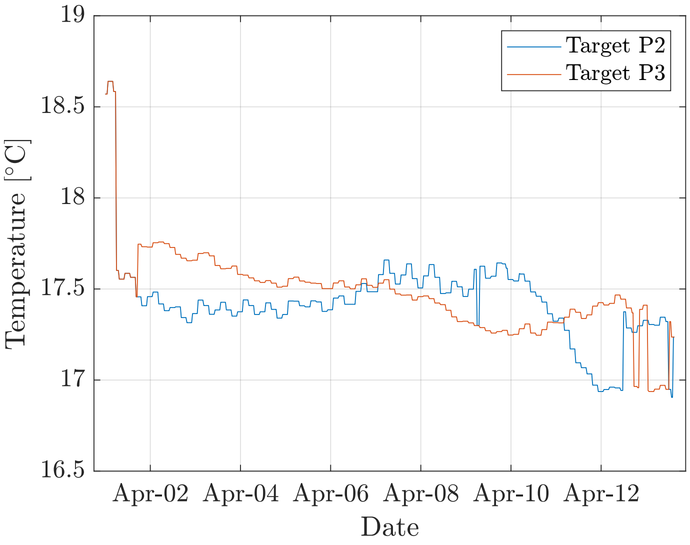

FIGURE 9: TEMPERATURE VARIATION FOR ENCLOSURE IN APRIL 2000 FOR TARGET LOCATIONS P2 AND P3 AND AN OPTIMAL SWIM SPEED OF 0.6 m s^{-1}.

5. DISCUSSION

The presented results have shown that a receding-horizon based management strategy is viable for a mobile aquaculture

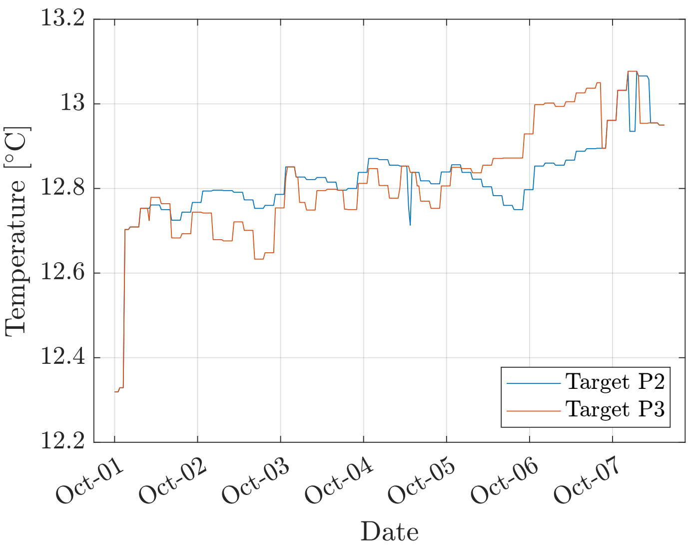

FIGURE 10: TEMPERATURE VARIATION FOR ENCLOSURE IN OCTOBER 2000 FOR TARGET LOCATIONS P2 AND P3 AND AN OPTIMAL SWIM SPEED OF 1.0 m s^{-1}.

TABLE 3: TEMPERATURE RANGE FOR TARGET LOCATION P2

		Swim Speed [m s^{-1}]					
		0.0	**0.2**	**0.4**	**0.6**	**0.8**	**1.0**
Jan.	**Min [° C]**	18.2	17.1	17.1	17.1	17.1	17.1
	Max [° C]	20.0	19.0	18.8	18.8	18.8	18.6
Apr.	**Min [° C]**	17.2	16.9	16.9	16.9	16.9	17.3
	Max [° C]	18.7	16.9	16.9	16.9	16.9	17.3
Jul.	**Min [° C]**	11.6	11.6	11.6	11.6	11.7	11.8
	Max [° C]	12.7	12.8	12.8	12.8	12.8	12.8
Oct.	**Min [° C]**	12.3	12.3	12.3	12.3	12.3	12.3
	Max [° C]	13.3	13.3	13.3	13.3	13.3	13.1

TABLE 4: TEMPERATURE RANGE FOR TARGET LOCATION P3

		Swim Speed [m s^{-1}]					
		0.0	**0.2**	**0.4**	**0.6**	**0.8**	**1.0**
Jan.	**Min [° C]**	18.2	17.1	17.1	17.1	17.1	17.1
	Max [° C]	20.0	19.0	18.8	18.8	18.8	18.6
Apr.	**Min [° C]**	17.2	16.9	16.9	16.9	16.9	17.3
	Max [° C]	18.7	16.9	16.9	16.9	16.9	17.3
Jul.	**Min [° C]**	11.6	11.6	11.6	11.6	11.7	11.8
	Max [° C]	12.7	12.8	12.8	12.8	12.8	12.8
Oct.	**Min [° C]**	12.3	12.3	12.3	12.3	12.3	12.3
	Max [° C]	13.3	13.3	13.3	13.3	13.3	13.1

system. In the present work we have shown that through the implementation of this strategy, optimal swim speeds for the fish can be achieved while allowing the system to roam. This capacity to roam presents a significant benefit to fish by maintaining optimal swim speeds throughout system operation, unlike fish culture in moored structures which typically only experience variable and uncontrolled flow conditions dictated by oceanic (or coastal) currents. The results also show that through the consideration of weather forecasts in the receding-horizon, the system is able to plan around changing weather, and shelter when needed. Comparing the results for an April deployment between the two target locations P2 and P3 (Figures 4 and 5 shows that some adverse weather event (high H_s) at P2 caused the system to head towards P1 prior to running out of food or energy, and then once the weather cleared, return out to P2. This behavior is not seen for the P3 case (Figure 5) showing that this weather event was localized to P2 and it is vital to include accurate, high-resolution weather data.

In the results presented, we have considered the swim speed and location as the key criteria in this management strategy, however, the receding-horizon strategy is equally applicable to any other parameter that may be of interest, given accurate means of forecasting the parameter. Future versions of this tool will therefore consider including the temperature and water quality as explicit objectives, allowing the system to select routes to optimize the conditions for the fish. Furthermore, factors such as optimal temperature, optimal swim speed, and food consumption all vary with age, species, season, and body length. Future versions of the strategy will therefore consider these for specific species as time and environment-dependent factors, allowing the system to dynamically adapt in an optimized manner to encourage fish growth. The final system aims to include a control system enabling adjustment of the fish enclosure's deployed depth. This would allow even greater flexibility to access more suitable temperatures for the fish. It would also add control over loads on the tether between the vessel and the enclosure, or relative motion between the ASV and the enclosure in response to metocean conditions, which govern the survival limits of the system.

As presented in Figures 9 and 10, for the site in Tasman Bay, the temperature experienced by the enclosure is principally governed by the season rather than by the target swim speed or the target location. Tables 3 and 4 show the minimum and maximum temperatures for the two target locations for each season and swim speed, highlighting, that there is little variation the sites for a particular season with at most 2 °C difference between the minimia and maxima. If, therefore, temperature is a key parameter, it is important to ensure that the system has a wide enough area to explore that will have sufficient thermal variation that it can find the necessary temperatures. Alternatively, future studies may wish to explore the impacts to the fish and ultimately the yields if the system deviates from the ideal temperatures.

6. CONCLUSION

In this paper, we have presented a vessel management strategy for mobile aquaculture systems, towed by an ASV. By integrating a receding-horizon, this management strategy is able to maintain optimal operational parameters, while planning its route, avoiding adverse weather, and ensuring that it returns to the sheltered, resupply, point before exhausting its food or fuel reserves. These initial results for a generalized salmonid have shown that the system can effectively plan its routes and maintain the desired swim speed conditions across the year. Monitoring the temperature, has highlighted that further constraints may need to be included to ensure that ideal temperatures are also maintained for the fish. Future work will extend this methodology to alternate sites, enabling site suitability for such a mobile aquaculture system to be compared and will also consider further parameters that can be optimized as part of the route planning process.

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