Multi-vessel Sea State Estimation Utilising Swarm Shepherding

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ABSTRACT

Sea State Estimation (SSE) remains critical to maritime operations worldwide. Presently, data on sea states is primarily collected by moored wave buoys in a relatively limited number of locations. Recently, research into the use of Uninhabited Surface Vessels (USVs), acting as an on-site wave buoy, has emerged. By measuring the response of the USV to wave motions and implementing a wave buoy analogy model, directional wave properties can be estimated.

This study investigates the benefits of utilising an intelligent swarm of USVs (greater than two), with each member acting as a wave buoy, to estimate an aggregated sea state in real-time. Swarm intelligence can be defined as an interaction between relatively simple agents leading to the emergence of complex behaviours. It is hypothesised that a USV swarm can collaborate to enhance sea state characterisation. The challenge of swarm guidance is addressed by introducing a shepherd which guides the swarm of USVs with the intent of achieving the desired objective estimation. This method of control mimics the way a sheepdog is able to herd sheep to a target destination.

A heuristic is presented which describes how a series of influential force vectors can generate swarm behaviours with the aid of a shepherd, and be used to distribute a network for the purpose of estimating the properties of a complex sea environment.

The ability to estimate wave properties, with a higher degree of confidence, in-situ in any geographic region would allow maritime vessels to enhance operability, improve safety, and extend service life.

1 INTRODUCTION

The effectiveness, efficiency, and safety of global maritime operations are reliant on having accurate knowledge of the prevailing sea states which affect marine platforms. Wave conditions have a direct impact on a vessel's fuel efficiency [1], crew safety, security and comfort [2], and cause damage to marine structures due to wave-induced loads [3]. Ship-to-ship, ship-to-coast, and ship-to-infrastructure interactions, in particular, require certain levels of sustained quiescence to avoid potentially catastrophic impacts. Additionally, with advances in automated control for maritime vehicles, it becomes vital for autonomous navigation systems to take into account ocean states to restrict the pitching and rolling motion of vessels, an acquired skill developed by experienced human pilots, for effective operation. Regions containing complex wave spectrum pose a particularly difficult problem for maritime navigation, especially those found along the coast or around ocean-based infrastructure. Examples of industries which could be affected by unknown rough sea states include cargo transportation, fishing, defence, oil and gas exploration and drilling, and offshore wind farming.

While numerous SSE techniques exist, such as the use of wave buoys [4], ship-based wave radar [5], and satellite altimetry [6], each encounter significant challenges as they rely on ad-hoc non-coordinated measurement or sensor distribution. Errors, uncertainties, and the lack of a clear approach to covering a range of local and regional sea spaces afflict current techniques. Therefore, a novel method for a dynamic, collaborative, and self-organising SSE mechanism would fundamentally augment the maritime industry's operational capabilities by permitting enhanced real-time, in-situ wave property data, especially for complex wave system identification.

To solve the problem of realising an in-situ, real-time comprehensive knowledge base of wave properties in complex environments, a network of SSE agents is proposed. The intricacies of sea states around coasts and ocean-based infrastructure elicits a cooperative approach which would permit an aggregated wave property distribution to be formed.

In order to distribute the network, a swarm (here defined as more than two agents) of self-propelling SSE devices offer a solution. Researchers have recently developed an SSE technique which utilises the ship as a wave buoy analogy; the motion of the ship itself is used to estimate the wave properties via a transfer function. Therefore, employing a swarm USVs, each utilising the wave buoy analogy, would enable the creation of a dynamic network of agile SSE devices.

However, a cooperative approach has its own costs. Cooperation could create severe demands on communication and complexities associated with multi-party negotiation. The latter could require high computational resources that are not expected to exist on a wave buoy. To scale the system, a level of centralisation of command is unavoidable, whereby airborne or surface parent vessels with sufficient computational powers could govern the low-cost distributed sensor network.

Therefore, the challenge of swarm guidance can be addressed by introducing a shepherd which can be used to effectively oversee and organise the network of sea state estimating agents. Shepherding guidance is a bio-inspired swarm control method derived from the behaviour exhibited by sheepdogs when herding sheep. Shepherding is suited to the problem due to its control technique being reliant on a simple library of primitive behaviours that collectively could generate complex guidance patterns. In its biological form, shepherding relies on its evolution based on collecting and driving a herd of agents (in nature, sheep) to an objective location, as well as introducing a simple distributed swarm control mechanism that can be implemented autonomously, in real-time, react to a dynamic environment, and permit effective agent self-organisation.

It is further proposed to use an Uninhabited Aerial Vehicle (UAV) as the shepherd to guide the swarm of USVs in order to obtain a combined SSE of a selected area. Benefits of utilising a UAV, alongside the USVs, include that situational awareness of the desired region can be maintained, communication with swarm members can be sustained, and it also enables the shepherd to fly over the top of obstacles throughout the SSE task. Figure 1 shows an example illustration of the UAV shepherd flying above obstacles in an ocean wave environment, while monitoring and guiding the USV swarm. Such a UAV does not necessarily need to be a low-flying platform as this is problematic in environments with harsh weather conditions. Moreover, the concept is extendible to a surface vessel acting as the sheepdog in place of the UAV.

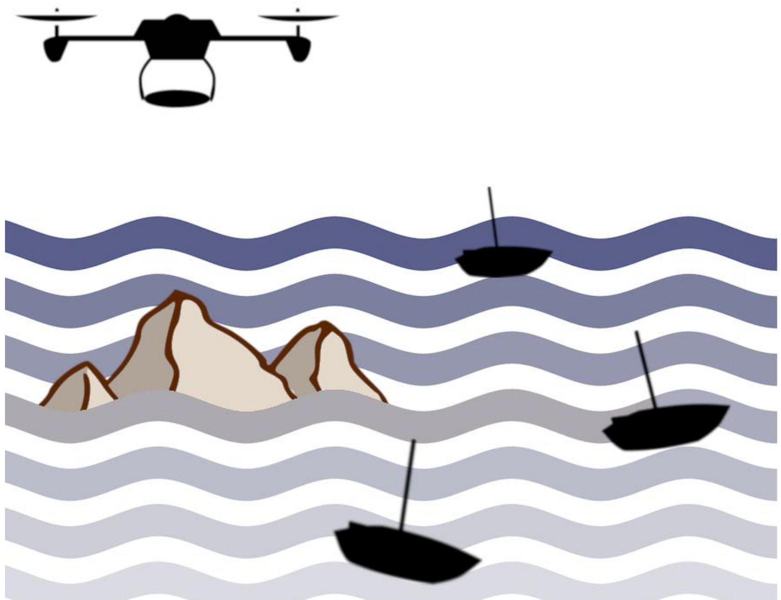

Figure 1 Illustration of a UAV shepherd guiding a swarm of USV agents on the ocean, while flying over an obstacle in the environment.

We hypothesise that a coordinated, distributed network of SSE devices could better capture complex wave system properties than any single- or multi-vessel non-coordinated SSE setup. This study gives a description of how the multi-vessel SSE concept of operation can be effectively carried out by employing a swarm shepherding heuristic.

The background literature contributing to this research problem definition is given in Section 2, followed by a description of the research gap and an outline of the SSE procedure in Section 3. Section 4 presents the design of the heuristic, and envisioned future research and the outcome if successfully implemented is explored in Section 5.

2 BACKGROUND RESEARCH

2.1 Sea State Estimation

SSE is a problem concerned with the estimation of wave properties such as wave height, frequency, and direction. Numerous methods for SSE are already being employed globally to improve maritime operations, aid in weather forecasting, for the study of oceanography, and to help understand coastal degradation. Popular techniques include the use of wave buoys, ship-based radar, satellite remote sensing and Global Navigation Satellite System (GNSS) geodesy, and an emerging method based on the ship as a wave buoy analogy.

The most common method of taking sea state measurements is via wave buoys; floating sensor-mounted platforms which are primarily located along continental margins [7]. Although wave buoys are useful for monitoring global sea conditions, they are few and far apart, and contain no means of locomotion, thus making them impractical for dynamic in-situ operations. Ship based radar systems solve this problem by allowing measurements to be taken during ocean transit, however, the radar requires frequent calibration, and often requires computationally heavy algorithms to interpret the radar data [8].

Another category of SSE methods employs the use of satellites to remotely detect sea surface properties, with two sub-branches being satellite altimetry (e.g. [6]) and GNSS geodesy (e.g. [4]). Satellite altimetry encompasses the procedures which involve measuring the time taken for a radar pulse, transmitted from a satellite, to reflect from the sea surface and travel back to the satellite or a separate receiver. The spatial resolution of satellite altimetry, however, is generally quite crude (on the order of 10-100km), as well as having coarse temporal resolutions [9]. GNSS geodesy uses the triangulation between a GNSS receiver at the ocean surface and global navigation satellites, however, requires a GNSS reference station for calibration, or an abundance of information with respect to the geoid and tides [10].

The use of the ship as a wave buoy analogy, whereby ship motions are passed into a transfer function able to estimate the causal wave properties, is a method for SSE which shows promise due to its adaptability to autonomous systems and flexibility in application. If wave conditions are assumed to be moderate, then the 6-degree-of-freedom motion of a ship, and resulting loads imparted on the hull can be described by an approximately linear relationship with respect to the causal incident waves [11]. This relationship can be elaborated to consider wave systems with multiple wave directions and properties. Using this information, a ship-specific transfer function can be formulated which takes into account ship characteristics such as form and loading condition.

While most of the work focussed on the ship as a wave buoy method has centred around wave analysis in the frequency domain, for real-time SSE to be made in-situ and on-demand, solving SSE in the time domain remains more viable as it only requires current vessel motion measurements (the frequency domain solution requires previous response history) [11]. Different approaches to estimating sea states in the time domain have been undertaken. Pascoal and Soares [12] developed a Kalman filtering-based algorithm for SSE, while Nielsen et al. [13] created a stepwise procedure for obtaining sea state information in the time-domain. This paper assumes that the SSE technique is refined enough to obtain sufficient sea state estimates and, rather, focusses on the USV swarm control and distribution framework. For more information on SSE methods, please refer to a survey written by Nielsen [11] on SSE techniques using the ship as a wave buoy analogy.

A further study by Nielsen et al. [14] is the only one to date to utilise multiple vessels for SSE. The authors mention the use of a network of SSE platforms to improve SSE performance; however, they focus on the use of multiple ships for the wave buoy analogy in their study. Nielsen et al. considered the SSE task to be performed by ships already at sea completing different operations, and as a result, cannot be dynamically employed for localised estimations. Simulations involving three different types of ship encountering a temporally fixed wave system were run (see Figure 2), where the SSE of each ship was weighted based on its dimensions and geometry, then combined. Overall, the weighted aggregate estimates performed better than the non-weighted or single vessel weighted estimates. The study, thus, supports the notion that multiple vessels can be used to improve upon in-situ SSE while at sea.

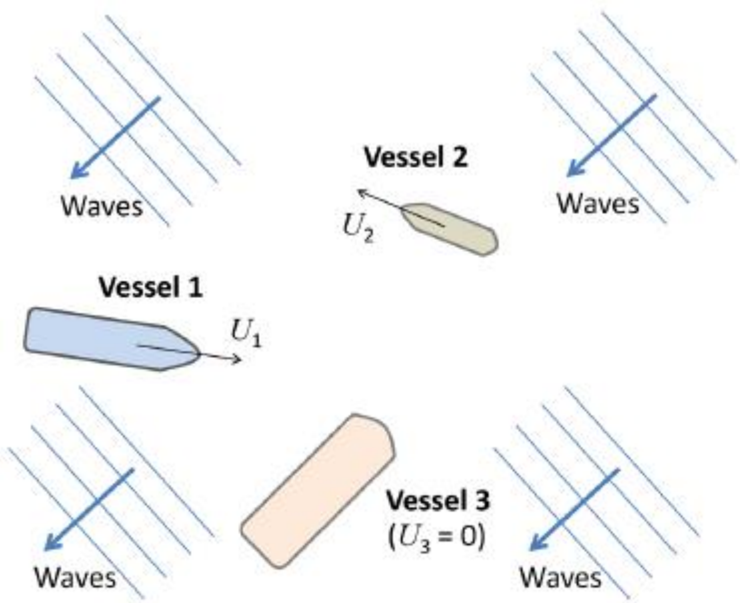

Figure 2 Multi-vessel SSE operational setup by Nielsen et al. [14]. Reprinted from Applied Ocean Research, Vol 83, U. D. Nielsen, A. H. Brodtkorb, and A. J. Sørensen, Sea state estimation using multiple ships simultaneously as sailing wave buoys, Page 71, Copyright (2019), with permission from Elsevier.

2.2 Swarm Shepherding

Swarm intelligence arises when a series of local interactions between a group of relatively simple individuals exhibit complex nonlinear behaviour at the global level. The intelligence of a swarm is normally defined as an emergent property; it manifests without any external control or regulation [15]. The benefits of a swarm intelligence system, such as in a swarm robotics system (in this case, the robots are USVs), include that each agent is simple to create and program, the system is highly robust as the failure of one agent does not necessarily lead to the failure of the system. The unit cost of each agent is relatively cheap to allow the system to be scalable, and permit a high degree of flexibility to the system.

Reynolds [16] introduced one of the first swarm control frameworks in 1987 for the purpose of controlling a flock of simulated birds. Reynolds developed an advanced particle system model which represented each bird agent as a boid; an object which has coordinate and orientation attributes. The boids’ motion was then dictated by several behaviours: collision avoidance, velocity matching, and flock centering. Collision avoidance is needed so that flock members do not collide with each other while swarming, as well as to navigate around obstacles. Velocity matching was used to keep the flock of bird agents moving in unison, and flock centring stopped the birds from scattering apart. These behaviours were enacted using a series of acceleration vectors.

A swarm control technique, known as swarm shepherding, was later developed based on the sheep herding method learnt by sheepdogs. Strömbom et al. [17] created a heuristic which mimics the approach taken by a sheepdog when herding sheep to a target destination. Two main herding actions are defined: driving and collecting. Driving is done when the sheep herd is dense enough, where the sheepdog positions itself behind the sheep to guide them in the opposite direction. Collection is undertaken when a sheep strays too far from the centre of mass of the herd. Strömbom et al. implement Reynolds’ boid model in their study, where each herd agent is defined as a boid, and manoeuvred by behaviours which are enacted via force vectors. Three behaviours are described for sheep herding: shepherd-to-sheep repulsion, sheep-to-sheep repulsion, and sheep attraction to the local centre of mass. The results of a series of simulations showed that the simulated shepherd and sheep motion was similar to that of the real-life herding task.

Shepherding, as a swarm control technique, has been expanded beyond the sheep herding task. Gee and Abbass [18] define shepherding as “externally influencing a swarm or a group of agents to guide them towards the Shepherd’s goal”. More abstract swarm control problems have, thus, emerged which take advantage of swarm shepherding. Chaimowicz and Kumar [19] ran a number of experiments involving a swarm of Uninhabited Ground Vehicles (UGVs) which explored an unknown urban terrain. In order to control the swarm, multiple UAVs were employed as ‘aerial shepherds’, such that both aerial and ground views (taken from vehicle-mounted cameras) could be combined to create a more comprehensive image of the environment. Two main behaviours were used: merging and splitting. Splitting involved a larger group of UGVs splitting into smaller sub-groups, and merging was the converse, where sub-groups merged into a larger group. Each group or sub-group was designated its own aerial shepherd which controlled the splitting and merging behaviours, which allowed for more robust navigation of the environment.

Clayton and Abbass [20], however, discuss how methodologies attempting to describe shepherding tasks (such as that of Strömbom et al. [17] and Chaimowicz and Kumar [19]) oversimplify the complex shepherd-swarm interactions, and are unable to be applied to general herding problems. Therefore, the application of shepherding to the SSE problem in a complex environment requires a new heuristic to be developed for that purpose.

3 HEURISTIC DESIGN

A boid representation of the swarm agents, as developed by Reynolds [16] and used by Strömbom et al. [17], is proposed for this study to define the USV swarm agents. Each USV will be represented as an object with three-dimensional coordinates and an orientation. The USV boids will react to four main behaviours: shepherd-to-swarm-agent repulsion, swarm-agent-to-swarm-agent repulsion, obstacle repulsion, and target location attraction. The relative location and status of each swarm member dictates what actions are taken at each time step. Each behaviour is enacted via a force vector which is activated if a swarm member falls within a radius of influence surrounding the shepherd, other swarm agents, obstacles, or the SSE target locations. Figure 3 shows an example of the shepherd and swarm agents interacting within an environment. The radii of influence (here, repulsion radii) are represented by the circular shadows surrounding the shepherd and swarm agents. This example gives a simplified approximation of the interactions between the shepherd and swarm agents. In the real case, the radii of influence will extend much further from each agent, and the agents will not remain stationary across time steps.

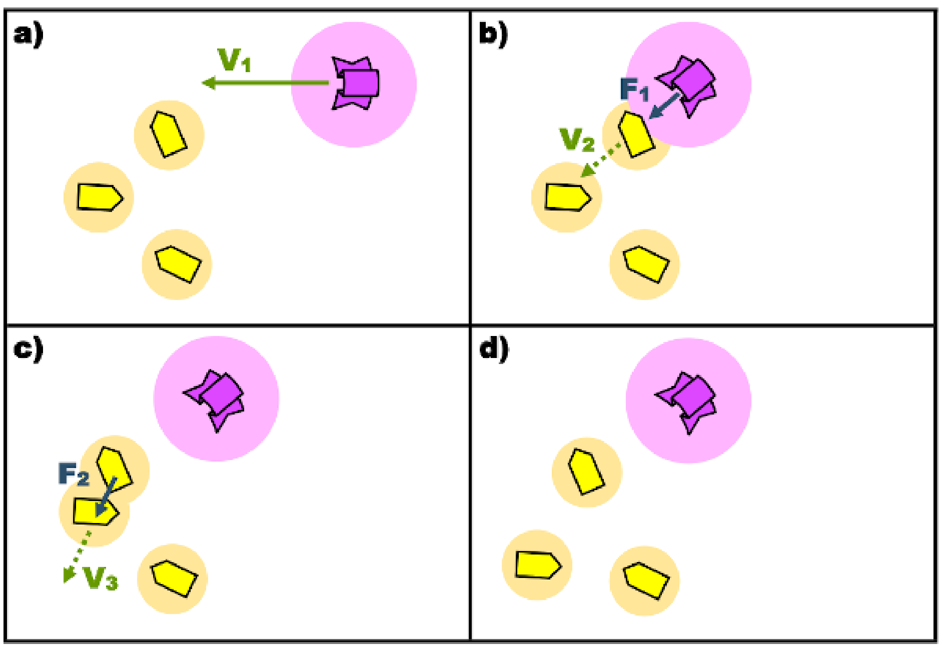

Figure 1 Repulsion radii between shepherd (pink) and swarm agents (yellow) are shown. **a)** Shepherd moves with initial velocity V_1. **b)** Swarm agent within repulsion radius of shepherd so force F_1 imparted on it, then agent moves away with velocity V_2. **c)** Swarm agent within swarm agent repulsion radius so force F_2 imparted on it, then it moves away with velocity V_3. **d)** Final position of agents.

Multiple target destinations replace the single target destination of the normal dog herding sheep exercise. Further, as opposed to an entire herd being guided to a common destination, the multiple targets in the environment require only one swarm member to reach them.

To begin the SSE task, an image of the environment is taken by a UAV, and locations for an initial measurement of wave properties are selected by a human operator. Figure 4a shows an example of an image as would be taken by the UAV, as well as the initial goal destinations to commence building a map of the wave system. The swarm of SSE agents are then deployed into the environment. In this case, the environment is the waters surrounding an island, where a ship may wish to dock during rough seas, thus, requires an SSE to ensure it is safe to proceed.

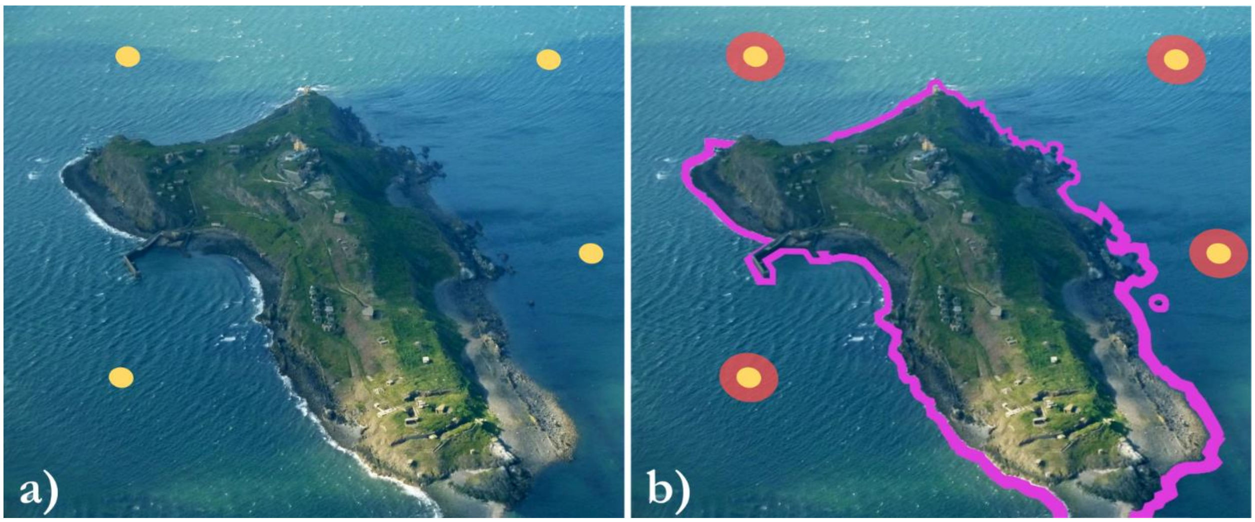

Figure 2 **a)** Initial SSE target locations (yellow dots) in an example environment. **b)** Target location attraction radii (orange shadows) and obstacle repulsion radii (pink shadow). The image has been modified from a picture taken by Gyula Péter, available on Wikipedia Commons [21].

In order to ensure that a swarm member reaches a target destination, the attractive force vector is introduced, radiating out from the goal locations (seen as the orange shadows surrounding the goal locations in 4b). Obstacles within the environment are avoided by repulsing any agent which falls within their own radii of influence (as seen in red in the example given in Figure 4b, where the coastline and rocks are obstacles present, assuming that the sea is sufficiently deep across the environment).

The USV swarm will move throughout the environment, being repulsed by other agents, attracted by the target locations, repulsed from the obstacles, and guided by the repulsive force of the UAV shepherd. A “random walk” term will be incorporated to stimulate interactions between the agents and the environment, and to help to reduce the chance of a swarm member becoming stuck.

Once any single agent reaches a target destination, *all agents stop* (after force reactions are complete) and each makes an SSE. The SSE of adjacent agents are compared, and if a discrepancy tolerance is reached (for wave properties: height, direction, or frequency), then a new target destination will be generated between the neighbouring swarm agents. The SSE task then continues, new target positions radiate out a new attractive force and, once a swarm agent is ensnared, a new estimate can be taken to validate or improve upon the previous estimates. This process continues until all target locations have been reached and smooth transitions between adjacent SSEs exist, or until a time limit is reached.

The simplicity of each swarm agent is evident in the fact that they do not have any information about their objective, only the shepherd 'knows' their objective The shepherd's purpose is to coordinate the swarm, improve the efficiency of the SSE task, and to enable cooperative swarm behaviour without the need for communication between swarm agents. The shepherd is able to sense each swarm agent's location and orientation and, thus, able to infer which forces are being activated at each time step. When a critical situation arises, the shepherd acts as a referee. An example of this is if two agents are at the same distance from a target location and within its radius of influence. In this case, the shepherd will move to disperse one of the agents away from the goal or push one into it. Further, if agents reach a local solution, then the shepherd will scatter agents across the environment to ensure a global solution is attained.

Variables in the SSE task include how much time is allocated for making an SSE, how much time is required to create a complete SSE map of a given environment, how many swarm agents are needed to attain the SSE, and which force and velocity magnitudes produce the best results.

4 CONCLUSION

A multi-vessel SSE heuristic utilising swarm shepherding has been described in the preceding section. The heuristic framework expands on the multi-vessel SSE described by Nielsen et al. [14] by introducing a coordinated swarm of self-propelling SSE devices which could be better implemented during dynamic operations for complex wave property measurement. Using the ship as a wave buoy analogy for SSE, a network of USVs would support the effort to create a controllable, aggregated sea state map for enhanced situational awareness. Addressing the control of the USV swarm, shepherding shows promise when it comes to a simple and autonomous solution. Chaimowicz and Kumar [19] give an analogy to the way in which shepherding could distribute the USV network around land masses and ocean-based structures. The heuristic describes a boid-based swarm agent system, governed by several behaviours, which can act as a basis for a distributed SSE under the guidance of the shepherd, and the procedures required to achieve the SSE task are defined.

An initial two-dimensional simulation of a shepherd guiding swarm agents to goal locations within an environment is under development, with results expected to be published in the near-future. Further experiments will then elaborate upon these, incorporating full three-dimensional wave system simulations and USV geometries. Should our hypothesis be proven true, then the safety, reliability, and effectiveness of maritime operations can be improved by obtaining in-situ, real-time knowledge of the prevailing sea state in order to evaluate how to best navigate the oncoming marine environment. Moreover, the viability of shepherding as a swarm control technique can be further substantiated or discredited.

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