A Mine Countermeasure System with Low-Cost AUV Swarms

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ABSTRACT

The use of Autonomous Underwater Vehicles (AUVs) could provide a significant help to create fully automated and unmanned mine countermeasure (MCM) systems, with a significant reduction of risks for ships and their crew [7]. In this work, we present the design of an AUV swarm formation performing MCM operations, composed of a leader node equipped with all the expensive equipment needed to perform advanced tasks, and 2 to 4 follower nodes equipped with low-cost devices to perform mine detection and disposal tasks. All AUVs in the formation are equipped with low-cost acoustic modems to coordinate the mission. The followers track the mines, while the leader decides the formation path sending the next waypoint to each follower and, when a mine is detected it elects one of the followers for the mine disposal task. This hybrid formation both reduces the deployment cost and avoid loss of expensive equipment if something goes wrong. We simulate this MCM scenario with the DESERT Underwater framework [1], in order to investigate its feasibility and evaluate the system performance in terms of probability of finding and neutralizing all the mines in a given area by observing the mission time and the power consumption obtained by following three different trajectories to scan the same area. We observe the performance of a formation composed by 3 and 5 AUVs. While the former requires a smaller number of AUVs, hence, a lower cost of deployment, the latter provides a better trade-off between mission time, power consumption and mine detection probability.

CCS CONCEPTS

• **Networks** → **Network simulations**; **Network performance analysis**; **Peer-to-peer protocols**.

KEYWORDS

AUVs, underwater acoustic networks, DESERT Underwater, underwater communications

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1 INTRODUCTION

The use of low-cost Autonomous Underwater Vehicle (AUV) [5] swarms is a topic of large interest nowadays, since their missions can cover a large set of applications [10], such as coastal monitoring, surveillance, and mine countermeasure (MCM) missions. Typical AUVs used in these scenarios are equipped with expensive acoustic modems, navigation, positioning and sensory systems: the overall cost of a fully equipped large AUV can easily exceed 1 million Euros. While this type of AUV can perform very complex tasks, including image processing and machine learning-related activities, deploying a swarm of these expensive AUVs becomes prohibitive. Fortunately, the recent availability of low-cost AUVs [4], acoustic modems and positioning systems [3], makes an AUV swarm deployment more practical and cost-effective.

A typical MCM task consists of four stages: detection, classification, identification and disposal [7]. Detection consists of finding targets from different signals (either acoustic or magnetic), while classification is needed to determine whether or not the target is a mine-like object. Identification uses additional information (e.g., using a camera) to validate classification results. Finally, disposal consists of neutralizing the identified mine. AUVs can perform these tasks in a rather efficient way at zero risk to human life. Neutralization, however, may require to sacrifice a vehicle in some circumstances, hence the AUVs performing the neutralization task have to be significantly low-cost (ideally, with a price of about 30'000 EUR or less, all equipment included). In contrast, AUV navigation systems are usually very expensive, and so are multibeam [9] , forward-looking [6], and side-scan [12] sonars used for sub-sea mapping. For this reason, in our scenario (presented in Fig. 1) we envision to equip only one of the AUVs of the formation (the leader, depicted in green) with the complete navigation system, while the other nodes (followers, depicted in blue) use only low cost equipment [3]. Follower AUVs are small low-cost vehicles [8], that can perform only basic positioning and tracking tasks, using low-cost Doppler Velocity Loggers, low-cost modems [14] and low-cost scanning imaging sonars.

In this paper, we investigate the feasibility of a complete automated MCM process, analyzing the behavior of an AUV swarm patrolling the seabed in search of mines. We assume the identification and neutralization phases to happen in a fixed time of 250 seconds. The leader is the only AUV aware of the mission path, that for the purposes of this work is preloaded in advance as a sequence of positions (waypoints). Moreover, the leader is responsible for deciding and sending new destination waypoints to the followers: a waypoint can either be the next position of the path followed by the formation, or a spot where a mine has been detected by one of the followers. We analyze the system performance when the swarm follows three different path: i) a deterministic sinusoidal path, ii) a deterministic path which covers the whole patrolling area, iii) a stochastic uniformly distributed random path.

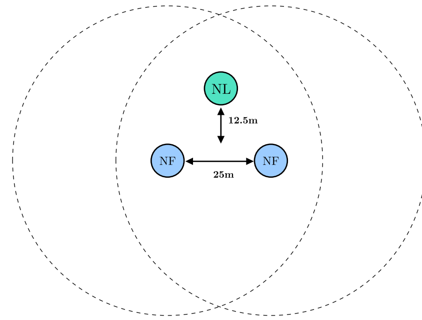
As shown in [13], there are several optimal strategies and metrics to attain the performances of an AUV swarm performing MCM operations. Similarly, in this paper we compare the swarm performances in the three paths by analyzing the probability of detecting and neutralizing all the mines in the patrolling area and the time it takes to complete the mission with a given probability interval. We consider both swarms composed by 3 and 5 AUVs, comparing the results obtained with these two solutions.

The rest of this paper is organized as follows: Sec. 2 describes the swarm formation and the proposed paths, Sec. 3 presents the simulation modules we used to study the system performance, while Sec. 4 discusses the simulation settings and the results. Finally, Sec. 5 concludes the paper.

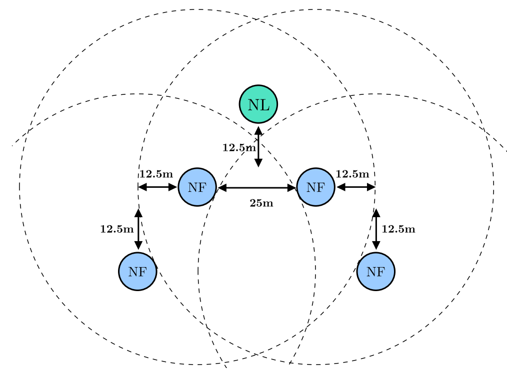
2 SCENARIO

We propose two MCM solutions, the former, named `formation1` composed of a swarm with 3 AUVs (Fig. 1a), while the latter, named `formation2`, is composed of a swarm with 5 AUVs (Fig. 1b). The choice of the number of AUVs is made to ensure symmetrical coverage of the patrolling area by the swarm. Both swarms move in an arrowhead formation with a speed of 1 m/s, where the leader (NL, in the figures) is located at the vertex of the arrow. Follower nodes (NF, in the figures) receive information about the next destination from the leader who has the complete knowledge of the path. The leader has a significantly lower probability of failure compared to the followers as it is a more sophisticated device. In the event of a failure, recovery operations will be required, e.g., with all AUVs resurfacing and sending ping signals to the main ship. The destination can be the next waypoint of the preloaded path or a position where a mine has been detected. On the other hand, every time a follower node detects a mine, it informs the leader node which in turn decides whether or not the follower has to go in place and identify/dispose the mine. In order to reduce the cost of AUV followers, they are equipped with a scanning mechanical imagining sonar (e.g., the Ping 360 [15]), which can scan a circular area of radius 50 m in 6.7 s. With such a slow scanning time, to detect the mines with a high probability we decided to place the AUVs in such a way they have a partial overlap in the scanning area, with the followers located 12.5 m behind the leader and 25 m apart from each other. In addition to imaging sonar, we equip both the leader and the followers with a low-cost acoustic modem (e.g., the ahoi modem) so they can communicate with each other. Specifically, we enable only communication between leader and followers.

We evaluate the performance of our system in three different paths, with 100 waypoints each. The first path (`path1`), depicted in Fig. 2a, emulates the motion of an AUV swarm on a 3D sinusoidal path, along the x axis from -100 m to 100 m. The second path (`path2`), represented in Fig. 2b, enables the AUV swarm to cover the entire patrolling area while moving along the x axis from -100 m to 100 m. The third path (`path3`) is represented in Fig. 2c and is composed of uniformly distributed random waypoints inside the patrolling area, which in all the above cases is a volume of 200×40×4 m^3. For the purpose of this paper, we consider the mines as uniformly distributed in the patrolling area.

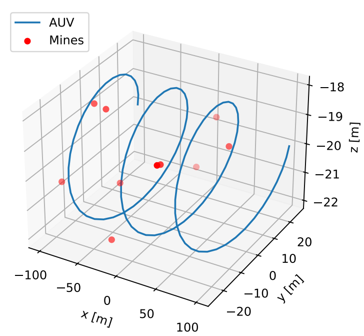


(a) `formation1`: swarm with 3 AUVs.

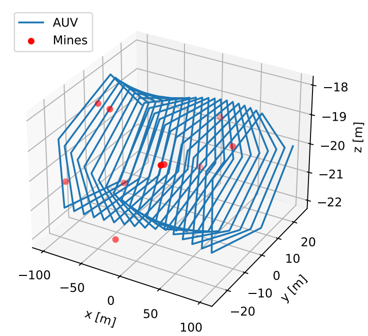


(b) `formation2`: swarm with 5 AUVs.

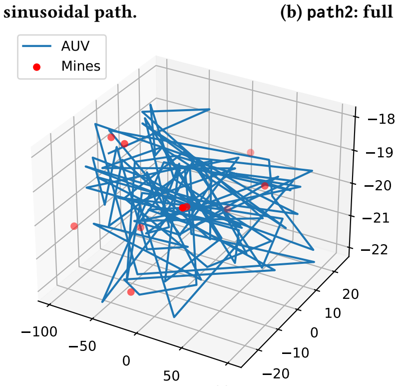
Figure 1: Swarm formations.



(a) `path1`: sinusoidal path.



(b) `path2`: full coverage path.



(c) `path3`: uniformly distributed random path.

Figure 2: Swarm paths.

3 PROTOCOL STACK

In this paper, we simulate the AUV MCM swarm mission with the DESERT Underwater network simulator and experimentation tool [1]. For the purpose of this paper, we focus on the application layers of the protocol stacks implemented in the leader node and follower nodes. The application layer of the leader AUV is composed by three modules, namely *UwMissionCoordinator*, *UwSCROVCtr*, and *UwSCTracker*. These modules are described as follows.

- *UwMissionCoordinator* is responsible of monitoring and coordinating the follower nodes: it does not generate packets itself, but communicates with *UwSCROVCtr* and *UwSCTracker* modules via cross layer messages. Specifically, it receives the updated position of the follower nodes from the *UwSCROVCtr* module, and receives notifications from the *UwSCTracker* whenever a mine is tracked or removed. It further checks whether the mine has to be identified and disposed and issues *UwSCROVCtr* to send the new destination to one of the follower nodes.
- *UwSCROVCtr* is used to control and monitor the position of a follower node; the leader AUV has one instance of this application for each follower in the swarm. This module receives two types of messages from the *UwMissionCoordinator* module. The first type contains the new destination of the associated follower, which is then forwarded to the *UwROV* application of the follower in a packet of 32 B. The second type of message contains the status of the follower, which can be busy if it is detecting a mine or idle otherwise.
- *UwSCTracker*: the leader AUV has one instance of this application for each follower in the swarm. This module is used to monitor the tracking information; it receives the tracking position inside packets sent from the associated follower node and forwards it to the *UwMissionCoordinator* using cross layer messages. It may also receive packets containing the status of the follower, which is in turn forwarded to the *UwMissionCoordinator*.

The application layer of the followers is composed of two modules, namely *UwROV* and *UwSCFTracker*, described as follows.

- *UwROV*: is used to send the follower AUV's current position to the leader AUV. Every 60 s it sends the follower's current position and speed to the leader's corresponding *UwSCROVCtr* application, inside packets of 32 B.
- *UwSCFTracker*: sends every 60 s a packet of 32 B to the corresponding UwSCTracker application of the leader node whenever a mine is in the node tracking range. Furthermore, it has a timer of 250 s which starts when the node is identifying and disposing a mine. After the timer has expired, we assume the mine has been neutralized.

Both stacks also include *UwUDP*, *UwCSMAAloha* and *UwAHOIPhy* layers. *UwUDP* is a transport layer module responsible of forwarding packets to the right application. *UwCSMAAloha* and *UwAHOIPhy* are, respectively, a simple MAC layer module with a behavior similar to Aloha, and the physical layer module that simulates the behavior of the ahoi modem [2], mapping, in form of lookup-tables (LUTs), the performance figures of the modem in terms of packet delivery ratio vs distance and packet size, and packet delivery ratio vs signal to interference ratio measured in real scenarios. The maximum communication range of this modem depends on the environmental conditions: the LUTs used for our simulations have a packet delivery ratio higher than 50% for a range of less than 150 m. In order to mitigate the effects of packet loss, *UwCSMAAloha* was configured to use acknowledgements and allow up to two retransmissions.

4 SIMULATION RESULTS

In this section we present the simulation results, first introducing the simulation parameters and settings (Sec. 4.1) and then discussing the feasibility of the proposed scenario in light of the system performance (Sec. 4.2).

4.1 Simulation Settings

Table 1: Underwater network settings

Parameter	Value
Carrier frequency	65.2 kHz
Bandwidth	25 kHz
Data rate	200 bps
Transmission power	156 dB re 1 μPa
Packets period	60 s
Waypoint, position and track packets size	32 B

In all our simulations, we have a network setup with carrier frequency 65.2 kHz, bandwidth 25 kHz, data rate 200 bps, and source level 156 dB re 1μ Pa measured at the distance of 1 m from the transmitter. We assume the leader AUV has a preloaded path to follow and that every 60 s it sends a waypoint packet of 32 B to each of the followers: this packet includes the next destination that a follower needs to reach. The leader computes this destination based on its next waypoint and applies an adjustment to maintain the formation, except when it is a mine position. On the other hand, follower AUVs send their current position every 60 s to the leader AUV inside position packets. Every follower node is equipped with a 360 scanning imaging sonar that performs a complete circular scan of 50 m radius every 6.7 s. When one of the mines is detected by the imaging sonar of the follower node, the application *UwSCFTracker* is responsible for generating and sending track packets to the leader. Each of these packets contains the mine 3D position and the tracking measurement timestamp [11]. Whenever a follower node is chosen to identify and dispose a mine, it spends 250 s in the area and then leaves, assuming that the mine has been successfully neutralized.

To assess the system performance, we perform 100 independent runs for each network configuration. Both `path3` waypoints and mines are randomly generated with a uniform distribution in each run. In each iteration, the number of neutralized mines is divided by the number of generated mines to determine the detection probability.

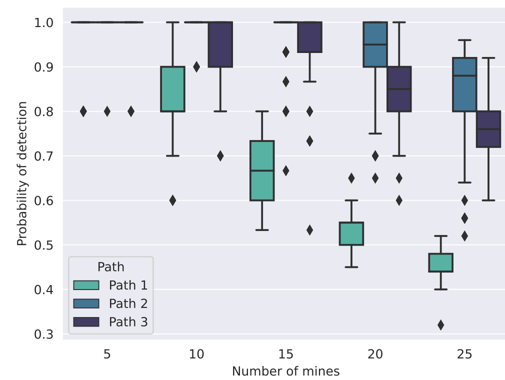
4.2 Results

Results are discussed hereafter, observing average values, confidence intervals and box-plots of the analyzed metrics.

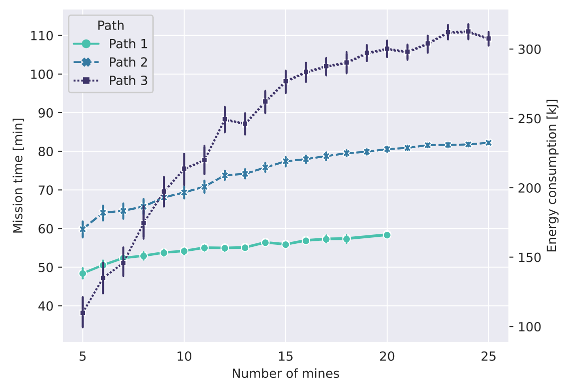
Fig. 3a shows box-plots representing the probability of detecting and neutralizing all mines when employing `formation1`. When the number of mines in the patrolling area is less than or equal 15, on average, the system achieves a detection probability higher than 60% across all the three paths. Regarding path1, there is a linear decrease in the probability of detection as the number of mines increases. On the other hand, path2, which is designed to ensure that the AUVs scan the whole area always guarantees an average detection probability above 85%, with some inefficiency due to the equipment used. Follower AUVs are equipped with a low-cost sonar, which takes 6.7 s to scan a circular area of 50 m. Given that the AUVs are moving during the scanning process, it can happen that a mine placed at the edge of the scanning area is not seen as the AUVs may move away from that mine before completing the scan. Finally, also path3 yields to high detection probabilities. This is essentially because the waypoints are uniformly distributed, increasing the likelihood of passing through a certain areas multiple times. Nevertheless, given the random nature of the trajectory, there remains a non-zero probability that some mines are missed, resulting in an overall detection performance worse than the one obtained by path2. Increasing the number of AUVs from 3 to 5 (Fig. 4a) gives a slight improvement in all the considered paths. Irrespective of the increasing number of mines in the area, the system consistently maintains an average detection probability above 60% across all three paths. Even though, for path1, there still is a linear decrease in the probability of detection as the number of mines increases. Conversely, in the path2 case, the probability of detection remains remarkably high, leading to higher results than path3. Both path2 and path3 attain a 100% detection probability in some cases, regardless of the number of mines.

To assess the system's performance, we also examine the mission time required to achieve a probability of detection above 70%. Since the quantity of mines in the area is not known beforehand, the mission time is determined at the simulation's end, corresponding to the time when the last mine detection takes place.

Fig. 3b shows the plots of the mission time in minutes vs the number of mines, utilizing formation1. For path1 and path2, we observe different mission times as the number of mines increases. For path1 the mission time ranges, approximately, from 48 to 58 minutes. Despite the decreasing probability of detection as the number of mines increases, the mission times remains relatively consistent. For path2, instead, the mission time varies from approximately 60 to 82 minutes. Despite the higher probability of detection, this path requires longer mission time compared to path1. Finally, for path3 the mission time tends to increase as the number of mines grows, suggesting that, as the complexity of the environment and the number of mines increase, the random path takes longer to complete the mission. In particular, when the number of mines is less than 10, following path3 leads to a shorter mission time than the one required for path2 in the same conditions. However, as the number of mines increases, path3's mission time becomes approximately 30 minutes larger than path2's one. Fig. 4b shows the line plots representing the mission time when employing formation2. Comparing these results to those obtained with formation1, we observe that there is little difference in mission duration. Nevertheless, path3 shows a substantial improvement, especially when there are less than 20 mines.



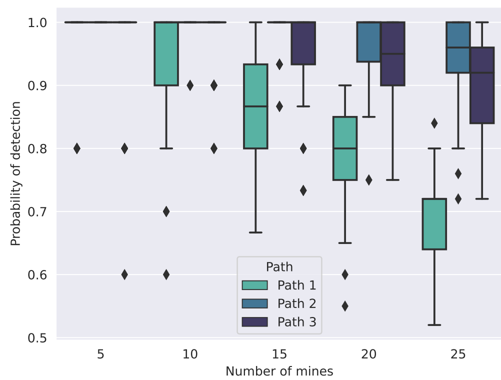
(a) Probability of detecting N mines vs number of mines with formation1.



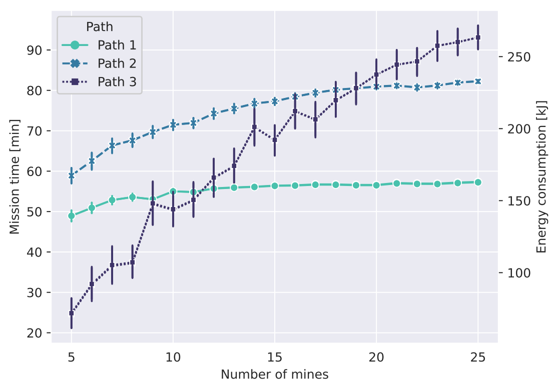
(b) Mission time vs number of mines with probability ≥ 0.7 and formation1.

Figure 3: Simulation results with formation1 (3 AUVs).

In addition to the mission time, we also consider the corresponding energy consumption per AUV. Analyzing the energy consumption along the mission times, we better understand the overall efficiency and feasibility of the system in practical deployment scenarios. For the purpose of this paper, we assume to use low-cost AUV models for the followers, such as the Remus 100 AUV [8], which, in a 24 hour mission, has an estimated energy consumption of 1 kWh (which corresponds to 3600 kJ per 24 hours, i.e., 2.5 kJ per minute) when moving at a speed of 1 m/s. Hence, dividing the energy consumption by the 24 hour mission, we have a power consumption of 41.7 W. As to the ahoi modem, its transmit power is 5 W and the receive power is 0.3 W, allowing us to determine the energy consumption for transmitting and receiving a single packet by multiplying the transmit/receive power by the packet duration. We recall that each AUV generate 1 packet (of size 32 bytes, sent with a bitrare of 200 bps) per minute, and in formation1 82.21% of these packets are correctly received, while with formation2



(a) Probability of detecting N mines vs number of mines with `formation2`.



(b) Mission time vs number of mines with probability ≥ 0.7 and `formation2`.

Figure 4: Simulation results with `formation2` (5 AUVs).

we observed a packet delivery ratio of 85.25%. Given that the receiver address is most likely to be inserted in the packet preamble, that has a size that is significantly smaller that the payload, and that with the ahoi modem most of the reception failures are due to preamble misdirection rather than errors in demodulating the payload, we compute the power consumption only for packets correctly received for the intended destination. Additionally, the Ping 360, with a power consumption of 5 W, exhibits a constant energy consumption.

Fig. 3b shows that following `path1` yields an energy consumption approximately from 140 kJ to 160 kJ. And when following `path2`, the energy consumption for a single AUV ranges from 170 kJ to 235 kJ, considering both `formation1` and `formation2`. On the other hand, the power consumption for a single AUV following a random path, in swarms of 3 and 5 AUVs yields some slightly different results. In the first case the energy consumption is between 110 kJ and 300 kJ, while in the second case it ranges from 70 kJ to 260 kJ, approximately. These results demonstrate that employing a swarm of 5 AUVs following a random path yields a slight reduction (about 13%) of the energy consumption per AUV.

5 CONCLUSION

In this paper, we have presented a possible design of an automated MCM system exploiting a swarm of cost-effective and low energy consumption AUVs. Our study revealed that following a deterministic path which covers the entire patrolling area produces the most favorable results in terms of probability detection, when employing an AUV swarm with 3 or 5 vehicles, and maintains a relatively consistent mission time and energy consumption. Due to the uniform distribution of its waypoints, which allows the AUVs to traverse certain areas multiple times, also using random trajectories produces optimal results in terms of probability of detection, especially with a formation of 5 AUVs. Nevertheless, it does have a significant drawback - the mission time greatly increases with the number of mines, leading to longer missions (and higher energy consumption).

Future work on this topic involves the development of a communication system that allows the followers in the swarm to coordinate more effectively. By improving their communication, the AUVs in the swarm can work together more efficiently, increasing the probability of successfully locating mines. Additionally, this improved coordination could lead to a reduction in mission time, resulting in lower energy consumption and improved overall efficiency.

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