Cooperative Mission Planning for Autonomous Vehicles

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***Abstract*—Autonomous vehicles are playing an increasingly important role in industry, particularly for tasks such as exploration and inspection. Combining different types of autonomous vehicles such as Autonomous Underwater Vehicles (AUVs) and Unmanned Aerial Vehicles (UAVs) can enhance operational efficiency and accelerate mission completion. This paper introduces a novel approach to cooperative mission planning, demonstrated through a simulation-based case study in a harbor environment. We designed and evaluated various swarm formations using the OMNeT++ simulation framework to assess the execution of inspection missions, with the target to detect pollution in the water. The evaluation compares multiple swarm configurations, including two AUVs, three AUVs in a triangular formation, and a hybrid AUV-UAV swarm. For baseline comparison, missions using individual AUVs and UAVs were also analyzed. The results show that the hybrid swarm achieves the fastest detection and response times, emphasizing the advantages of cooperative mission planning across heterogeneous autonomous systems.**

***Index Terms*—AUV, UAV, Simulation, Swarm**

I. Introduction

Autonomous vehicles are assuming an increasingly prominent role in both industry and everyday life. The range of tasks performed by these vehicles is particularly diverse in the industrial sector, where a wide variety of vehicles, including Unmanned Aerial Vehicles (UAVs) and Autonomous Underwater Vehicles (AUVs), are employed. The scope of tasks performed by these vehicles is extensive, with a primary focus on exploration and inspection of designated areas. To accomplish these tasks, a mission must be carefully planned. The collaborative potential of autonomous vehicles, enabled by sophisticated mission planning mechanisms, offers a significant opportunity to enhance efficiency and accelerate the completion of missions.

Building on this potential, the following paragraph highlights the importance of cooperative autonomous vehicles in the maritime domain, with a focus on inspection and maintenance tasks in harbor environments.

The economy is projected to undergo robust growth in the ensuing years, signifying an escalation in the export and import of goods. In light of the anticipated surge in maritime trade, ports are expected to assume an even more significant role. To ensure the seamless functioning of these ports, regular inspections and maintenance are essential. This includes the monitoring of port infrastructure, such as the harbor basin and harbor wall. To address the challenges posed by access restrictions, the use of autonomous vehicles, such as AUVs for underwater inspections and UAVs for aerial surveys, is recommended. These vehicles will inspect the harbor basin in a collaborative manner, exhibiting cooperative, communicative, and partially autonomous behaviors. During the course of this inspection, conspicuous areas in the water will be examined and checked for pollutants. In the event that any areas are found to contain pollutants, a more thorough examination will be conducted to ensure precise mapping.

To evaluate such missions and their requirements, we rely on simulation-based methods, which make it possible to test different swarm configurations and mission strategies before deploying them in real-world harbor operations.

Conducting practical experiments with AUVs and UAVs in harbor environments is costly, logistically complex, and often difficult to reproduce under comparable conditions. Simulation therefore provides an essential tool for analyzing cooperative missions, enabling systematic evaluation of swarm concepts in a controlled yet realistic setting. In this work, the network simulator OMNeT++ [1] serves as the foundation, extended with a modular simulation model based on the DUNE runtime environment [2]. This model incorporates the specific characteristics of UAVs and AUVs, adapting relevant parameters accordingly. On this basis, algorithms were developed that enable both simple follow-me missions and more complex cooperative scenarios, taking into account swarm control and interaction between heterogeneous vehicle classes.

In summary, the contribution of this paper is twofold: first, we present an application example for cooperative harbor inspection using heterogeneous swarms of AUVs and UAVs; second, we demonstrate through simulation-based case studies how different swarm configurations perform in terms of mission efficiency. By systematically comparing these configurations, we highlight the advantages of cooperative swarm behavior for this application domain.

The remainder of this paper is organized as follows: Section II discusses related work in the field of cooperative mission planning. Section III provides the necessary background on swarm algorithms, communication strategies, and relevant tools. Section IV introduces the mission concept and scenario. Section V presents the implementation details and evaluation results. Finally, Section VI concludes the paper and outlines directions for future work.

II. Related Work

A substantial volume of research is currently underway in the field of cooperative mission planning, particularly focusing on one recurring theme. In the context of swarm algorithms, a salient consideration is the configuration of vehicles. In the work [3], the authors examine the formation process and subsequent movement within a formation. The paper outlines the process by which a group can form a formation. The study focuses on UAVs and emphasizes the maintenance and control of these vehicles during operation. The authors constructed a dynamic model to summarize several aspects of the formation. A range of values was considered in the process. We have adapted and integrated some of these aspects. The main distinction is that our work also involves AUVs, where additional factors come into play. In their model, the authors consider factors that are important for determining a UAV's speed, orientation, and movement angle. For our use case, we developed our own set of factors based on their model [3]. In another work [4], the authors proposed a model for UAV swarms, aiming to establish coordinated formations of multiple UAVs. Several possibilities have been proposed for this phenomenon. One mechanism transforms a random arrangement into a V-shaped or linear formation. Another referenced configuration is the circular one depicted in the illustration, which also shows the UAVs' trajectories. To achieve the desired formation, the following steps must be taken. These steps typically include leader election, relative position estimation among vehicles, and iterative trajectory adjustments until the target formation is reached. Another papers deal with this topic, with a focus specifically on swarm formation [4]. We used their formations as a foundation and developed a formation tailored to our use case. A key difference lies in the number of vehicles involved and the integration of heterogeneous types, which makes the varying heights of the vehicles a relevant factor.

III. Background

The following section provides an overview of the fundamentals of AUVs and UAVs as well as communication and swarm algorithms. Additionally, it introduces DUNE and Neptus which were used as part of the simulations in OMNeT++.

A. Autonomous Underwater Vehicles

In the early 1960s and 70s, the development of unmanned vehicles started with the goal to make a wide variety of missions possible [5]. The reason for this was that manned missions require vehicles that meet the highest safety standards, as people have to operate in sometimes hostile environments. Manned vehicles have the advantage of performing complex tasks and enabling active decisions by the crew. Unmanned vehicles, on the other hand, are not only more compact but are able to reach places that would not be accessible by manned vehicles.

There are two types of unmanned underwater vehicles, namely remotely-operated vehicles (ROVs) and AUVs. ROVs are vehicles that are connected by a cable to a ship, land, or other platform. They are controlled manually by a person. Through the cable, information is exchanged with the ROV, and in some cases the cable is used to provide power. ROVs are limited in their use because they are limited by the cable, in terms of range, and supply. They are used for exploration and mapping of the seafloor, as well as for sampling, maintenance, and many other tasks [5].

AUVs, on the other hand, are vehicles that act autonomously and without direct connection to an operator. The AUV can perform tasks autonomously and requires no or minimal human supervision. The tasks must be defined before the start of a mission and is handed over to the AUV, since communication with the vehicle is limited or even impossible during a mission. Due to limited communication, AUVs must be able to react immediately and independently to sudden events, such as the appearance of an obstacle. Power is supplied by rechargeable or primary batteries.

B. Unmanned Aerial Vehicles

Unmanned aerial vehicles (UAVs) are also commonly referred to as drones [6]. The usage of the term 'drone' can be traced back to the 1920s or 1930s. During this period it was employed in the context of unmanned aircraft. The early use of the term 'drone' referred to remotely operated aircraft, which lacked autonomy and required constant human control. The later introduction of the term UAV emphasizes the ability of such systems to take off, navigate, and operate autonomously using aerodynamic forces. The term UAV denotes an aircraft capable of taking off, navigating, and operating autonomously using aerodynamic forces, without human control. Unmanned aerial vehicles can be of any type of aircraft, including the category of aeroplane. The aeronautical vehicle under discussion is of the rotary-wing variety, characterized by one or more rotors.

C. Communication

Effective communication is essential for the coordination of autonomous vehicles and can be broadly categorized into three types: AUV-to-AUV, UAV-to-UAV, and AUV-to-UAV communication. AUV-to-AUV communication typically relies on underwater acoustic modems, as acoustic signals are currently the most viable method of transmitting data in underwater environments. These signals can travel over relatively long distances, but are constrained by low data rates, high latency, and susceptibility to noise and multipath propagation. UAV-to-UAV communication, by contrast, generally utilizes wireless broadband technologies. These technologies offer high bandwidth and low latency in open-air environments, enabling real-time data exchange and swarm coordination [7]. Communication between AUVs and UAVs presents a unique challenge due to the fundamentally different propagation media water and air. Direct communication is not feasible across the air-water interface with conventional transceivers. To bridge this gap, a surface-based relay or base station is typically required. This relay, which could be mounted on a buoy or a vessel, is

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equipped with both acoustic and radio frequency (RF) interfaces. It acts as a communication gateway, receiving acoustic signals from submerged AUVs and RF signals from aerial UAVs, translating and forwarding messages between the two domains. This architecture ensures interoperability and enables coordinated missions between heterogeneous autonomous systems operating in different physical environments.

D. Swarm Algorithms

Swarm algorithms are primarily used to simulate swarm intelligence, enabling autonomous vehicles to collectively pursue a shared goal through coordinated behavior. These algorithms leverage the capabilities of individual agents within a network, allowing them to operate as a cohesive unit without centralized control [8]. A key aspect of swarm behavior lies in the way agents move, communicate, and make decisions within the swarm. In terms of movement, two main strategies can be identified. One approach assigns specific roles or destinations to each vehicle, often based on a ”Follow Me” principle where a lead vehicle defines the path and others adapt their movements accordingly. The alternative is a fully decentralized method in which all vehicles follow local rules and react independently to their environment. Efficient communication within the swarm is critical and must address the frequency, modality, and structure of message exchange. It remains an open question whether communication should only occur in response to changes in state or be maintained continuously. In either case, the ability of vehicles to share information reliably and efficiently is essential to swarm coordination. Ultimately, swarm algorithms must balance autonomy and cooperation, allowing agents to dynamically adapt their behavior while contributing to the overall mission.

E. DUNE

DUNE [9] is a software framework developed by the Underwater Systems and Technology Laboratory (LSTS) at the University of Porto. It serves as the core runtime environment for controlling AUVs and managing all onboard operations during a mission. Designed as a modular and lightweight operating system for embedded platforms, DUNE is responsible for coordinating a wide range of processes, including communication, navigation, control, and mission execution [9]. Throughout a mission, DUNE handles sensor integration, actuator control, and data acquisition, while also managing the mission flow and reacting to environmental inputs. Each functional aspect—such as telemetry handling, guidance, or acoustic communication—is implemented as a separate module, contributing to the system's flexibility and reusability. This modular architecture allows for tailored configurations depending on mission requirements and vehicle capabilities. Mission planning is carried out using Neptus, another tool developed by LSTS, which interfaces with DUNE to upload mission plans, monitor execution, and visualize telemetry in real time. DUNE has undergone continuous development and refinement over several years and has been successfully deployed in a variety of research and operational scenarios involving AUVs and other types of autonomous systems. Its proven reliability and extensibility make it a widely used platform in the field of maritime robotics.

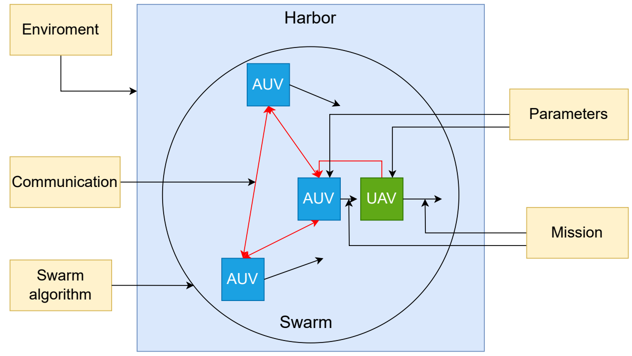

Fig. 1. Key factors in mission planning.

F. Neptus

Neptus [10] is a mission planning and control framework developed to support the operation of various types of unmanned vehicles, including surface, aerial, and underwater platforms. It plays a central role in this study, particularly in conjunction with DUNE, by enabling detailed planning, simulation, and post-mission analysis. One of Neptus' key strengths lies in its ability to define missions with a high level of precision. Since DUNE requires an exact and structured mission plan to execute operations autonomously, the planning process within Neptus is critical. Users can define vehicle behaviors step-by-step, specifying routes, maneuvers, sensing tasks, and communication actions. These elements can be tailored individually, allowing even complex multi-phase missions to be designed and validated before deployment. Neptus also allows for the inclusion of mission-specific waypoints, known as stations, which are strategically positioned along the planned route. At each station, the vehicle can perform a designated task, ranging from simple navigation commands to sophisticated measurement procedures or communication protocols. Through this flexibility, Neptus provides a robust environment for preparing, executing, and analyzing autonomous missions with high reliability.

IV. Concept for Mission Planning

This section describes the concept of cooperative mission planning based on a representative application scenario. The selected use case is a harbor inspection, in which the swarm algorithm and the communication strategy are identified as key aspects relevant to mission planning. The conceptual framework is inspired by the architecture of DUNE that was previously integrated into OMNeT++. To enable this integration, DUNE libraries were incorporated into OMNeT++ as well as adapted and extended to ensure a seamless functionality. A central component of this integration was the implementation of a task bridge that enables message translation between the different systems [2]. Effective mission planning involves several interdependent factors including the operational environment, communication strategy, swarm algorithm, mission objectives, and various additional configuration parameters as illustrated in Figure 1. Each of these components plays a critical role in the planning and execution of cooperative missions.

A. Environment

The environmental factors primarily include the geographical characteristics of the mission area, such as its size, as well as the known locations of objects within it. Since this paper focuses on a harbor scenario, the environment is defined by port infrastructure. Harbor walls define the operational area's boundaries, and ongoing ship traffic may result in currents or other water movements. Environmental pollution can appear in various forms, affecting mission planning and vehicle behavior.

B. Parameters

Parameters play a crucial role in distinguishing between different types of vehicles, such as AUVs and UAVs. While these vehicle types share some similarities in terms of modules, there are key differences in specific values, such as battery capacity. On average, AUVs can operate for longer periods on a single battery charge than UAVs can. Additionally, different communication technologies may result in different communication ranges and data rates.

C. Mission Objectives

The mission defines both the overall objective and the strategy for achieving it including the specification of the mission route. In this scenario, the objective is to detect and quantify areas in the water that exhibit signs of potential pollution. According to the mission protocol, the vehicles are programmed to navigate to predefined locations, where they collect measurements from multiple angles. The goal of this operation is to generate an accurate map of the affected areas.

D. Communication

Communication is of critical importance, as the vehicles must be able to exchange information to operate cooperatively. In the context of AUV-UAV communication, the different transmission media, i.e., water and air, must be carefully considered. This led to the development of several implementation strategies.

One solution involves the use of a ship as a relay station, where each vehicle first transmits its data to the ship which then forwards the message to the intended destinations. Alternatively, the AUV can employ a surface-based communication approach in which it periodically surfaces to transmit messages directly to the UAV. The latter involves the deployment of an airborne antenna on the AUV as illustrated in Figure 2, which additionally allows to bypass underwater transmission limitations.

E. Swarm Algorithm

The swarm algorithm plays a central role in this context, as the vehicles cannot work in an uncontrolled manner. Instead, their actions must be systematically controlled and organized. To achieve this, various factors must be defined, including the

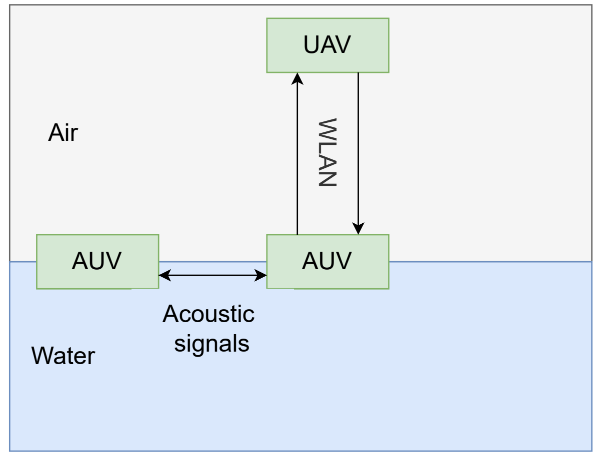

Fig. 2. Communication strategies between AUV and UAV via relay station or surfacing-based transmission.

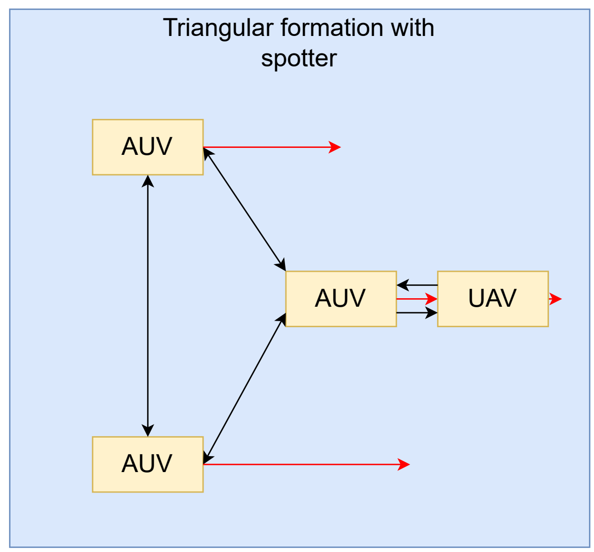

Fig. 3. Formation with three AUVs and one UAV.

type of communication. For simplicity, we select the approach in which the AUV partially surfaces the water to enable direct communication with the UAV. Another key aspect is the swarm formation. Rather than selecting a single configuration, we evaluate multiple formation types. The formations in the experiments range from basic swarms consisting of two identical vehicles to more complex triangular formations that incorporate additional airborne vehicles as well. Figure 3 shows a triangular formation with additional airborne spotter units.

V. Implementation and Evaluation

This section presents the implementation and evaluation of the proposed approach through a series of simulation-based

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case studies.

A. Implementation

The implementation of the proposed concept was realized using OMNeT++ version 6.0.2 in combination with libraries provided by DUNE. The system architecture follows a fully modular design, comprising multiple controllers, each responsible for a specific function. These controllers are interconnected via a central bus, enabling efficient communication between modules. This design adheres to the principles established by DUNE and utilizes its functional components to manage mission-related tasks.

Within the OMNeT++ framework, a collection of NED files defines the network structure. These files configure vehicle-specific properties such as controller assignments, battery capacities, and communication ranges. At the outset of development, particular attention was paid to distinguishing between vehicle types. One of the most significant differences lies in energy capacity: an AUV features approximately ten times the battery capacity of a UAV, although it also exhibits a considerably higher power consumption rate.

To support cooperative mission planning, the implementation involved modifying several controllers and integrating a swarm algorithm. This algorithm is responsible for establishing and maintaining the swarm.

B. Case Study Setup

The simulation begins under the assumption that all vehicles are initially located at random positions within the mission area. Before the mission start, a lead vehicle must be designated. At mission start, all vehicles initiate a discovery protocol, exchanging signals to locate each other. Once all units have identified their peers, the swarm formation is established.

The final formation consists of three AUVs arranged in a triangular pattern underwater, with one UAV positioned above the lead AUV. Communication between AUVs takes place via acoustic modems suitable for underwater transmission, while the UAV maintains a Wi-Fi connection to the lead AUV. This lead AUV acts as a communication relay, forwarding relevant data to the rest of the underwater swarm.

Once the formation is in place, the mission proceeds along a predefined route. The path is defined for the lead AUV and the UAV, with the remaining AUVs following at a specified distance to maintain formation. However, the vehicles may temporarily break formation if a conspicuous spot is detected. In such cases, individual AUVs navigate to the detected location to perform measurements.

Spot detection occurs through two mechanisms. First, each AUV is equipped with sensors that allow it to detect anomalies or points of interest within a defined radius. Second, the UAV utilizes a downward-facing camera to scan the water surface and identify potential points of interest from above. In the simulation, these detection processes are simplified. When a conspicuous spot is detected, the swarm navigates toward it, and the AUVs approach the location from three different angles to collect data. This maneuver, illustrated in Figure 4, provides three distinct measurement points that can later be used to estimate the spatial spread of the swarm during the inspection process.

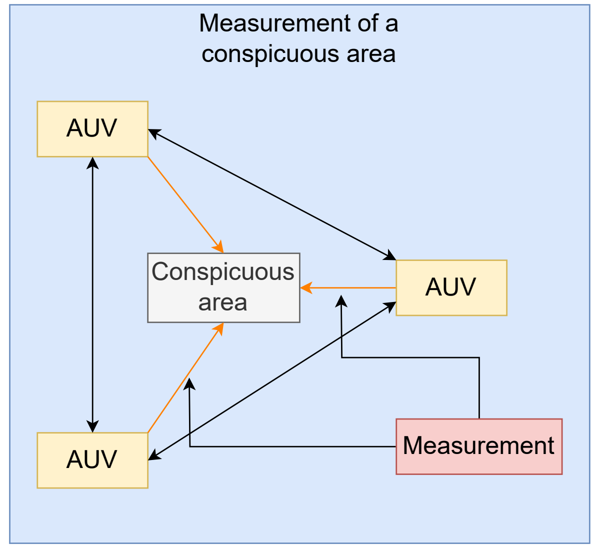

Fig. 4. Swarm approach to a detected spot with three AUVs collecting measurements from different angles.

C. Evaluation

To evaluate the proposed concept, five case studies were designed, corresponding to the swarm configurations listed in Table I. Two baseline scenarios with a single AUV and a single UAV serve as benchmarks. In addition, two all-AUV formations were examined: a simple follow-me formation and a triangular formation. Finally, a hybrid configuration combined three AUVs in a triangular formation with a UAV acting as a spotter (triangular formation with spotter). This systematic comparison enables an assessment of how vehicle composition and formation influence mission performance.

The final phase of this study focused on evaluating the effectiveness of the implemented simulation model. The objective was to assess the functionality of the proposed concept and the time required for different swarm configurations to detect a target and respond accordingly. To this end, a series of case studies was conducted and analyzed to compare the expected behavior with the actual outcomes observed in simulation.

For each case study, a predefined route was created in Neptus (see Figure 5), which the swarm was instructed to follow. A simulated pollutant source was placed within the mission area, and the swarm's task was to detect and move toward this location. Upon arrival, the AUVs were expected to approach the spot from different angles and carry out measurement tasks. The collected data were then stored and transmitted to a central database, where the location could be recorded and targeted for cleanup in a subsequent mission.

Five swarm configurations were implemented, differing primarily in vehicle composition and spatial arrangement, to compare their performance, particularly in terms of detection time

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TABLE I
MEASURED TIMES OF THE CASE STUDIES [S]

	Test 1	Test 2	Test 3	Test 4	Test 5	Mean
AUV	960	958	957	957	958	958
UAV	838	840	838	838	835	838
Follow Me	958	959	957	960	958	958
Triangular Formation	903	900	903	905	904	903
Triangular Formation with Spotter	839	837	838	838	838	838

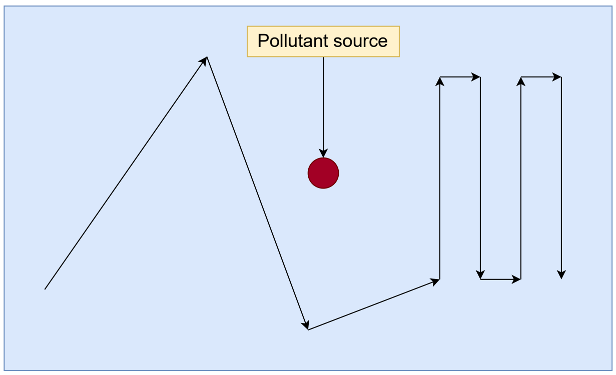

Fig. 5. Predefined mission route used for evaluating swarm configurations in simulation.

and response speed. Two benchmark scenarios were included for reference: one using a single AUV and another using a single UAV. Additionally, two all-AUV formations were evaluated—one employing a simple follow-me behavior and another forming a triangle. The final configuration combined three AUVs in a triangular formation with a UAV acting as a spotter, referred to as the triangular formation with spotter.

The results of these case studies, as shown in Table I, demonstrate that the hybrid AUV-UAV swarm achieved the fastest detection and response times. Compared to the benchmark formations, the triangular formation with spotter performed best, followed closely by the all-AUV triangular formation. The single AUV and the follow-me AUV formation were the slowest to detect the target and initiate movement. While the single UAV matched the speed of the hybrid formation in locating the target, it was unable to perform measurements, highlighting a critical limitation in using UAVs alone for this type of mission.

These findings emphasize the benefits of cooperative mission planning with heterogeneous autonomous systems, particularly the combination of aerial surveillance and underwater measurement capabilities.

VI. CONCLUSIONS

The paper contributes an application example for cooperative port inspection using autonomous vehicles, in particular, by combining AUVs and UAVs. For this purpose, a simulation concept for the application scenario was developed and fully implemented in OMNeT++, leveraging a simulation model based on the DUNE architecture. The implementation involved the adaptation of several existing functions and the introduction of new ones to enable cooperative mission planning and execution. Furthermore, the configuration files were modified to allow a clear differentiation between individual vehicles. These vehicles are capable of forming and maintaining a swarm, enabling them to execute missions collaboratively. The swarm navigates predefined routes as a coordinated unit to reach and inspect designated locations.

The conducted case studies demonstrated the feasibility and advantages of cooperative missions involving both AUVs and UAVs. The integration of a UAV significantly reduced the mission duration. In particular, the swarm consisting of three AUVs and one UAV completed the mission in the shortest time. In the study, the mission duration is primarily influenced by the type of detection method used. While UAV-based scanning enables the coverage of larger areas compared to AUVs, thereby accelerating object detection, the AUVs provide more detailed scan results once the area of interest has been reached.

REFERENCES

[1] A. Varga, "Omnet++," in *Modeling and tools for network simulation*. Springer, 2010, pp. 35–59.

[2] C. Pommerencke, W. Brekenfelder, H. Parzyjegla, and P. Danielis, "A modular architecture for simulating autonomous underwater vehicles in omnet++," Nov. 2024. [Online]. Available: https://doi.org/10.5281/zenodo.14214820

[3] X. Fu, J. Pan, H. Wang, and X. Gao, "A formation maintenance and reconstruction method of uav swarm based on distributed control," *Aerospace Science and Technology*, vol. 104, p. 105981, 2020.

[4] T. Sousselier, J. Dreo, and M. Sevaux, "Line formation algorithm in a swarm of reactive robots constrained by underwater environment," *Expert Systems with Applications*, vol. 42, no. 12, pp. 5117–5127, 2015.

[5] Ali, Zain, Nasim, Shahzad, Liaquat, Faraz, Wasi, Sarwar, Shafiq, and M., "Autonomous under water vehicle," *Advanced Materials Research*, vol. 816-817, pp. 1073–1076, 09 2013, last visited 16.12.2022.

[6] P. G. Fahlstrom, T. J. Gleason, and M. H. Sadraey, *Introduction to UAV systems*. John Wiley & Sons, 2022.

[7] B. Li, Z. Fei, Y. Zhang, and M. Guizani, "Secure uav communication networks over 5g," *IEEE Wireless Communications*, vol. 26, no. 5, pp. 114–120, 2019.

[8] A. Chakraborty and A. K. Kar, "Swarm intelligence: A review of algorithms," *Nature-inspired computing and optimization: Theory and applications*, pp. 475–494, 2017.

[9] Laboratório de Sistemas e Tecnologia Subaquática. (2023) Dune unified navigation environment. Last visited 28.01.2025. [Online]. Available: https://www.lsts.pt/software/64

[10] ——. (2024) Neptus command and control software. Last visited 05.07.2024. [Online]. Available: https://lsts.fe.up.pt/index.php/toolchain/neptus