

# Autonomous Collaboration in Underwater Environments: Exploring Swarm Intelligence for Multi-AUV Systems

Peter Danielis\*, Veera Vishnu Pavan Lanka\*, Willi Brekenfelder\*, Helge Parzyjegl\*, and Frank Sill Torres†

*\*Institute of Computer Science, University of Rostock, 18051 Rostock, Germany  
{peter.danielis, willi.brekenfelder, helge.parzyjegl}@uni-rostock.de*

*†Institute for the Protection of Maritime Infrastructures,  
German Aerospace Center (DLR), 27572 Bremerhaven, Germany  
frank.silltorres@dlr.de*

**Abstract**—The Earth’s oceans present formidable challenges to exploration and understanding. Their vastness, depth, and hostile conditions, such as under thick ice layers in polar regions or extreme depths under high pressure, make them difficult to navigate. It is essential to monitor the environment and collect data to assess marine biodiversity, ecosystem health, and the global ecosystem’s interdependencies. These are all affected by climate change, pollution, and human activities. Autonomous underwater vehicles (AUVs) have transformed ocean exploration. They navigate and collect data autonomously in challenging environments. Robust decision-making algorithms are essential for cooperative mission planning among AUVs. It is equally critical to select and implement algorithms that govern collaborative behaviors such as target acquisition and formation maintenance. This paper investigates algorithms for cooperative target search and capture missions, ensuring mission integrity between AUVs. The study employs simulation using the network simulator OMNeT++ to analyze and address these challenges, facilitating enhanced collaboration and efficiency in AUV operations.

**Index Terms**—Autonomous Underwater Vehicles, AUV Swarms, Collaboration, Multi-AUV Systems, Autonomous Decision-Making.

## I. INTRODUCTION

Exploring and understanding the Earth’s oceans presents unique challenges due to their vastness, depth, and often hostile conditions. For example, there are underwater environments beneath meter-thick layers of ice, as is the case at the poles, or areas so deep that the pressure there becomes so high that humans could not survive there for long, if at all [1]. Environmental monitoring and the collection of data on oceanographic parameters, marine biodiversity, and ecosystem health help people better understand the intricate dynamics of the marine environment and its interconnectedness with global ecosystems. Through comprehensive analysis of these data, scientists can assess the impacts of climate change, pollution, and human activities on marine ecosystems and develop evidence-based policies and management strategies for sustainable ocean conservation and resource management.

Humans alone cannot undertake these efforts due to the inherent risks of the harsh underwater environment.

With the advent of Autonomous Underwater Vehicles (AUVs), these limitations are being overcome. AUVs serve as invaluable tools capable of penetrating the depths of the ocean to autonomously collect data, conduct surveys, and monitor marine ecosystems. AUVs are untethered, self-propelled robots designed to explore the underwater environment. Unlike their tethered counterparts, Remotely Operated Vehicles (ROVs), AUVs operate without direct human control, following preplanned missions and are capable enough to make their own decisions.

In the context of cooperative mission planning for AUVs, the development of effective decision-making algorithms represents a significant challenge. The selection and implementation of an appropriate algorithm to achieve the mission objective is of great importance, particularly in the context of a cooperative mission to reach and acquire specified targets in specific formations. As AUVs operate as a team, it is imperative to carefully study challenges such as collision avoidance, the assignment of feasible formations, the maintenance of formation shape, and the switching between formations. This paper examines the assignment of a feasible distributed algorithm for target search and capture that ensures mission integrity. This necessitates the development of control strategies and the implementation of communication that permit AUVs to maintain their relative positions, adapt their movements in response to changing conditions, and share information in real time. By doing so, AUVs can effectively collaborate to perform complex tasks such as target hunting, surveillance, and inspection, while minimizing the risk of data loss and mission failure. This paper focuses on simulating a search and capture mission within the Objective Modular Network Testbed in C++ (OMNeT++) simulator and its framework INET to carefully analyze and address the challenges that are essential for collaborative operations involving AUVs [2], [3].

The remainder of this paper is organized as follows: Section II provides related work. Section III details the design of

the method developed for the cooperative mission of collaborative search and capture, and the architecture developed based on this design. Section IV presents the implementation of this architecture in OMNeT++, explores possible use cases for the method developed in Section III, and evaluates it. Section V provides a summary and discusses possible future work.

## II. RELATED WORK

Recent studies have proposed several approaches for cooperative mission planning and formation control of AUV swarms. A study by the authors in [4] introduced a multi-AUV cooperative target search method using a formation control algorithm. This algorithm uses an improved leader-follower mechanism in a triangular formation for large area searches. After target acquisition, the AUVs transition to a circular formation to gradually approach the target using position feedback mechanisms. Although effective, this study does not address the complexity of communication, which is critical to optimizing collaborative underwater missions.

Another significant contribution is described in [5], which addresses maintaining a circular formation of AUVs under limited communication ranges while translating the formation along a time-varying trajectory. This method is relevant for applications such as source seeking, where AUVs move towards an unknown target using realtime concentration measurements. The study develops a feedback control law to maintain stability and uniform distribution of AUVs, ensuring robust performance despite communication limitations.

Research at the University of Idaho (UI) focused on mapping mine countermeasure (MCM) missions with AUVs using the Autonomous Littoral Warfare Systems Evaluator–Monte-Carlo (ALWSE-MC) software [6]. This software simulates AUV decision making and communication using modified TDMA protocols and acoustic modems. Their communication strategy involves a structured cycle of 13-bit and 32-byte messages, facilitating effective coordination and data sharing among AUVs. Insights from this research, particularly the communication cycle and scheduling concepts, provide valuable knowledge for developing robust communication strategies in cooperative AUV missions.

These studies highlight various aspects of AUV swarm coordination, formation control, and communication strategies, and lay the foundation for further research to optimize cooperative underwater missions.

## III. COOPERATIVE MISSION PLANNING FOR AUVs

This section explains the methods used for cooperative mission planning of AUVs. In a cooperative mission, a group of AUVs perform tasks such as tracking, hunting, mapping, or formation control together by exchanging information. This paper focuses on the cooperative mission of target search in an unknown area and subsequent capture using three AUVs.

The mission is divided into two phases: search and capture. During the search phase, the AUVs are deployed in a specific area to locate the target object using their sensors. Once the target position is detected, the mission moves to the capturing

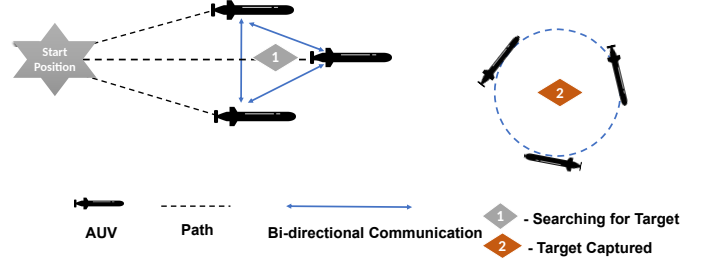


Fig. 1. Illustration of the cooperative mission.

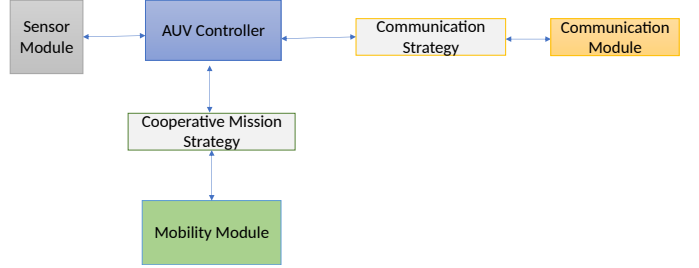


Fig. 2. Architecture of modules for every single AUV.

phase, where the AUVs approach the target close enough to capture it. However, the capturing phase can also be used for the close inspection of the target, which could be any object of interest (e.g. pipeline leak, shipwreck). Figure 1 illustrates the cooperative mission, showing AUVs in the searching phase (Stage 1) and the capturing phase (Stage 2).

### A. Architecture

Implementing a cooperative mission strategy for AUVs requires a well-designed system architecture to ensure efficient communication, coordination, and control among the vehicles. This subsection describes the system architecture for cooperative AUV missions, highlighting the modules and their functions that support the cooperative mission strategy. Understanding this architecture is critical to replicating the implementation in other simulation frameworks. Figures 2 and 3 illustrate the AUV-level architecture and the overall system architecture, respectively, detailing the interdependencies of the various AUV-related modules.

**Sensor module:** The sensor module in the architecture is responsible for collecting and processing data from the external environment, providing critical information for AUV navigation and target location. AUVs typically use imaging sound navigation and ranging (SONAR) techniques, which create acoustic images by rotating sound beams and sampling echoes to detect objects [7]. The detection techniques can vary in different environments. In this paper, it is assumed that AUVs have a detection range of 200 meters. When a target enters this range, the sensor module detects it and sends its position information to the AUV controller.

**Mobility module:** The mobility module in AUVs is responsible for navigation and movement, driven primarily by

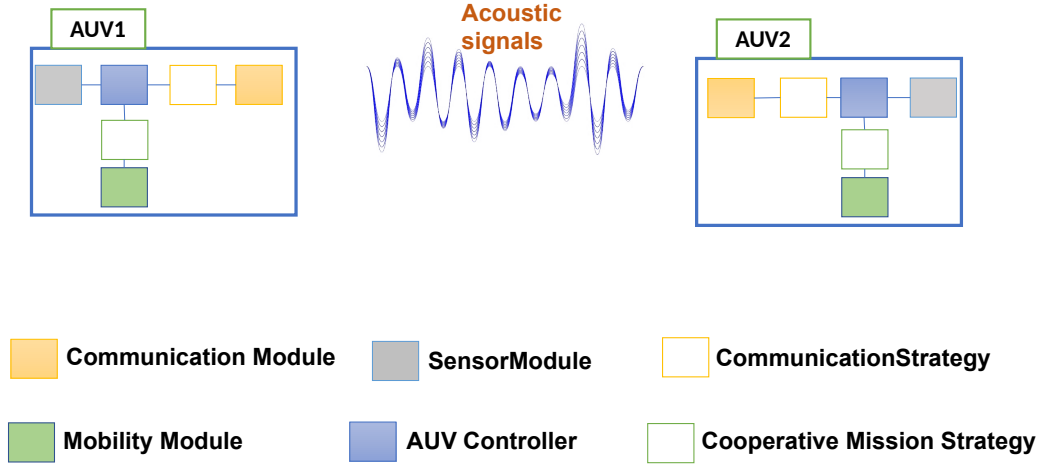


Fig. 3. Architecture on system level with shown communication between multiple AUVs.

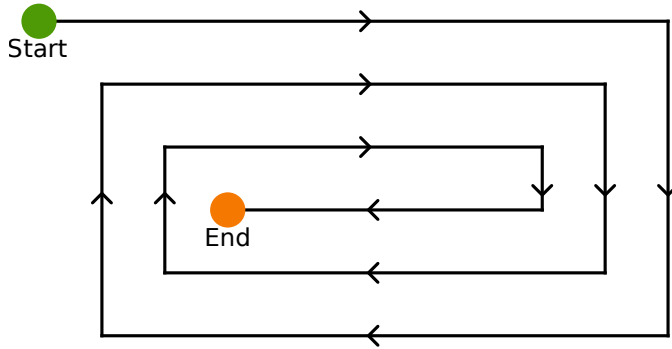


Fig. 4. Inward rectangular spiral search pattern [8].

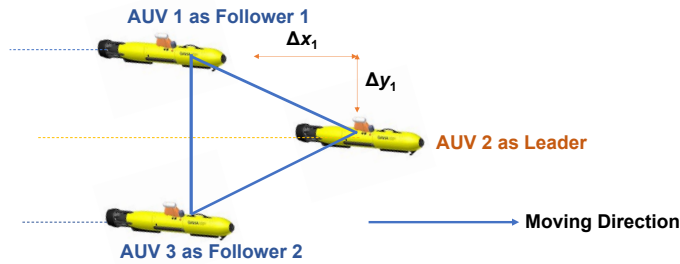


Fig. 5. Leader-follower approach.

a propulsion system consisting of electric motors, thrusters, and propellers. AUVs navigate using waypoints and move in straight lines between them. The type of mobility employed, is BonnMotion mobility, which allows dynamic waypoint navigation. In addition, circular mobility is used for formation control. This paper focuses on a 2D scenario with yaw (rotation around the z-axis), surge (translation along the x-axis), and sway (translation along the y-axis) motion.

**Communication module:** The communication module in AUVs facilitates essential interactions and data exchange

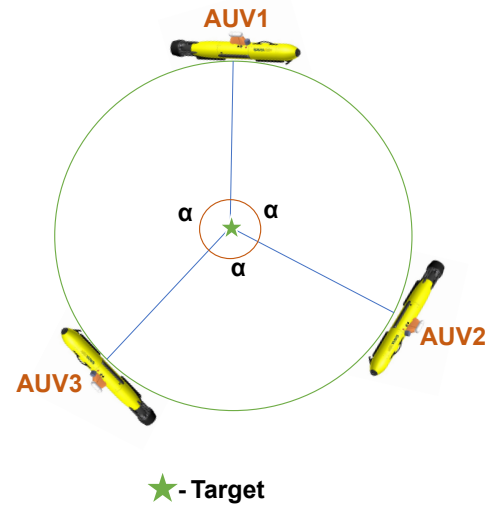


Fig. 6. Movement in circular formation with  $\alpha$  between  $115^\circ$  and  $125^\circ$ .

that are critical to cooperative missions in underwater environments. Unlike surface communication, which uses radio waves, underwater communication relies on acoustic waves due to the properties of water, where sound travels faster and more efficiently. Electro-acoustic transducers convert electrical signals into acoustic signals for transmission and reception. The module manages the transmission of data from sensors to the AUV controller, supporting mission execution by sharing critical information such as AUV positions and target status.

**AUV controller:** The AUV controller module processes data from the sensor module to determine the vehicle's position and orientation. It makes decisions based on mission objectives and environmental conditions and directs actions according to mission strategies. The controller manages the AUV's mobility by controlling thrusters and rudders to perform maneuvers and stabilize the vehicle. It also handles

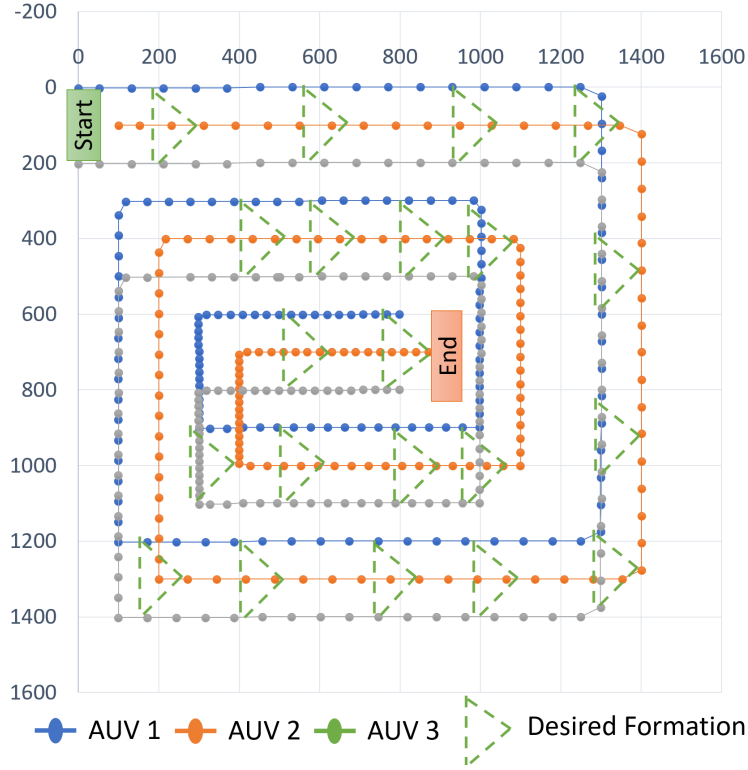


Fig. 7. Inward spiral search in the first case study.

communication with neighboring AUVs according to defined strategies, coordinating navigation, data collection, and other mission-specific tasks.

**Cooperative mission strategy:** The cooperative mission strategy involves a distributed algorithm designed for search and capture operations in unknown environments. This work focuses on the use of an inward rectangular spiral search pattern for efficient target localization, see Figure 4, ensuring comprehensive coverage of the search area with minimal redundancy [8]. The strategy as apparent from Figure 5 utilizes a leader-follower approach among three AUVs, where AUV2 acts as the leader and AUV1 and AUV3 act as the followers, maintaining a triangular formation during the search phase [4]. Once the target is located, the AUVs enter the capture phase where they maintain a circular formation with the desired angles between them regulated between  $115^\circ$  and  $125^\circ$  measured in a clockwise direction (see Figure 6). When the AUVs reach their positions with the desired angle, they begin to converge by reducing their radius by half in preparation for the next phase of the mission.

#### IV. IMPLEMENTATION AND EVALUATION

This section details the implementation of both the proposed architecture and the cooperative search and capture algorithm. Subsequently, the proposed search and capture algorithm is evaluated in case studies.

##### A. Implementation and Simulation Setup

The implementation of the proposed architecture (see Figure 3) in OMNeT++ involves mapping each module to dedicated files. In OMNeT++, modules are defined using .ned files to specify their structure, while .cc and .h files outline their behavior. The AUV module is defined in AUV.ned, which serves as the main file for the AUV controller. Communication functions are handled by CustomApp.ned, derived from UDPBasicApp.ned, which is responsible for generating and transmitting data packets, including custom data for the AUVs to get information about each other. The DynamicBonnMotionMobility.ned module manages mobility and extends the built-in BonnMotion model to dynamically alter movements or shift to new positions during simulation runtime, features not detailed in the BonnMotion trace file. Both the cooperative mission algorithm and the communication strategy are implemented in CustomApp.cc. These files, including AUV.cc and DynamicBonnMotionMobility.cc, define the behavior and characteristics of the module to ensure proper simulation operation. The WirelessMob.ned file describes the network structure and specifies node connections, while omnetpp.ini configures simulation parameters and settings.

Key simulation parameters include minimum AUV velocity set at 1.5 m/s, maximum velocity at 2.5 m/s, and desired velocity of 2 m/s. The desired angle between AUVs in circular formation ranges from  $115^\circ$  to  $125^\circ$ . AUVs operate within a sensing range of 200m and a communication range of 400m.

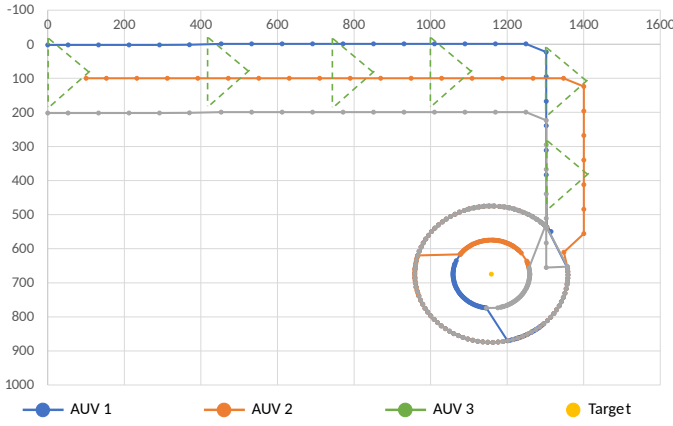


Fig. 8. Path traced by AUVs during second case study.

Distances from leader to followers in both x and y directions are maintained at 100m. The circular formation begins with an initial radius of 200m and shrinks to a radius of 100m during capture operation.

### B. Case Studies and Evaluation

The first case study examines the efficiency of an inward spiral search pattern conducted by three AUVs in a 1500 x 1500 m<sup>2</sup> area. The AUVs employed a leader-follower mechanism, implementing an inward rectangular spiral search pattern that progressively covered smaller inward rectangles. The objective of the test was to assess the efficacy of predefined waypoints in achieving comprehensive area coverage.

The results demonstrated a spatial search efficiency of 1, indicating that the AUVs successfully cover all 25 cells in the search area, thereby confirming 100% coverage efficiency. Figure 7 depicts the paths of the three AUVs during the search, demonstrating that the desired triangular formation was maintained throughout the operation. The leader AUV2 followed the predefined search pattern, while the follower AUVs, AUV1 and AUV3, adjusted their positions accordingly to maintain the triangular formation, as depicted by the green dotted line in the graph. This use case demonstrates the efficacy of the inward spiral search pattern and the predefined waypoints in ensuring comprehensive area coverage and maintaining formation integrity.

The second case study examines a search and capture operation for capturing and inspecting a missing vessel in the 1500 x 1500 m<sup>2</sup> area. The mission again involves three AUVs performing a cooperative search using the inward rectangular spiral search pattern as described above. AUV2 was programmed with predefined waypoints for the inward spiral pattern, while the formation and radius details were set for the circular capturing and inspection phase.

During the search, the AUVs initially form a circular formation with a radius of 200 meters. Upon locating the target, the radius is reduced to 100 meters for closer inspection and capturing. Figure 8 presents a graphical representation of

the movement of AUV1, AUV2, and AUV3 throughout the search. The target, indicated by a yellow dot, is identified by AUV3 at coordinates (1158.6, 674.688) approximately 930 seconds into the mission. Upon detection, AUV3 commenced a circling maneuver around the target, as evidenced by its change in direction and looping behavior.

Upon locating the target, AUV3 transmits its position to the other AUVs, prompting them to adjust their positions and form a circle around the target. The initial formation of the AUVs was circular, with a radius of 200 meters. This radius is later reduced for closer inspection. The gray dots indicate the path traced by AUV3, while the paths of AUV2 and AUV1, though not visible in the graph, followed similar trajectories at different speeds and times. This case study demonstrates the efficacy of circular formation in achieving successful target inspection and capturing in a search and capture mission.

### V. CONCLUSION

This paper addressed the challenges of ocean exploration by leveraging the capabilities of AUVs in cooperative missions. Through simulations in the OMNeT++ network simulator with the INET framework, we investigated decision-making algorithms with the objective of enhancing AUV collaboration and efficiency. The efficacy of inward rectangular spiral search patterns and circular formations in search and capture operations was demonstrated through the use cases. The results demonstrated that the cooperative strategies enabled the AUVs to achieve 100% area coverage and efficient target detection. These findings contribute to the advancement of ocean exploration and conservation efforts by improving the reliability and effectiveness of AUV cooperative missions.

### REFERENCES

- [1] J. Bellingham, "Platforms: Autonomous underwater vehicles," in *Encyclopedia of Ocean Sciences*, 2nd ed., J. H. Steele, Ed. Academic Press, 2009, pp. 473–484.
- [2] A. Varga, "Omnet++," *Modeling and tools for network simulation*, pp. 35–59, 2010.
- [3] L. Mészáros, A. Varga, and M. Kirsche, "Inet framework," *Recent Advances in Network Simulation: The OMNeT++ Environment and its Ecosystem*, pp. 55–106, 2019.
- [4] L. Li, Y. Li, J. Zeng, G. Xu, Y. Zhang, and X. Feng, "A research of multiple autonomous underwater vehicles cooperative target hunting based on formation control," in *2021 6th International Conference on Automation, Control and Robotics Engineering (CACRE)*. IEEE, 2021, pp. 22–27.
- [5] L. Brinón-Arranz, A. Seuret, and C. Canudas-de Wit, "Collaborative estimation of gradient direction by a formation of auvs under communication constraints," in *2011 50th IEEE Conference on Decision and Control and European Control Conference*. IEEE, 2011, pp. 5583–5588.
- [6] B. Johnson, N. Hallin, H. Leidenfrost, M. O'Rourke, and D. Edwards, "Collaborative mapping with autonomous underwater vehicles in low-bandwidth conditions," in *OCEANS 2009-EUROPE*. IEEE, 2009, pp. 1–7.
- [7] S. Zhao, T.-F. Lu, and A. Anvar, "Automatic object detection for auv navigation using imaging sonar within confined environments," in *2009 4th IEEE Conference on Industrial Electronics and Applications*. IEEE, 2009, pp. 3648–3653.
- [8] L. Li, Y. Li, Y. Wang, G. Xu, H. Wang, P. Gao, and X. Feng, "Multi-auv coverage path planning algorithm using side-scan sonar for maritime search," *Ocean Engineering*, vol. 300, p. 117396, 2024.