

Evolutionary Optimization for Unmanned Underwater Vehicle Navigation

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Abstract

Unmanned Underwater Vehicles (UUVs) play a vital role in various underwater exploration and surveillance tasks. However, the effective navigation of UUVs in complex underwater environments poses significant challenges due to factors such as limited communication, dynamic currents, and other difficulties. Evolutionary optimization techniques have developed as promising tools for enhancing UUV navigation abilities. This review provides a brief overview of the application of evolutionary optimization algorithms, including genetic algorithms, evolutionary approaches, and particle swarm optimization, in the context of UUV navigation. The fundamental principles of these algorithms and their applications in path planning, path optimization, localization, obstacle avoidance, and mission planning for UUVs are discussed in brief. Through an analysis of existing literature and case studies, the use of evolutionary optimization in improving the navigation efficiency, accuracy, and robustness of UUVs is highlighted. Additionally, current challenges were identified, and future research directions to advance the integration of evolutionary optimization techniques in UUV navigation systems are also discussed. Overall, this aims to provide insights into the potential of evolutionary optimization for addressing the navigation challenges faced by unmanned underwater vehicles and promoting advancements in underwater exploration and surveillance technologies.

Keywords: Unmanned Underwater Vehicles (UUV), Genetic Algorithm, Evolutionary Approaches, Particle Swarm Optimization, Path Planning, Obstacle Avoidance.

1. Introduction

Unmanned Underwater Vehicles (UUVs) have become essential resources in a wide range of underwater endeavors, including scientific research, environmental monitoring, and defense operations. Yet, navigating them through complex and dynamic underwater terrain remains a significant challenge. [1]. Constrained by limited communication bandwidth, unpredictable currents, and the omnipresence of obstacles, UUVs require innovative navigation solutions that can adapt to these challenging environments. In response to these challenges, evolutionary optimization techniques have emerged as promising avenues for enhancing the navigation capabilities of UUVs [2]. The inspiration gained from evolutionary theory, offers a framework for iteratively refining navigation strategies to navigate through complex underwater areas.

This review provides a complete exploration of the utilization of evolutionary optimization algorithms in the dominion of UUV navigation. Researching into the basic principles of genetic algorithms, evolutionary approaches, and particle swarm optimization, the study investigates the effectiveness of the evolutionary approaches in addressing various navigation obstacles encountered by UUVs. From explaining their applications in critical navigation surfaces such as path planning, path optimization, and obstacle avoidance, to create insights collected from existing literature and case studies, we aim to describe the transformative potential of evolutionary techniques in enhancing UUV navigation efficiency, precision, and resilience [3]. Additionally, efforts are made to address the ongoing challenges involved in integrating these techniques into UUV navigation systems. The aim is to provide discussions on future research paths to overcome these obstacles and develop advancements in underwater exploration and surveillance technologies

2. Evolutionary Optimization Techniques

In this section, the study embarks on a comprehensive exploration of evolutionary optimization algorithms, including genetic algorithms, evolutionary strategies, and particle swarm optimization, within the specific context of Unmanned Underwater Vehicle (UUV) navigation. These algorithms, moved by principles drawn from natural selection and population dynamics, offer sophisticated methodologies for addressing the complicated challenges posed by navigating UUVs through complex underwater environments [4]. At their

core, these algorithms employ mechanisms such as mutation, crossover, and selection to iteratively improve navigation strategies, reflecting the process of biological evolution in a computational basis. By connecting the power of iterative refinement and parallel exploration, evolutionary optimization techniques enable UUVs to adapt and optimize their navigation solutions in real-time, enhancing the precision and efficiency in underwater exploration and surveillance tasks.

Through a comprehensive examination of their fundamental principles and methodologies, this section endeavors to explain the workings of genetic algorithms, evolutionary strategies, and particle swarm optimization as applied to UUV navigation. From the exploration of various candidate solutions to the exploitation of promising navigation strategies, these algorithms offer a versatile toolkit for addressing the multifaceted challenges encountered by UUVs in their underwater missions. By providing a nuanced understanding of their capabilities and limitations, this section aims to lay a robust foundation for the practical implementation and optimization of evolutionary optimization techniques in the realm of UUV navigation. Finally, by connecting the potential of evolutionary algorithms, UUVs can navigate with improved accuracy, independence, and flexibility, unlocking new boundaries in underwater exploration and surveillance technologies [5].

2.1 Genetic Algorithms

Genetic Algorithms (GAs) are applied as an evolutionary optimization technique for enhancing navigation abilities. Genetic Algorithms (GAs) model potential navigation solutions as individuals within a population, constrained by limitations relevant to UUV paths, such as speed, direction, and depth. Through successive generations, GAs iteratively improves these solutions by selecting individuals with higher fitness, representing better navigation approaches, and applying genetic operators like crossover and transformation to generate new solutions [6]. By imitating the principles of natural selection and genetic difference, GAs enable UUVs to adapt and optimize their navigation paths in dynamic underwater environments, finally enhancing efficiency and accuracy in navigation tasks.

Cui et al [12] the Genetic Algorithm works by using a population-based approach to determine best charging paths for Unmanned Underwater Vehicles (UUVs). To begin with, key parameters such as genetic population size, maximum iterations, number of UUVs,

minimum distance of UUV, mutation, and crossover possibilities are prepared. Following this, an initial population of possible solutions representing charging paths is created. Then, each solution's fitness is estimated based on criteria including total distance traveled, genetic number index, insertion points, and individual UUV distances. Through genetic operators like mutation and crossover, new genetic populations are created and UUV arrangement is updated, causing iterative improvement across multiple generations. Finally, the algorithm selects the best solution based on fitness evaluation, concluding in an optimized charging path that minimizes UUV travel distance while efficiently servicing sensing nodes. This approach connects principles of natural selection and evolution to iteratively improve solutions, confirming the effectiveness and efficiency of UUV operations in charging scenarios. Figure 1 depicts the UUV network model.

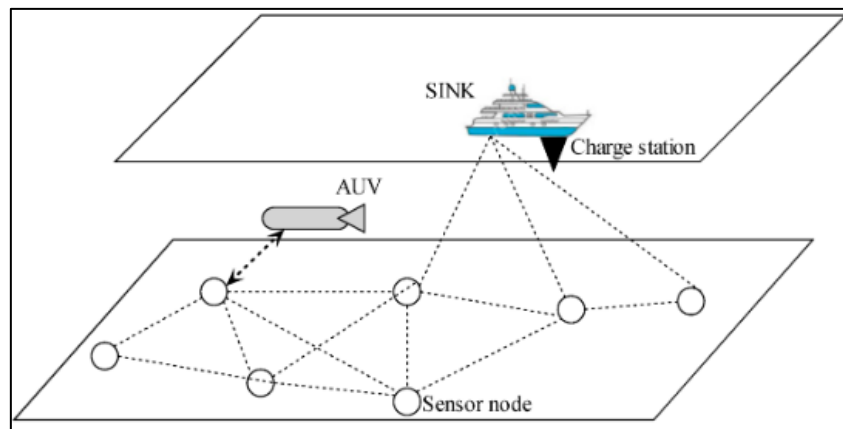


Figure 1. UUV Network Model [15]

2.2 Evolutionary Strategies (ES)

Evolutionary Strategies (ES) in the context of Unmanned Underwater Vehicles (UUVs) involve optimization methods inspired by genetic evolution. ES models potential navigation solutions as a population of individuals, each representative is a candidate path for the UUV. Over successive repetitions, ES adjusts the parameters of these paths using alteration and recombination operators, targeting to improve the navigation performance based on a defined fitness standard [7]. Unlike Genetic Algorithms, which naturally operate on fixed-length binary or real-valued encodings, ES often employs self-adaptive approaches, allowing for dynamic adjustments to transformation rates and step sizes during the optimization process. By

iteratively refining navigation strategies in response to environmental challenges, ES improves the flexibility and efficiency of UUV navigation in complex underwater environments.

Communication, direction finding, and observation face unique hurdles in the underwater surface. Communication is delayed by slow speeds and limited bandwidth, demanding cautious transmitter use and complicating data transmission. Navigation wants satellite support, relying instead on onboard sensors, possibly resulting in reduced accuracy, particularly with low-cost sensors, and degraded accuracy over time. Meanwhile, observation methods, whether optical or sound, encounter limitations such as short range for optical systems and difficulties in converting sound data into actionable data. These factors collectively amplify the difficulty of underwater communication, navigation, and observation when contrasted with other environments. As a solution Tomasz Praczyk et al [13] presents a neural control system for a group of Unmanned Underwater Vehicles. The group consists of a leader vehicle that guides the group along a programmed path while detecting obstacles. Follower vehicles follow the leader in a specific formation and avoid collisions with the leader and each other. The followers are prepared with a neural control system designed with a neuro-evolutionary algorithm. The system is fed with information from three sources: the leader through sound communication about plans and desired formation, sonar for sensing other vehicles and obstacles, and cameras located around each vehicle. The proposed control system was tested in simulation conditions and proved effective at maintaining formations while avoiding obstacles.

2.3 Particle Swarm Optimization

In Unmanned Underwater Vehicles (UUVs), Particle Swarm Optimization (PSO) serves as a powerful evolutionary optimization technique. Inspired by the collective behavior of bird groups or fish schools, PSO directs the search space by modeling possible solutions as particles within a swarm. Each particle denotes a candidate navigation solution, categorized by its position and velocity in the search space. Through iterative updates, particles adjust their positions based on their own best-known position and the best-known position of the entire swarm, guided by a capability function that evaluates navigation performance [8]. By leveraging social connections and individual experiences, PSO enables the exploration of promising navigation paths while maintaining a balance between exploration and exploitation. This allows UUVs to efficiently navigate through complex underwater environments, adapting

their paths in real-time to optimize performance based on environmental conditions and mission objectives.

Jialei Zhang et al [14] presents a particle swarm optimization (PSO) algorithm-based approach for spatially restricting and detecting electrified subsea cables using an Unmanned Underwater Vehicle (AUV). The method contains the UUV collecting electromagnetic signal measurements along premeditated survey lines vertical to the cable. These signals are then used as inputs to a PSO algorithm, along with limitations like a region of interest, to localize the position of the cable. Based on the localization results, new survey lines are determined online to continuously track and detect the cable. Simulation results demonstrate the effectiveness of the approach under different noise conditions and PSO parameter settings. Figure 2 shows the detection system is integrated on the UUV platform.

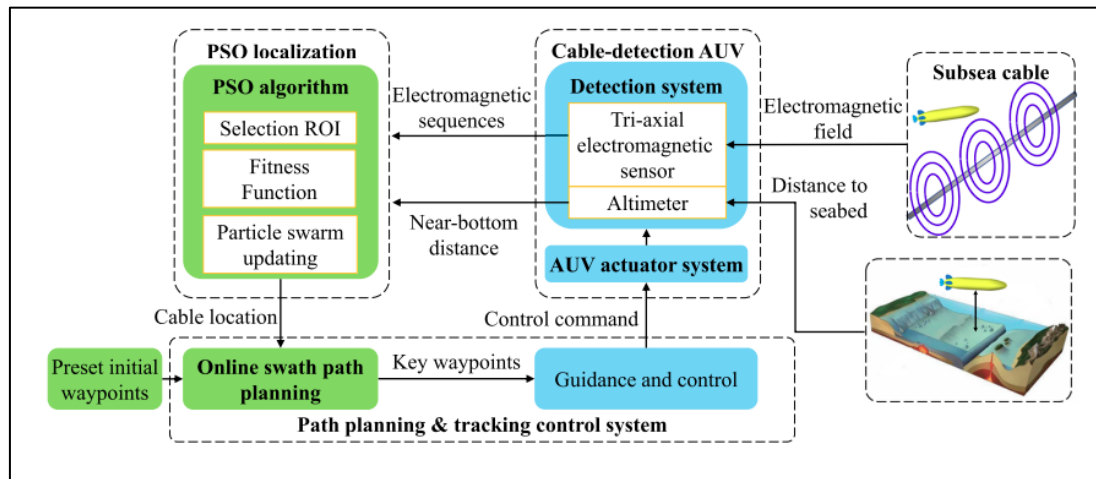


Figure 2. The detection system is Integrated on the UUV Platform [16]

3. Applications of Evolutionary Optimization in UUV Navigation

Evolutionary optimization techniques offer a various range of applications in Unmanned Underwater Vehicle (UUV) navigation, contributing to improved performance and flexibility in various features of underwater exploration and surveillance [9]. The applications include Path planning, Path Optimization, Localization, Obstacle Avoidance, and Task Planning.

- **Path Planning**

Evolutionary optimization algorithms are used to determine optimal paths for UUVs to navigate through complex underwater atmospheres whereas avoiding obstacles and reducing energy consumption. By iteratively filtering navigation strategies, these techniques enable UUVs to automatically plan efficient routes to reach designated waypoints or explore specific areas of interest.

- **Path Optimization**

Evolutionary optimization is employed to improve UUV paths, confirming smooth and efficient movement through dynamic underwater currents and changing environmental conditions. By altering navigation parameters such as speed, direction, and depth, these techniques enable UUVs to adapt their paths in real-time to achieve selected points while minimizing deviations and maximizing mission efficiency.

- **Localization**

Evolutionary optimization algorithms play a vital role in improving UUV localization accuracy by improving sensor fusion techniques and filtering localization algorithms. By integrating data from multiple sensors such as GPS, inertial sensors, and acoustic beacons, these techniques enable UUVs to accurately estimate their position and location in underwater environments, enabling exact navigation and mission implementation.

- **Obstacle Avoidance**

Evolutionary optimization techniques are applied to develop advanced obstacle avoidance approaches for UUVs, allowing them to navigate safely through cluttered underwater environments while avoiding crashes with obstacles such as rocks, reefs, and underwater constructions. By dynamically adjusting navigation paths and speeds based on real-time sensor response, these techniques improve UUV safety and consistency during navigation missions.

- **Task Planning**

Evolutionary optimization algorithms are employed to optimize UUV task planning, including task allocation, preparation, and resource allocation. By considering task objectives,

limitations, and ecological conditions, these techniques enable UUVs to autonomously plan and execute multiple tasks with multiple objectives while maximizing completion rate and efficiency of the task. Overall, the applications of evolutionary optimization in UUV navigation are diverse and complicated, offering valuable solutions to the challenges of navigating in complex underwater environments and advancing the capabilities of UUVs in various underwater exploration and surveillance tasks.

4. Challenges and Future Directions

Unmanned Underwater Vehicles (UUVs) using evolutionary optimization methods present several challenges and prompt exploration of future directions to improve their effectiveness. One challenge depends on scalability, as the density of underwater environments and mission requirements may surpass the abilities of traditional evolutionary algorithms [10]. Also, computational complexity poses an obstacle, particularly for real-time navigation applications where quick decision-making is crucial. In addition, confirming robustness and dependability in dynamic and uncertain underwater conditions remains a challenge, necessitating advancements in algorithmic stability and flexibility. Furthermore, the integration of evolutionary optimization techniques with other navigation methodologies and sensor technologies presents interoperability challenges that require careful attention.

Moreover, ensuring robustness and dependability in dynamic and uncertain underwater conditions presents another set of challenges. Evolutionary optimization techniques must oppose with the unpredictable nature of underwater environments, including changing currents, variable visibility, and unexpected obstacles. Developing algorithms that can adapt to these conditions and maintain navigation accuracy and stability in adverse situations is critical. Also, the integration of evolutionary optimization techniques with other navigation methodologies and sensor technologies presents interoperability challenges. Consistent diverse systems and ensuring continuous communication and coordination among different components of UUV navigation systems demand careful attention to integration strategies and standards.

Looking to future directions, research efforts are focused on addressing these challenges and evolving the state-of-the-art in UUV navigation. Novel evolutionary algorithms tailored exactly for underwater environments, such as hybrid and adaptive approaches, hold promise in overcoming scalability and computational complexity problems [11]. Also,

leveraging advances in sensor technologies, including improved sensing capabilities and reduction, can improve the robustness and dependability of UUV navigation systems. Furthermore, research activities focus on integrating evolutionary optimization with machine learning and artificial intelligence techniques to enable UUVs to learn and adapt to dynamic underwater conditions automatically.

Also, interdisciplinary association among researchers from various domains, including marine robotics, computer science, and oceanology, is essential for tackling the complicated challenges in UUV navigation. By developing collaboration and knowledge exchange, future research can lead to innovations that develop UUV navigation capabilities, paving the way for safer, more efficient, and autonomous underwater exploration and surveillance tasks.

5. Conclusion

In conclusion, the integration of evolutionary optimization techniques in Unmanned Underwater Vehicle (UUV) navigation presents both opportunities and challenges. While these techniques offer promising solutions for autonomous navigation in complex underwater environments, challenges such as scalability, computational complexity, and interoperability must be addressed. Future research directions focus on developing tailored algorithms, leveraging advancements in sensor technologies, and development interdisciplinary association. By overcoming these challenges and implementing emerging technologies, we can improve the efficiency, accuracy, and autonomy of UUV navigation systems. Ultimately, the application of evolutionary optimization in UUV navigation allows to revolutionize underwater exploration and surveillance, enabling safer, more efficient, and autonomous missions in the huge and unexplored depths of our oceans.

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