Integrated Mission Planning and Adaptable Docking System for AUV Persistence*

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***Abstract*— Mission planning for underwater area coverage missions has typically been completed separately to development of charging infrastructure. This paper presents a proof of concept for an integrated mission planning approach and docking system to enable underwater persistence. The mission planner follows a genetic algorithm approach to generate trajectories for working AUVs to perform an area coverage mission and locations for docking stations to respond to AUV energy needs. The docking system is a light weight, portable dock that is adaptable to a wide range of AUVs and can be mounted on small marine platforms. Experimental validation of the docking system was completed using a Bluefin SandShark due to the ease of customization of the payload bay. Validation of the planned missions was completed using an OceanServer Iver3 equipped with an enhanced sensor suite. Experimental results in open water validate the concept of an integrated mission planner and docking system to enable multi-robot systems to operate long-term missions without manned support.**

***Index Terms*— Marine Robotics; Motion and Path Planning; Autonomous Underwater Vehicle; Mission Planning; Docking**

I. INTRODUCTION

Autonomous area coverage in underwater environments is typically limited by platform endurance and requires manual recharging and retasking between missions. The feasibility of using docking stations for charging of autonomous underwater vehicles (AUVs) has long been considered, however these docking stations have typically been costly installations and platform-specific, reducing their adoption [1]. Additionally, most AUV missions follow a traditional 'lawn mower' pattern for area coverage that can encounter problems with regard to energy limitations on long duration missions. Persistent AUV operation is currently limited by the lack of not only feasible docking stations, but also a comprehensive planning strategy to overcome the energy limitation inherent in the design of underwater robotics platforms.

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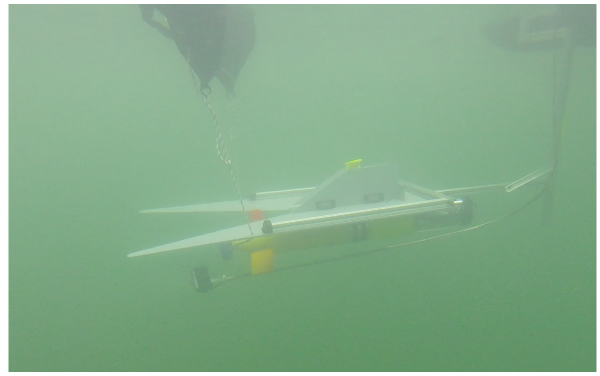


Fig. 1: The AUV is charged at docking station during coverage mission.

Deploying multiple docking stations has been studied recently to extend the operation of AUVs and increase the mission area size for long-term missions [2]–[4]. Without an efficient planning approach that can manage multiple stations and AUVs, the performance of the system will be limited and the mission outcome will be affected adversely. A planning approach that is compatible to different docking platforms is required. Our approach solves underwater mission planning problems with different objectives and constraints and is based on a Genetic Algorithm (GA) [5]. GA is a global optimization method which has been widely applied to generate paths for robots due to its high flexibility [6], [7]. Our method generates trajectories for AUVs and locations for docking stations to satisfy mission requirements for integration with docking systems.

Docking system design has typically followed a funnel [8], [9] or pole [10] design. While these existing stations are able to support charging of AUVs, they have not seen widespread adoption. Docking station deployments are limited due to lack of flexibility to support a wide range of AUVs, high costs, and the conservative nature of marine engineering. Existing docking stations are compared extensively in [1], [11].

This paper presents an integrated planner and docking system that can be used to enable AUV persistence. The planner applies a genetic algorithm approach for generating charge-aware AUV trajectories and scheduling multiple charging rendezvous with fixed docking stations. The trajectory allows the area coverage mission to be operated for an extended period of time and increases coverage size. The mission planning algorithm presented here is adaptable to different mission scales and vehicle counts. The docking station is a lightweight, portable system based on a simplified funnel design. The docking station can be mounted on a small surface platform for easy deployment. Experimental validation of the planner and docking system was carried out using an OceanServer Iver3 and a Bluefin SandShark. The Iver3 was programmed to follow the genetic algorithm developed trajectories while the SandShark was deployed to complete docking missions. Experimental validation on the two platforms indicates that the planning and charging infrastructure could be used to enable mobile underwater persistence.

The remainder of this paper presents the mission planner in Sec. II, the docking system in Sec. III, experimental results in Sec. V, and a conclusion and future work in Sec. VI

II. Mission Planner

A charge-aware Genetic Algorithm (GA) approach in a multi-vehicle system was designed in our previous work [12]–[14]. The developed GA approach obtains optimized trajectories of working robots and locations of charging stations including consideration of various environmental constraints. In this work, the method generates trajectories for AUVs and places docking stations to facilitate full coverage of the mission area considering energy limitations.

The GA approach uses fixed-length decimal encoding to represent AUV trajectories and charging points. To encode trajectories, each GA chromosome (candidate solution) comprises of a permutation of mission points (genes) as an ordered list. The ordered genes in the chromosome represent the order of mission points to be visited by AUVs. Charging points, encoded by a sub-population, indicate where AUVs need to get charged. The sub-population is used to decide the location of docking stations at the end of the algorithm.

In each GA iteration, chromosomes are evaluated by the fitness function F, calculating the travel distance of AUVs and the cost associated with the charging points

$$F = \omega E + S, \tag{1}$$

where E is the travel distance of AUV, S is distance between each charging point, and ω is the weight. The weight ω is set based on mission requirements and balances the trade-off between length of trajectories and number of recharging attempts.

Chromosomes with lower cost in each generation are selected to produce the population for the next iteration. The selected chromosomes are used for single parent, two-point crossover [15] to avoid producing duplicated genes. In addition, the sub-population representing charging points is adjusted in the crossover process. The GA stops when the number of iterations reaches the maximum number. The chromosome with the lowest cost, F, in the last generation and its associated charging locations are the output of the GA. An example multi-vehicle, multi-charger trajectory is shown in Fig. 2 for three AUVs and two docking stations.

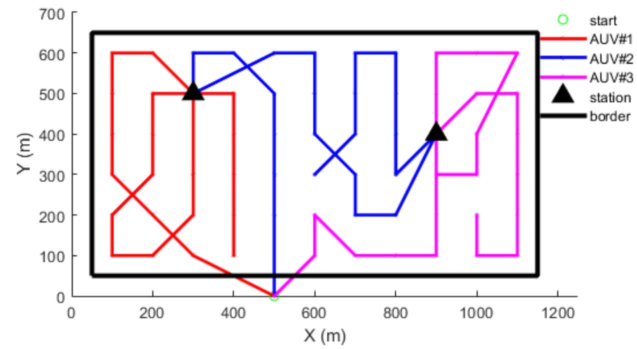


Fig. 2: GA result for three AUVs (lines) and two docking stations (black triangles) for a 0.66 km^2 area. The area covered is located in Eagle Harbor on Lake Superior, USA.

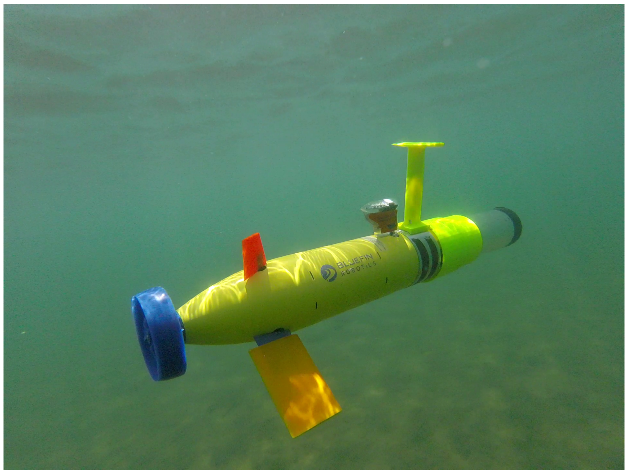
III. Docking System

The docking system used is a simplified funnel design first presented in [16]. This docking system is low-cost and easy to deploy. The dock features a single active light beacon that is used for homing and can be mounted off of the transom of any small marine craft. For the purposes of this work, an inflatable dinghy was used to carry the docking station.

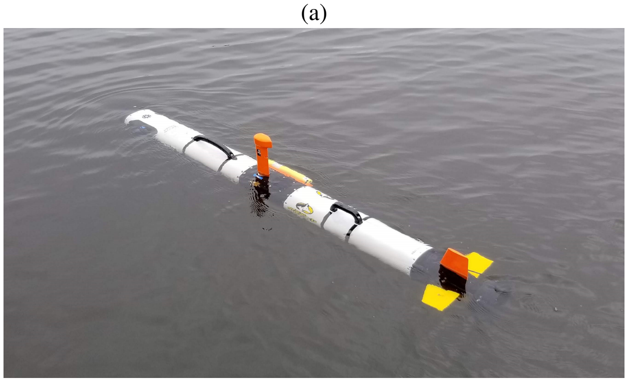
Attached to the AUV is the docking adapter. This docking adapter takes the shape of a ‘T’ and mounts on top of the vehicle similar to a mast. The docking adapter is the only component of the AUV that contacts the docking station. This means that a single docking station could potentially support a wide range of AUVs.

During the docking process, the AUV navigates independently towards the start of the docking trajectory. Once in the terminal homing stage, control is handed off to the backseat docking controller [17]. The backseat controller is a local navigation controller that takes over command of the vehicle actuators during the docking maneuver. The backseat navigates the AUV towards the dock using a single camera, single beacon approach similar to [18]. Specifically, the backseat controller has a camera located on the nose of the vehicle. The image from this camera is processed to identify the brightest region where the beacon light and dock are located. The output is then fed into a PID controller that controls rudder angle. Depth is controlled independently based on a known docking depth.

As the vehicle approaches the docking station, the docking adapter will impact the simplified funnel. The resulting force will guide the AUV towards the center of the docking station. During the final maneuver, the guide planes on the top of the docking adapter slide upwards along the docking station ramp. This pulls the vehicle up and into the docked position. Once docked, the vehicle is coupled to the dock with a non-contact magnetic latching system at which point power and data are transferred through a WFS Seatooth Connect.



(a)



(b)

Fig. 3: The two AUVs used to test the scenario. a) a Bluefin SandShark and b) an OceanServer Iver3.

IV. Experimental Vehicles

Two AUVs were used to validate the test scenario; a Bluefin SandShark (Fig. 3a) and an OceanServer Iver3 (Fig. 3b). The SandShark was used for docking tests due to the easily modified nature of the payload bay. The overall mission validation was completed with the Michigan Tech OceanServer Iver3 due to the improved sensor suite onboard that allowed more accurate trajectory following.

The Bluefin SandShark is a small, low-cost AUV designed with a large, reconfigurable payload bay. It also features the ability to use a frontseat-backseat control scheme [17]. To enable docking, the payload bay has been replaced by a pressure hull with a Raspberry Pi and a webcam, additionally, a docking adapter has been mounted on top of the vehicle. Control of the SandShark during docking operations is completed using the backseat controller implemented on the Raspberry Pi. This controller uses the webcam to look for a single beacon light on the dock. With the pre-set docking depth the AUV is able to successfully navigate into the dock.

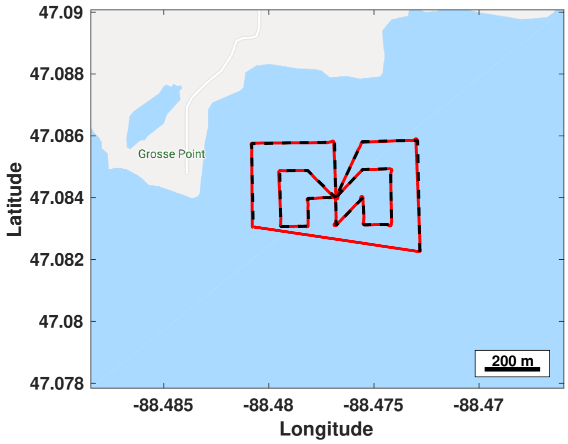
To validate the overall mission trajectories an OceanServer Iver3 was used. The Iver3 is slightly larger than the SandShark and features a full sensor suite for enhanced navigational performance. The Michigan Tech Iver3 is configured with a Doppler Velocity Log (DVL), inertial navigation, side scan sonar, forward looking obstacle avoidance sonar, and camera. Using these sensors, the vehicle is able to accurately navigate transits in challenging environments with currents.

Fig. 4: Iver3 in the water next to the Michigan Tech Osprey boat. The Osprey was used to transit to the test location from Michigan Tech facilities.

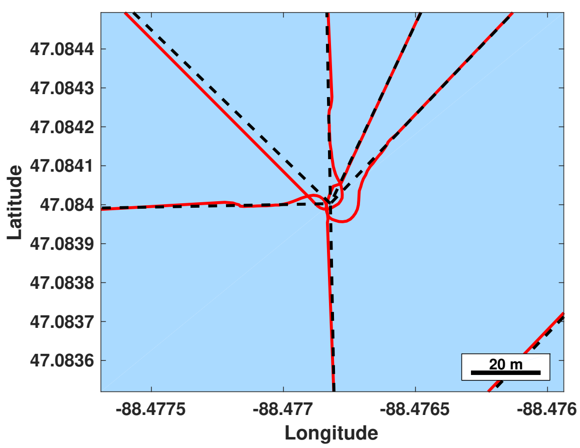
V. Experimental Results

Mission planning validation was completed in Portage Lake, Michigan near Grosse Point using the Michigan Tech Iver3. For mission validation, the AUV was configured to operate at 2 meters below the surface. Testing conditions were calm water and 5 to 10 knot winds, Fig. 4. The operational area is sheltered from prevailing winds and waves and is a consistent 10 meters deep with a solid bottom. The Iver3 was commanded to follow a single AUV-single charger GA planned trajectory in an area of 600 meters by 300 meters. The overall mission length is 3684 meters with a mission time of 47 minutes. The mission was configured with 25 meter GPS alignment legs to start every submerged linear transit. The planned trajectory and the trajectory followed by the Iver3 are shown in Fig. 5. In Fig. 5a, the overall trajectory that the Iver3 followed was very close to the planned trajectory. The vehicle was put in the water near the end of the trajectory (bottom left) and transited towards the start of the trajectory (bottom right). Once at the start, the vehicle followed the trajectory through three rendezvous' with the fixed station location before reaching its finish location. The detail of the trajectory followed at the fixed rendezvous location is displayed in Fig. 5b. During the entire trajectory, the vehicle averaged 0.46 meters distance to track with a maximum of 7.63 meters at a sharp change in heading such as at the rendezvous location.

To validate the docking system design, a Bluefin SandShark was equipped with the docking adapter and backseat control payload. The SandShark was then deployed in the Michigan Tech pool for 50 hours of development and validation. Pool development focused on core functionality such as accurate depth tracking and homing towards the dock. An example trajectory logged using an overhead camera



(a)



(b)

Fig. 5: a) The trajectory followed by the Iver3 during a multiple rendezvous mission generated by the genetic algorithm. Dotted lines are the desired trajectory, solid lines are actual path followed by the vehicle. b) Zoomed in on details of rendezvous location.

system is shown in Fig. 6. Pool testing shows the SandShark successfully docking with several meters of initial cross track and heading error. Limited open water testing was completed before the end of the testing season 2018. These tests primarily focused on feasibility of the docking system in real world conditions.

The transition from pool to open water presented some unique challenges. This is largely because the docking system has been designed to operate in deep and calm water conditions with a truly fixed station location. Prototype testing was completed in shallow water with the docking station attached to a very small inflatable boat. Therefore, the docking station was effected by wave state. Moreover, the water was much brighter than originally planned for. The surface wave action caused the docking station and the AUV to be disturbed in all directions. This was particularly challenging in the vertical plane as the AUV attempted

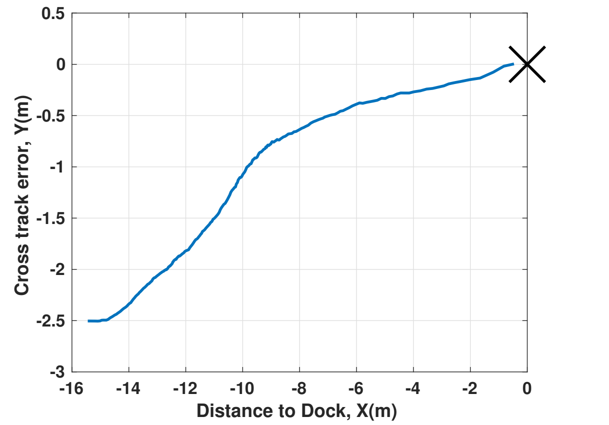


Fig. 6: Example docking trajectory followed by the SandShark during pool testing. In this test the AUV was launched with a 2.5 meter initial cross track error and successfully docked.

to maintain the target docking depth despite wave action. Additionally, the image processing algorithm was unable to differentiate between the sun and the beacon light on the dock. This has caused misidentification of the dock several times and resulted in missed approaches. While prototype testing performed in shallow water has presented challenges, these problems are not expected to appear in oceanic deployments. Addressing the challenges of operating in littoral zones off of small support crafts will make the docking system more robust for deep ocean operation.

VI. Conclusion & Future Work

This work presented an integrated mission design approach. This approach includes a genetic algorithm to create trajectories with scheduled chargings and an adaptable docking system. Open water validation of the generated trajectories was completed using an OceanServer Iver3. The AUV was able to follow the prescribed trajectories with an average 0.46 meters cross track error. Pool validation of the docking system was completed using a Bluefin SandShark. The system was evaluated from a wide range of initial starting locations and attitudes. Preliminary open water docking was also completed between the SandShark and an inflatable dinghy. Open water tests in shallow water presented unique challenges such as false beacon identification and vertical disturbances from surface waves. Despite these challenges, docking was successfully performed in Lake Superior.

Future work with this project is extensive. We will focus on improving positive beacon identification and localization to the dock. This will be accomplished by implementing machine learning for identification and localization of the dock. Validating the charge transfer process using a WFS Seatooth Connect inductive power module is another aspect of the ongoing research effort. Following improved image recognition and wireless power transfer, the AUV will be deployed on long duration missions with multiple charges required to complete. The ultimate goal of the integrated mission planning and adaptable docking system is deployment of a multi-vehicle, multi-dock collaborative network of robots.

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