

Coordinated Localization with Multiple Autonomous Underwater Vehicles

I. PROBLEM ADDRESSED AND ITS IMPORTANCE

REMOTELY operated vehicles (ROV) are used in a number of underwater applications. Human operators use ROVs equipped with video cameras to inspect the hulls of ships and detect faults in underwater cable lines. Also, ROVs with robotic arms are used to repair underwater structures that are at depths that are too dangerous for humans. Unfortunately, ROVs are inherently operated by humans, which occupies an operator's time while he could be performing other tasks. This is an especially important problem with the United States Navy's new surface ship, the Littoral Combat Ship, where there are more autonomous vehicles than human operators on board. Two of the main obstacles to a fully automated underwater vehicle are the lack of underwater robotic localization and the lack of reliable communications links. Localization for ground and aerial robotic platforms is often solved with the use of the Global Positioning System (GPS). However, radio frequency (RF) propagation is highly attenuated in water and is often a function of water salinity. Thus, an autonomous underwater vehicle (AUV) could rely upon a form of Simultaneous Localization and Mapping (SLAM) in order to determine its location in a marine environment. There are number of sensors that could be incorporated in the SLAM feedback loop to provide the AUV with data about its environment, such as a high resolution sonar image, video camera, or Doppler velocity logger. However, depending on the sensor, the AUV must be at a minimum or maximum distance away from the seafloor and surface. Also, using video data to localize underwater can be difficult due to a lack of features in deep water or lack of water clarity. The issue with maintaining a specific distance from the seafloor or surface is that this restriction can impede the AUV from tending to its actual mission objectives. A possible solution to this problem is to implement a network of AUVs that can communicate and collaborate. Within the network, AUVs would be assigned specific roles, such as observing the seafloor for localization or scouting ahead for targets of interest. Thus, the AUVs would only have to maintain localization relative to each other in the network, while only a single AUV would have to maintain global localization. While a network of AUVs could surely replace ROVs with human operators in the previously mentioned missions, a network of AUVs could also be used in coastal protection to prevent illegal smuggling into the country. Multiple AUVs could also be used to autonomously measure contaminants in the ocean where companies drill for oil. Finally, a network of AUVs could be utilized to take scientific measurements in dangerous locations, such as the north and south poles. There are a number of challenges involved with implementing a network of AUVs that can maintain localization, but the final product

has a number of valuable applications.

II. STATE OF THE ART AND NEED

Due to the multidisciplinary nature of underwater robotics, a survey of the state of the art in the field can be broken down into three categories: Sensors and Computer Vision, Communications, and SLAM.

In the domain of land-based and aerial autonomous systems, a video camera for detecting features and obstacles is often an important sensor. In the field of underwater robotics, vehicles have been equipped with video cameras to detect underwater cables and the seafloor [1]. However, turbulence in the water can fill the water column with dust and other particles that obfuscate the video camera's view of the seafloor. Also, the AUV would have to remain only a few meters from the surface at all times to ensure that it could detect the floor due to the high attenuation of light in water. In underwater settings, sonar imagers often replace video cameras as a means of detecting features. The use of a Mechanically Scanned Imaging Sonar (MSIS) to perform underwater SLAM with a single vehicle was demonstrated in [2] and [3]. The MSIS process involved rotating a mounted sonar while measuring the sonar pulse echo intensities over time. Unfortunately, the process of making a 360° sonar image took over 13 seconds due to the inherent mechanical delays in MSIS. Another popular sonar option in the underwater domain is the side-scan sonar, which was used in [4] to perform underwater SLAM. The authors of [4] described side-scan sonar as being a viable option for AUVs due to the low-cost of side-scan sonars. However, in their paper, the authors stated that the complexity of mapping observed landmarks to features using a side-scanning sonar could be unsuitable for an embedded application, as they relied mostly upon post-processing to perform SLAM. Doppler Velocity Logs (DVL) have only recently become available for small AUVs due to miniaturization of components. DVLs operate by emitting acoustic pulses directed at the seafloor and measuring the Doppler shift of the echo signal. The Doppler shift is used to determine the velocity of the AUV, which can be used to resolve dead-reckoning in localization. Researchers at the SeaVision Underwater Solutions, Inc. utilized a DVL on an ROV to improve localization in [5]. The researchers determined an error of 3.3% in localization with the use of dead-reckoning with the DVL over 166.4 meters. Although, they did mention that the error seemed to grow with more tests, which might indicate that localization with DVL could be unbounded. Thus, DVL could be used to improve dead-reckoning, but another method of "closing the loop" will be required. A third category of sensors is called the Inertial Navigation System (INS). This is a common sensor to all types

of vehicles that measures accelerations and forces which can be integrated to determine vehicle velocities and positions. Researchers in [6] were able to use a INS in concert with a DVL to achieve localization errors of less than 0.2%.

Fast and reliable underwater communications is an unsolved problem. Due to the high attenuation of RF signals in water, acoustic signals are used to transmit data between AUVs. The Woods Hole Oceanographic Institution's (WHOI) micro-modem is probably the most popular acoustic communications device in AUVs due to its small size and ease of integration [7]. Still, underwater acoustic communication channels are inherently slower than air-based communications; thus, any network of AUVs will be required to strictly regulate its severely limited communication bandwidth.

The final piece of the SLAM puzzle is the actual probabilistic algorithm that fuses the data from the sensors and its inherent knowledge of the environment to achieve accurate localization. The two most common Artificial Intelligence techniques to perform SLAM are Extended Kalman Filter (EKF) SLAM and Particle Filter (PF) SLAM [8]. EKF-SLAM relies upon Gaussian distributions in the motion model and the measurement model to determine a maximum likelihood for the vehicle's position. Decentralized and centralized versions of AUV EKF-SLAM were compared in [9], where the authors concluded that Decentralized EKF-SLAM is more costly in terms of communication, but it is feasible. Still, the authors noted that when multiple AUVs shared observations the errors in landmark detection were significantly decreased compared to not sharing landmark observations. PF-SLAM is part of the Monte Carlo family of SLAM methods. [8] described how PF-SLAM maintained a finite set of discrete hypotheses of the vehicle's state; but, EKF must maintain a complete Gaussian distribution. However, the PF does not maintain a "best guess" for the AUV position, which EKF does; thus, in the PF algorithm, the weighted mean of the distribution must be computed [8].

III. PROPOSED TECHNICAL APPROACH

The main purpose of the proposed research is to develop a network of AUVs that can cooperatively perform Decentralized EKF-SLAM. The development of the AUV network will take part in two parallel stages: software simulation and hardware implementation. The software architecture will heavily rely upon the Robot Operating System (ROS) [10], a popular publish-and-subscribe architecture for robotic platforms, for communication between actuator, sensor, and decision-making nodes on a single AUV. ROS will also be used for the simulation environment for the development of the Decentralized EKF-SLAM. ROS was chosen for the software environment because any software developed in ROS on a standard desktop computer can be executed on the final robotic platform's embedded Linux computer without any code modifications.

A. Vehicle Development

The network of AUVs will be implemented with three Yellowfins. The Yellowfin is an AUV that was developed at the Georgia Tech Research Institute (GTRI) for the purpose of

researching autonomous behaviors. Currently, the Yellowfin is fitted with an INS, acoustic communications module, compass, GPS, depth sensor, and single-board computer with a Linux operating system. In order to improve its localization, the Yellowfin will be retrofitted with a downward-facing DVL. The DVL will be used in concert with the INS to measure the vehicle's velocity as described in [6]. To improve the AUVs underwater vision, two side-scan sonars will be added to the Yellowfin. The side-scan sonar's primary function will be feature detection along the seafloor. Experiments and research will have to be performed to determine the best methods of classifying an underwater feature. As the underwater landscape can vary greatly throughout the world, a harbor area such as the one found at Savannah's Skidaway waterway will be targeted.

B. Decentralized EKF-SLAM Development

The Decentralized EKF-SLAM architecture that will be implemented will most closely resemble that of the one described in [9]. Each vehicle will maintain a complete map of the work area and the vehicles will only directly communicate detected landmarks via acoustic communications. Thus, each vehicle will be able to generate state estimates from directly measured landmarks, internal predictions, and communicated landmarks. Unlike [9], this research will place an importance on maintaining relative localization within the network of AUVs by using a variant of the Long Baseline (LBL) localization method. In the standard LBL, sonar buoys are located in the water that emit a time stamp. With the use of synchronized clocks and a determination of the Time-of-Flight (TOF) of the sonar signal, the AUV can triangulate itself between several buoys with the use of its depth sensor, as shown in Figure 1. In

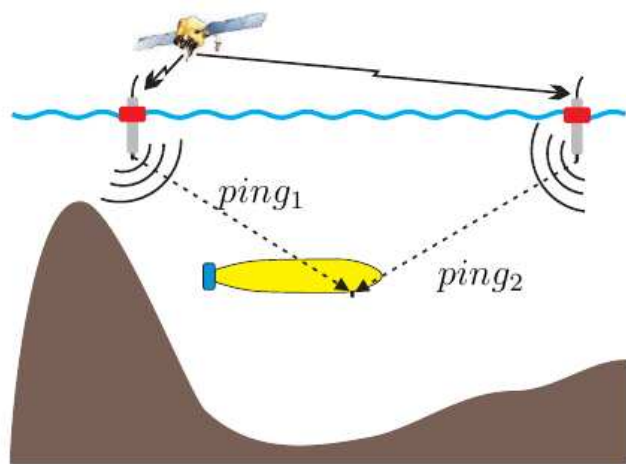


Figure 1. AUV localization with beacons and LBL [8]

this implementation, whenever a vehicle communicates the observation of a landmark, the data packet will also include a time stamp from which a TOF can be calculated. With this scheme, the vehicles will be able to implement both a feature-based Decentralized EKF-SLAM as well as localize relatively within the network. Command messages will also be incorporated in the communications architecture that allow

for a vehicle to communicate its exact known position when it is surfaced and has a GPS lock. The other receiving vehicles would then be able to adjust their estimated states based on this confident measurement.

IV. PROPOSED EVALUATION

The AUV network of three Yellowfins will be tested at the Skidaway Institute of Oceanography. The experiment will begin with the three Yellowfins in the water, at which point one of the AUVs will dive to a depth such that its DVL can lock onto the seafloor. The second AUV will dive to a depth halfway between the ground-tracking AUV and the AUV that has GPS lock at the surface. At this point, the GPS-locked AUV will transmit its location to the other AUVs, which will set a base location for the AUV network. The GPS-locked AUV will then submerge below the surface, thus losing its GPS lock, and then the network will move towards one of its 10 defined waypoints. The AUVs will each be running the previously described Decentralized EKF-SLAM while using TOF to localize within the group. The final metric that will be used to determine the success of the SLAM algorithm will be the AUV network's localization error from ground truth. The ground truth will be measured with the use of a surface test vehicle with a GPS lock. The surface test vehicle will keep open communication with the AUV closest to the surface and the surface vehicle will log the AUV's estimated location. The localization error in this experiment will be compared against the error from [6], which used a DVL with an INS. The method of measuring the TOF from the transmitted landmark observations is novel and will greatly improve the overall accuracy of the network localization. The improved relative localization will also enable the network of AUVs to implement formations for improved landmark detection and special formations for specific mission objectives.

V. RESEARCH PLAN

The proposed research will require one graduate student to complete within a year. The graduate student will focus on retrofitting the Yellowfin AUVs with side-scan sonars and DVLs as well as implementing the Decentralized EKF-SLAM algorithm. The research will culminate with the testing at the Skidaway Institute of Oceanography in Savannah, Georgia. The project will start May 1, 2011 and end April 30, 2012. See Table I for a detailed description of the project milestones for the student. The dates listed in Table I are the completion dates for the specific project milestones. It is clear that all purchases are made early in the project to avoid delays due to long-lead items. The student will have to develop both the software and the hardware in parallel. This will allow him to incrementally test the system as the project progresses, which will ensure the overall stability of the system. One of the most important milestones, "Decentralized EKF Algorithm implemented," is listed later in the project only because it relies upon the completion of previous steps. With a properly architected system the final algorithm development will be successful.

Milestone Description	Milestone Date
ROS installed on Yellowfin computer	May 30
Surface test vehicle selected and purchased	June 15
Auto-CAD drawings of hardware changes finalized	June 30
Drivers written for DVL	July 15
Drivers written for side-scan sonar	August 1
Acoustic comm architecture finalized	September 30
TOF calculation algorithm finished	November 15
Sonar and DVL fitted to all three Yellowfins	December 15
Landmark feature parameters defined	December 30
Feature extraction algorithm complete	January 1
Multi-AUV ROS software simulator implemented	January 15
Decentralized EKF Algorithm implemented	February 20
Software for test surface vehicle finished	March 1
Testing finished at Skidaway	March 30
Paper finished about AUV Decentralized EKF-SLAM	April 30

Table I
PROJECT MILESTONES

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