

A Testbed for Performance Evaluation of Underwater Vehicle Team Formation and Steering Algorithms

Baozhi Chen and Dario Pompili

Department of Electrical and Computer Engineering, Rutgers University, Piscataway, NJ 08854

Emails: baozhi_chen@cac.rutgers.edu, pompili@ece.rutgers.edu

Abstract—Underwater testbeds are key tools for performance evaluation of underwater communication and coordination algorithms to enable swarming of autonomous vehicles. We describe a demonstration of underwater vehicle team formation and steering algorithms using our underwater testbed. The testbed allows the user to configure ocean currents and underwater communication parameters so to study properties of these algorithms such as stability, robustness, and convergence.

I. INTRODUCTION

UnderWater Acoustic Sensor Networks (UW-ASNs) [1] have been widely deployed to carry out collaborative monitoring tasks including oceanographic data collection, disaster prevention, and navigation. Autonomous Underwater Vehicles (AUVs) equipped with sensors are used for underwater exploration and information gathering. Underwater gliders are a energy-efficient class of AUVs; they are battery-powered vehicles that change their buoyancy with hydraulic pumps to power forward motion.

Acoustic communications outperform radio frequency and optical communications underwater and hence are used to exchange information between AUVs and, eventually, to a surface station where the data is gathered and analyzed. While acoustic waves is the only communication technology for ranges above a hundred of meters, path loss, noise, multi-path, Doppler spread, and high propagation delay affect performance. All these factors make the channel bandwidth and data bit rates limited and dramatically dependent on both range and frequency.

Several software simulators (e.g., [2]) have been proposed for underwater communication networks. While these simulators model some of the underwater acoustic channels properties, they do not capture the characteristics and constraints of real acoustic modems such as WHOI, Benthos, and LinkQuest. For example, packet transmission and processing delays as well as internal latencies, which are not negligible in real acoustic modems, may be in the order of seconds [3] and are not considered in existing software simulators. Such delays may greatly increase the delay between communication pairs, which, in turn, may affect the performance of Medium Access Control (MAC), routing, and transport protocols. On the other hand, experiments on real testbeds such as [4] are usually expensive and time consuming, and so are the field deployments at the ocean. Also, few researchers in the community have all of the necessary equipment to conduct field experiments, or even simulations, as underwater vehicles and acoustic modems are very expensive mainly due to the lack of economies of scale.

To overcome these limitations, we developed a testbed that fills the gap between the existing methods for simulation

and field trials. Our testbed can increase the accuracy of the simulation environment by using a hybrid simulator/emulator approach. It has the same modem interfaces as found on underwater vehicles so that - once proven in the testbed - a communication protocol may be used for field testing without major changes. Moreover, vehicle team formation and steering algorithms can also be implemented and tested on our testbed.

To illustrate the use of our testbed, we propose a demo of our underwater glider team formation and steering algorithms presented in [5] using the WHOI acoustic Micro-Modems [3]. A Graphical User Interface (GUI) is also implemented to configure the parameters and to present a 3D visualization of the movement of the vehicles. The user can define the number of gliders, team formation geometries, and steering trajectories; also, the user can specify *environment parameters* (3D region, ocean current models, current directions, and current velocity) as well as *communication parameters* (data and control packet types and lengths, transmission power, and battery capacity). The user is able to evaluate the effect of ocean current and underwater acoustic communication impairments on the vehicle coordination algorithms. Hence, the feasible regions of the algorithms can be studied.

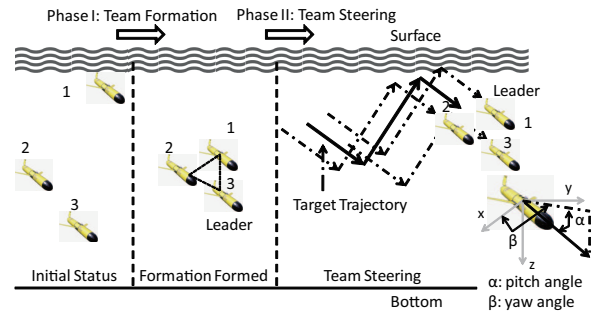


Fig. 1. Overview of the proposed solution for team formation and steering.

The remainder is organized as follows: in Sect. II we summarize our solutions for team formation and steering; in Sect. III we describe our testbed and in Sect. IV we provide the demo details; the demo requirements are listed in Sect. V.

II. TEAM FORMATION AND STEERING

In [5], we proposed novel algorithms to form a team of gliders into a specified geometry and steer it through the 3D region of interest to take measurements in space and time. As depicted in Fig. 1, given i) the number of scattered gliders, ii) the corresponding geometry formation, and iii) the target

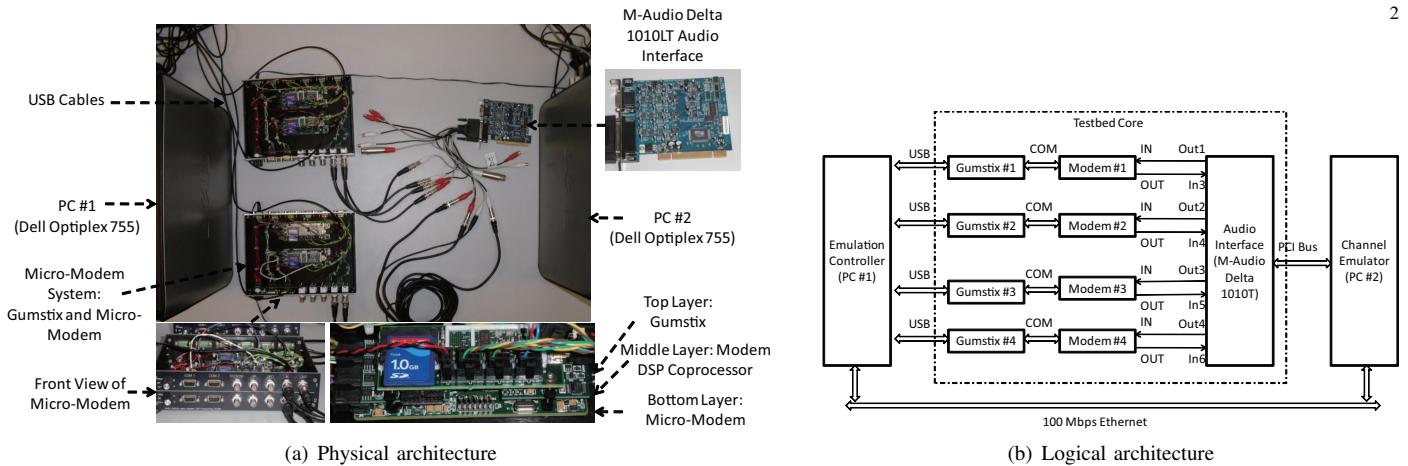


Fig. 2. Testbed architectures.

trajectory, two phases of operations are required to perform the monitoring mission: 1) the selected gliders need to be mapped into a specified geometry formation making sure that no glider collisions occur (*Phase I*); 2) after the first phase, the team needs to steer through the region of interest along the predefined trajectory while maintaining the formation (*Phase II*).

In Phase I, the problem is to map every glider to its position in the formation. Selecting a position in the formation for a glider depends upon factors such as the time for that glider to reach this position, the possibility of collision with other gliders, and the permutation of the gliders with the formation positions. We proposed an algorithm in [5] to minimize the time to form the specified geometry under a sufficient condition to avoid vehicle collision. In Phase II, team steering is divided into *two subproblems*: 1) steering the team to follow the planned team trajectory, and 2) maintaining the formation.

For the first subproblem, the AUV that surfaces last is selected as the leader as it has the most accurate location information. The *leader* estimates the team ‘displacement’, i.e., the deviation from the target trajectory, and then leads the whole team back to the target trajectory; the other gliders, i.e., the *followers*, will then focus on maintaining the geometry of the formation, i.e., following the leader’s path.

For the second subproblem, we use a hybrid approach to keep the team formation depending on whether the position information is *absolute* or *relative*. Specifically, *Absolute Formation Adjustment (AFA)* is used when absolute information such as gliders’ position is available; whereas *Relative Formation Adjustment (RFA)* is used when relative information such as inter-vehicle velocity is available. The reason for this hybrid approach is to reduce the communication overhead for position information dissemination. Due to space limitation, we cannot give a detailed description of these two algorithms, but more details can be found in [5].

III. DEMONSTRATION TESTBED

Our solution is closely coupled with the communication functionalities of WHOI Micro-Modems. Therefore, in this section, we present the *physical* and *logical* architecture of

our underwater network testbed [6]. Our underwater testbed relies on a multi-input multi-output audio interface installed on a Personal Computer (PC) and can process real-time signals via software. With the help of software tools such as MATLAB, we can precisely adjust the signal gains, introduce propagation delay, mix the acoustic signals, and add ambient and man-made noise as well as interference in real time. Consequently, accurate underwater acoustic communications can be emulated. To our knowledge, our testbed is the first to accurately emulate underwater acoustic communications using real hardware.

The physical architecture of our testbed includes (Fig. 2(a)):

- **WHOI Micro-Modem.** A low-power underwater acoustic modem developed by WHOI. It can transmit 4 different types of packets at 4 data rates in 4 different bands (3–30 kHz). Control of the modem is by NMEA commands [3].
- **Audio Interface.** M-Audio Delta 1010LT PCI Audio Interface. It is a 10-In 10-Out 24-bit PCI audio interface card with maximum sampling rate of 96 kHz. It can process the audio signals from multiple inputs in real time and route them to corresponding outputs.
- **Gumstix Motherboard (GM).** The embedded system with Marvell PXA255 400 MHz processor, 64 MB RAM, and 1 GB SD disk storage. It runs OpenEmbedded Linux and controls the modem via serial port. It is connected to personal computers through the USB port.
- **PC #1.** A Dell Optiplex 755 desktop with Intel 2.4 GHz Quad Core CPU and 2 GB RAM. It runs the computer emulation controller software commanding the GMs. It also controls the channel emulator running at PC #2 via Ethernet and collects the emulation results from the GMs.
- **PC #2.** The same configuration as PC #1. It listens to the control information through the Ethernet from PC #1 and emulates the underwater communication channels.

The logical architecture of our testbed is shown in Fig. 2(b). When the emulation starts, the Emulation ConTroLler (ECTL) at PC #1 issues commands to the channel emulator at PC #2, which will then start to emulate the channel according to the parameters provided. ECTL then requests the GMs to run their network tasks. Whenever a packet is transmitted or received,

the GMs inform the ECTL via USB connection so that ECTL can collect the emulation results and issue further commands. Upon receiving the command from PC #1, the channel emulator at PC #2 will adjust the gains of input signals, mix them, emulate the propagation delay, add ambient noise, and route the processed signals to the corresponding outputs. Acoustic signals are processed in real time with MATLAB using real-time audio processing package *Playrec* [7].

IV. PROPOSED DEMONSTRATION

As shown in the snapshot reported in Fig. 3, our demo visualize the 3D movement of underwater gliders following our team formation and steering algorithms. On-going communications among the gliders is also monitored through networking metrics, such as link quality (Fig. 4), link latency, received signal strength, received Signal-to-Noise Ratio (SNR), and energy consumption, which are plotted in real time. The 3D visualization is developed using the Python 3D graphical module VPython [8], which makes it easy to create navigable, flexible, and sophisticated 3D displays and animations. Moreover, because it is based on Python - a flexible and powerful programming language - it has also much to offer to developers and researchers in terms of reconfigurability and extensibility.

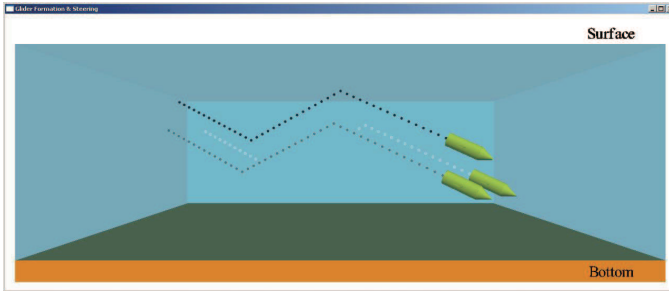


Fig. 3. Visualization of 3 gliders forming an equilateral triangle.

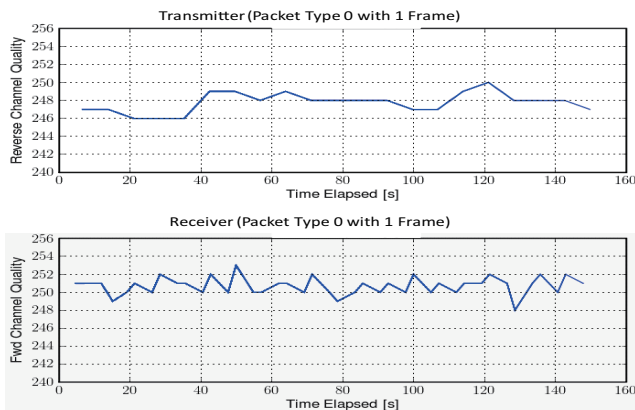


Fig. 4. Snapshot of forward and reverse communication channel quality.

Our demo is designed to be flexible so that environment- and communication-specific parameters can be configured through a GUI, as shown in Fig. 5. In addition to the glider parameters and the 3 required inputs mentioned in Sect. II, the user can select different ocean current models and specify current direction

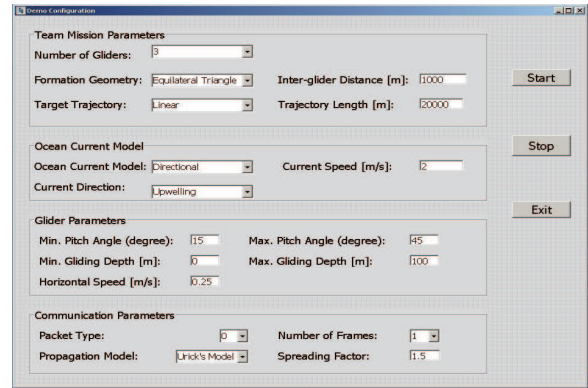


Fig. 5. Demo parameter configuration GUI.

and velocity so as to see their effect on the algorithms. The user can also choose different communication parameters of the WHOI Micro-Modem such as underwater propagation models, packet types (i.e., modulation, channel coding, and bit rate) and packet length (i.e., number of frames within a packet), in order to see the effect of underwater communications on the algorithms. As a consequence, the user will see how well the team formation and steering algorithms work in different configurations and, hence, explore the feasibility region of the algorithms (stability, robustness, and convergence). Last, but not least, our testbed adopts a modular design approach so that different team formation and steering algorithms can be replaced and tested without changing the other components.

V. DEMONSTRATION REQUIREMENTS

The demo requires the following pieces of equipment (which we will provide): 1) Four sets of WHOI Micro-Modem & Gumstix Motherboard; 2) One M-Audio Delta 1010LT Audio Interface; 2) One Desktop PC; 3) One Laptop; 4) Four USB A/Mini-B 4-pin Cables; and 5) Two Ethernet Cables.

In order to run the demo, we will need: 1) a standard demonstration table, 2) Ethernet connections to our desktop and laptop, and 3) a power strip with more than four outlets.

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