Multiple Underwater Vehicle Coordination for Ocean Exploration

R. Martins, J. Pinto, P. S. Dias, P. B. Sujit and J. B. Sousa
Department of Electrical and Computer Engineering
University of Porto, Portugal

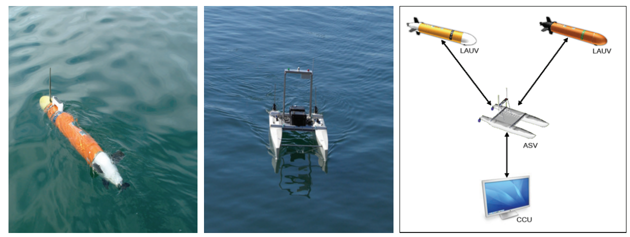
Abstract

In this paper, we present a cooperative control design for multiple underwater vehicles performing an ocean exploration mission. Underwater vehicles have limited communication range and low bandwidth for coordinated maneuvers and for human-in-loop missions. Autonomous surface vehicles (ASV) can be configured and tasked to act as mobile communication (acoustic and wireless) gateways. This is especially important for high speed data transfers which have to rely on wireless communications. We developed the control technology required for an ASV to provide high speed wireless links to multiple AUVs and demonstrated the new capabilities in a field experiment with two underwater vehicles and one ASV. The results show that the developed technology is adequate and addresses most of the underwater missions and hence can be used for large scale vehicle deployment.

1. Introduction

Unmanned vehicles have long been used for performing dangerous, dull and repetitive tasks (Girard, Sousa, and Hedrick 2001). They have significantly widened the operating envelop of the humans for these missions. The mission time for most of the underwater assignments is high, to reduce the mission time and increase robustness of the mission, it is necessary to deploy of multiple unmanned vehicles. Also, for critical decision-making human operators must be in the loop. Designing cooperative control algorithms with human-in-loop is a difficult task. The complexity increases with underwater vehicles as underwater communications are either non-existent or very unreliable and invariably provide very low bandwidths. In this paper, we design a cooperative system and the required hardware and software technology for such a deployment.

We consider an exploration mission with two autonomous underwater vehicles (AUVs) (Figure 1(a)) that explore a river with sensors, while an autonomous surface vehicle (ASV, Figure 1(b)) is deployed to coordinate the mission with the AUVs and the human operators present at the base station as shown in Figure 1(c). We developed the required software and hardware for the vehicles to conduct such a mission. In this paper, we show the required technology that is required for such operations and prove its significance through a demonstration.



(a) (b) (c)

Figure 1: (a) Autonomous underwater vehicle (b) Autonomous surface vehicle (c) Coordination system with ASV interacting with the AUVs and the human operators.

The paper is organized as follows: we describe our goals towards networked vehicle systems and the various subsystems that have already been developed in Section 2. Then, we describe our field-test demonstration in Section 3.Finally, we conclude by evaluating the results of the experiment and provide future research direction in Section 4.

2. System description

The Underwater Systems and Technologies Laboratory (USTL) is developing several new technologies towards the goal of designing a networked system composed of multiple heterogeneous vehicles, sensors and human operators. USTLs main goal is the development of a single system integrating different kinds of unmanned vehicles, non-actuated sensors and software tools that seamlessly enable human operators to monitor and control. The integrated system can be used for applications like adaptive sampling (Curtin et al. 1993), border patrolling (Girard, Howell, and Hedrick 2004), search and rescue operations, automated warfare (Sousa, Simsek, and Varaiya 2004), etc.

Human operators interface with the system under mixed-initiative interaction. In other words, operators actively

Figure 2: Drifting sensors and its receiving base station.

Figure 3: Autonomous vehicles that can be used in coordination.

modify the vehicle tasks based to the perceived world state of the vehicle. On the other hand, the vehicle controllers can demand for human operator intervention when its assigned task is incomplete. The presence of human operators in the loop is necessary as they are experienced personnel (geologists, biologists, sailors) to detect relevant or abnormal underwater features (and consequently change the system behavior). This expertise cannot be translated into a set of mathematical formulas that can be interpreted by a computer (Sousa, Simsek, and Varaiya 2004).

Non-actuated Sensors

USTL is developing various low-cost drifting sensors capable of communicating their positions and sensor states in real time using GSM/GPRS communications. These devices are based on Telit GM862 modules that provides complete communication requirements, GPS positioning and an onboard microcontroller which can be programmed in (a stripped version of) the Python language. In order to measure water current, these devices are placed inside a water-proof and slightly buoyant container. This container includes underwater sails that make it accurately follow water currents near the surface. A drifting sensor deployed in an ocean is shown in Figure 2.

In order to collect data that is spread across large areas, USTL is also using power-efficient wireless sensor networks capable of measuring data and using multi-hop radio communication to transfer this data at real time to a centralized base station. In order to enlarge the monitoring areas, various WSNs can coexist, relaying all the collected data to a central server. USTL is currently using a web-based approach to this problem (Pinto et al. 2009), having a central web server that stores the received data from various sensor networks. Sensor updates can then be disseminated to other systems like operational consoles and unmanned vehicles.

Unmanned Vehicles

A great effort is going towards the creation of different robotic vehicles such as remotely operated submarines, autonomous submarines, autonomous surface vehicles and unmanned aircraft. Some of the vehicles currently being operated by USTL are shown in Figure 3. In this paper we use LAUV and ASV vehicles to demonstrate the developed cooperative system. The details of the other vehicles can be obtained in (USTL 2009).

Light Autonomous Underwater Vehicle The AUV shown in Figure 1(a) is a low-cost, small (diameter of 0.3m and 1.2m long) yet modular autonomous submarine that can be used for different types of operations depending on payload configuration (sensors and communication requirements). Hence, they are called light autonomous underwater vehicle (LAUV). USTL has started developing this vehicle in 2006 and currently has 4 operational LAUVs.

LAUVs use Long Base Line (LBL) acoustic navigation which means that there are two or more acoustic transponders at known locations immersed underwater. These transponders emit acoustic signals at predefined frequencies. Distance to the transponders can be calculated in the vehicle based to the arrival time of the messages from each transponder and triangulate its location. Moreover, these vehicles also carry digital compasses and Inertial Measuring Units (IMU) that allows them to estimate their position and attitude at high frequency with low fidelity.

When vehicles are at the surface they can use the onboard GPS to obtain their world position and also use GPRS and/or Wi-Fi communications to interact with the base station. The vehicles also carry an underwater acoustic modem which enables them to communicate with the base station. However, the communication link has low data rates with by high transmission losses. Optional sensors that can be used by the vehicle include CTD (Conductivity, Temperature and Depth) and sonar. The firmware architecture is modular and requires only a device driver and definition of a new message

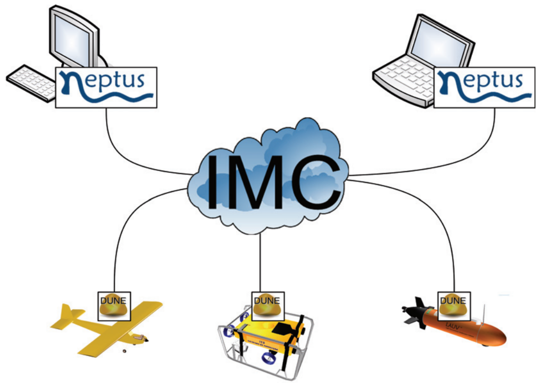


Figure 4: IMC interacting with vehicles and the human operators.

structure to support new hardware. The nominal velocity of these vehicles is 1.5 m/s for continuous operations lasting more than 8 hours with standard batteries.

Swordfish Autonomous Surface Vehicle The Swordfish ASV in an electric-powered catamaran that uses propellers equipped with differential drive mechanism to control its motion. This vehicle can carry different sensor and communication payloads according to planned operation. The ASV used in the demonstration has an acoustic modem to act as a communications gateway between air and underwater communications and an echo sounder to derive bathymetric profiles. The ASV can also have an onboard video camera for collision avoidance and remote operations.

This vehicle uses a GPS compass (3 GPS receivers) to accurately determine its position and heading. Moreover it uses an IMU in order to get state estimates at higher frequencies and its current attitude (roll, pitch and yaw). The vehicle can carry over 150 Kg of equipment which allows the inclusion of two heavy-duty batteries for long endurance missions (more than one day).

Software tool chain

In order to integrate non-actuated sensors, unmanned vehicles and human operators into a single system, a modular software tool-chain is developed at USTL. The software is divided into various inter-operating subsystems. Because of its architecture, it is easy to add new vehicles and sensors of any type. All software systems use the same communication protocol to transfer information, called IMC (Martins et al. 2009). IMC is a message-oriented protocol which uses a single XML file to define all message structures. These structures are parsed by a translator application which generates bindings for different languages like Java, C++ and C#. IMC is the key component that interacts with the vehicles through DUNE and the command and control center (Neptus) that are described below (see Figure 4).

To abstract vehicle hardware and specifications, we use the DUNE onboard software on every vehicle (and some non-actuated sensors). DUNE is composed of a set of asynchronous tasks that communicate between each other using the IMC protocol. Some of these tasks may be coupled to a sensor (publishing messages) or actuator (consuming messages) or to a high-level navigation or control algorithm.

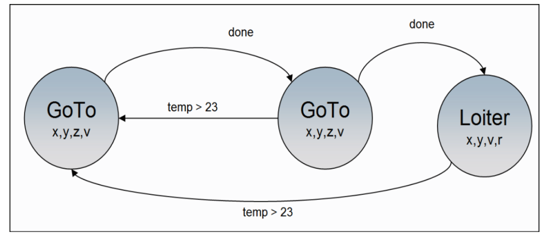


Figure 5: Plan definition example

In order to coordinate the actions of multiple vehicles and systems, we developed the Neptus command and control platform (Pinto et al. 2006). Neptus is a software platform that supports all the phases of a typical operational mission life-cycle of unmanned vehicles: Planning, Simulation, Execution and Revision.

In our system, missions are specified as a set of environmental maps (obstacles) and a set of vehicle-specific plans. The plans are defined as a directed graph whose nodes are maneuvers to be executed and edges are possible transitions between maneuvers as shown in Figure 5. In Neptus, each vehicle has a configuration file that described the supported maneuvers, transition conditions and default parameters. A new vehicle can be added by providing a new configuration file (and optionally specific 3D models and images).

Neptus supports multiple operators operating simultaneously. Each operator can receive state updates from all the vehicles in the network. The console creates a tree of variables available for the interface components. This feature allows the end-users to adapt existing consoles (using a console builder) to match vehicle, mission or personal needs.

3. Demonstration

To demonstrate our system in action, we used two LAUV vehicles carrying CTD sensors and the Swordfish ASV. The submarines perform coordinated temperature samplings maneuvers while the ASV performed the task of extending the network range. The vehicles and the base station (consisting of three laptop computers, a power generator and a wireless router) were deployed close to the Tapada do Outeiro outfall in the Douro river in Portugal. This outfall creates a plume which is basically characterized by the temperature field. Prior to the deployment, the map of the environment and planned surveys were created using the Neptus software. One of the main goals of this experiment was to use the ASV as a communication bridge between the base station and the submarines, so we chose locations for temperature surveys

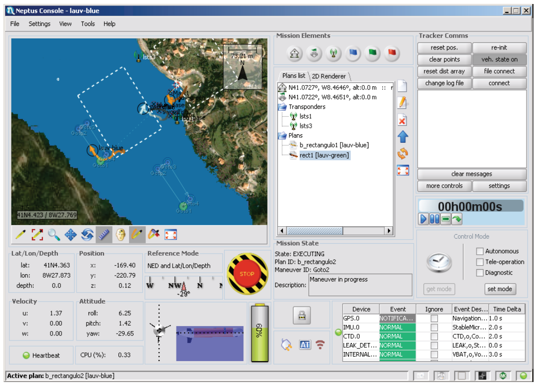


Figure 6: Neptus console for operating the AUVs with mission state.

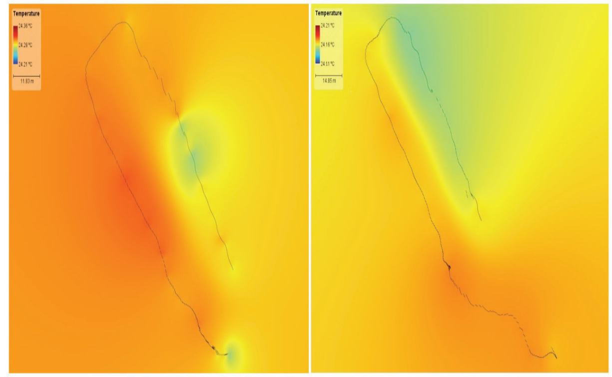


Figure 7: Temperature surveys of the mission carried by two LAUVs.

with distances surrounding 200 meters.

For safety reasons (this is a river with considerable amount of traffic), we carried out an initial communications coverage test by driving around the zone using a boat accompanied by the two AUVs. The Swordfish ASV was stationed near the base station acting as a communications bridge between the base station and the vehicles in the boat. Based on the tests, an area of 200m×200m was defined which is a low traffic zone with good communication links.

In a second phase, the vehicles were deployed in the water and a survey mission was conducted to test the communication ranges with AUVs operating at water surface. This test served as a sanity check of the system as well as it helped us verify the best locations for positioning the surface vehicle to cover both the AUVs and the base station.

For the final demonstration, we deployed the AUVs and the ASV with three human operators. Each operator is responsible for a specific vehicle that inlcudes defining the vehicle behaviors according to the mission state, monitoring vehicles hardware and most importantly to prevent eventual encounters with traffic. The operator also has the access to view and modify other vehicle states and behaviors.

All three operators were able to follow the vehicle deployment in real-time and also communicate with the LAUVs while operating at the surface. After the execution of the mission, the operator uploads the mission log to a local FTP server which allowed the remaining operators to revise data from other vehicles. Data revision was carried out with the help of the Neptus Mission Review and Analysis which eases the comprehension of large data-sets (see Figure 6).

In this experiment, positioning of the ASV was carried out by an operator at the base station who had access to the plans and updated positions of the vehicles in the water. We used tele-operation because the ASV operated in a traffic zone. Figure 7 shows the temperature profiles of the mission segments. Although, the mission was carried for a short duration, the goal of the mission was to demonstrate the developed technologies to carry out a networked operation.

4. Discussion and future work

In this paper, we presented a cooperative control framework for multi-vehicle deployment and demonstrated their applicability for simultaneous collection of co-located data. We deployed two LAUVs and bridged the communication gap between the LAUVs and the base station with an ASV. This configuration has significantly increased the communication range and access to the current data for situational awareness and operational capability. This demonstration is seen as a proof of concept operation towards seamless integration between multiple autonomous vehicles. In the demonstration, coordination algorithms were not applied and the coordination was carried out by human operators who were continuously monitoring the situation and hence achieving a stable human in the loop system. We have achieved a partial success as far as complete autonomous operations is concerned due to successful integration of human-in-loop. However, a complete success was achieved as far as the technology required to deploy such a mission is concerned.

In near future we will develop autonomous waypoint tracking for the ASV that can intelligently maneuver itself to minimizes the no communication windows between AUVs and the base station while carrying out a large scale mission. Also, in future experiments we would like to develop new autonomous cooperation algorithms that dynamically adapt to a variable number of vehicles, using these resources automatically as they appear in the network. We are also interested in using a Service-Oriented Architecture where vehicles become servicers of maneuvers. In this architecture, services may be orchestrated in a hierarchical way so that the execution of a specific service requires the execution of other services in the network.

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