Facilitating Multi-AUV Collaboration for Marine Archaeology

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***Abstract*—Autonomous Underwater Vehicles (AUVs) have been widely used in assisting scientific operations. They can increase the scientific output by performing operations in a cost effective and safe manner. This paper focuses in the underwater archaeology scientific discipline. It presents the distributed high level architecture developed by the Heriot Watt University Ocean Systems Laboratory (HWUOSL) in the scope of the ARROWS project. This architecture utilises a distributed world model operating over an acoustic communications channel for achieving the coordination of a heterogeneous team of robots. Simulation results are presented showing the efficiency of the distributed world model architecture and the coordination performance.**

I. INTRODUCTION

Autonomous Underwater Vehicles (AUVs) have been used to facilitate scientific research and military operations [1],[2],[3]. In the scope of the ”ARchaeological RObot systems for the World's Seas” (ARROWS) project [4] AUVs are used to enable marine archaeology missions. A marine archaeology mission requires a fleet of AUVs to map an area of archaeological interest and search the area for potential archaeological artefacts. Then the potential artefacts are to be inspected and classified. Finally, this information has to be persistently stored so that the area can be periodically monitored for changes.

To achieve collaboration, the robots must be able to store, process and communicate information in an efficient manner so as to plan their actions. Persistent information storage is required for revisiting an area and monitoring for any changes. Moreover, this information can be used for post-mission analysis and visualisation aiding to the scientific effort. Communication is required for the efficient fleet collaboration and is achieved using underwater acoustic modems. Underwater communications are known to be low bandwidth, high latency and error prone [5], [6], [7].

This paper addresses the software design aspects for the high-level control, planning and communication of the multi-AUV team. It describes the main aspects of the system which form the ontology-based distributed world model high level control architecture that addresses the needs posed by the Archaeology Advisory Group (AAG). These aspects include how the system operates over an underwater acoustic communication channel, how the architecture is utilised in robot task planning and execution, and the flow of the system from user input to mission completion.

The rest of the paper is organised as follows: Section II presents the high level control architecture of the robotic team. Specifically, subsection II-A describes the distributed world model architecture, subsection II-B refers to the underwater communications and subsection II-C analyses the high level mission planning and coordination. In section III simulation results are presented and analysed. Finally, in section IV the paper concludes.

II. ARCHITECTURE

The high level architecture, in compliance with ARROWS' software development guidelines, uses the Robot Operating System (ROS) framework allowing simple communication between processes. ROS is used to aid in software integration between project partners as well as between modules in the high level control software. Described in this section are the three main subsections of the architecture showing how the software is interconnected to provide the desired functionality. The first section describes the distributed world model architecture that enables the robots to share information efficiently under communication uncertainties. The second section gives details of how the communication is achieved between the vehicles. Finally, the third section describes the mission planning and how it interacts with the world model and the payload of the vehicle.

A. Distributed World Model

For the successful collaboration of a multi-robot team, the robots need to store and share information regarding the mission that they are executing. Ontology-based world modelling allows for storage of semantic information. This semantic information can be used by the robot to reason and plan its future actions [8], [9], [10]. Semantic information has been shown to aid the planning effort as shown in [11]. For the ARROWS project it was chosen to use an ontology-based distributed world model as first described in [12]. It is a client-server based approach, which allows for efficient storage and transmission of information as described below.

One of the purposes of the ontology-based world model is to store the information generated by the vehicles during mission execution. The information is stored in the ontology in a temporal manner, allowing the robot to know how the environment changes. This information can be used to assist

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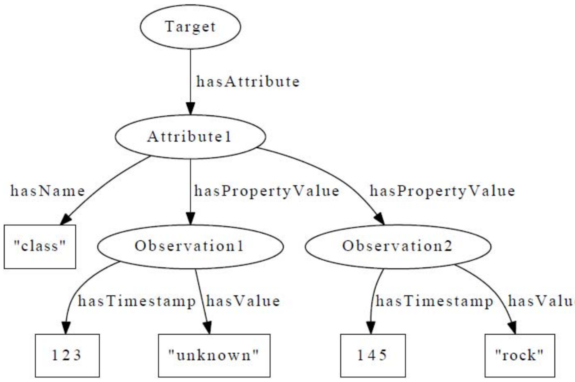

Fig. 1. Temporal storage of data in the world model ontology. Each instance has properties whose values are updated using timestampped observations.

the robot plan it's future actions. Additionally, it is used for monitoring the environment for any changes over longer periods of time as missions are repeated. The ontology-based world model can be stored in a persistent storage medium and be reloaded each time the mission is executed. Another benefit is that this temporally stored information can be used for post mission analysis. Ontologies store information in a human readable form and allow the user to study the evolution of different items in the ontology during the mission execution.

The temporal data storage is inspired from [13]. Each concept in the ontology has one or more attributes, with each attribute having a name and a property value. Whenever a new item of a concept is inserted into the ontology a new instance is created and the property values of that instance are populated by timestampped observations. As the mission continues, new information can be obtained for that instance. This is represented by new observation information as the property value. An example of the temporal storage method regarding classification information of a potential archaeological target can be seen in Fig. 1. There, a new target instance is generated when the target is first discovered. As the target is not yet classified it has an initial classification value of ”unknown”. After the target is inspected and classified the class property is updated with the class value of that target.

Another feature of the distributed world model aims for efficient sharing of information among the members of the robotic team. This is achieved through an exchange manager module as it can be seen in Fig. 2. The exchange manager is responsible for the selection and transmission of semantic information from the world model in a push based manner. The information selection process is performed based on the information needs of the other vehicles. In the beginning of the mission, each vehicle publishes it's information needs to the other vehicles. Using this method, the exchange manager transmits only what is required by other robots. This proves extremely important due to the limited bandwidth of the underwater communications.

Additionally, the exchange manager handles the errors in communications in an efficient manner. By employing different message acknowledgement methods it minimises the information that need to be retransmitted in case of communication errors. One other important feature of the exchange manager is that it runs as an independent module. This means that communicating information doesn't require to be planned by the robot planner, thus making the planning effort easier. Results regarding the usage of the distributed world model for multi-robot communication can be found in [7] and [12].

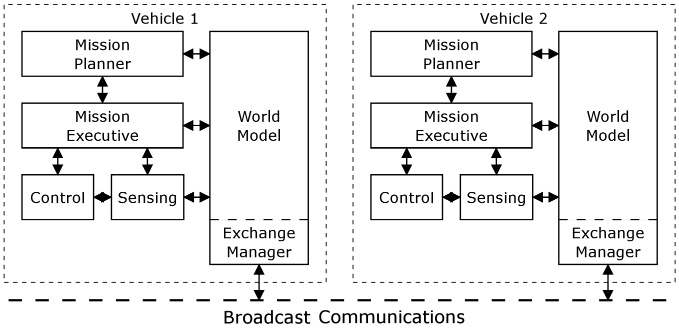

Fig. 2. The distributed world model architecture. Each of the robot planning and control modules can access the ontology world model using a client. The exchange manager accesses the world model and selects data to transmit over broadcast acoustic communications.

B. Communications

Communications is essential for the success of a multi-robot team. It allows the robotic team to coordinate and execute complex missions in an efficient manner. Without communications, the distributed mission execution would be impossible.

A standard approach for underwater communications is the use of acoustic modems. They can provide good communications range but at the cost of being low bandwidth, high latency and prone to errors [5], [6], [7]. For the ARROWS project, acoustic modems produced by Evologics GmbH were the first choice.

Given the nature of the underwater environment, there is only one channel that can be used to communicate acoustically. Therefore, for robust multi-vehicle operations it is imperative that all communication is synchronised. Synchronisation is achieved using a time division multiple access (TDMA) protocol. The TDMA approach was chosen as it is simple to implement, yet effective in the high latency underwater environment.

C. Mission planning

As described in section I, the multi-robot team must search an area for items of archaeological interest and then inspect them. To achieve this, two types of vehicles are used: the first type, called the search AUV (SAUV), is a fast moving vehicle capable of mapping the area and detecting targets of potential interest using sidescan sonar; the second type, called an inspection AUV (IAUV), is equipped with cameras and lights and can inspect and classify the objects. These two vehicle types collaborate using the distributed world model architecture described in the previous section.

The first step in the mission execution procedure is the user to define the area that needs to be inspected. For this purpose a Graphical User Interface (GUI) which communicates

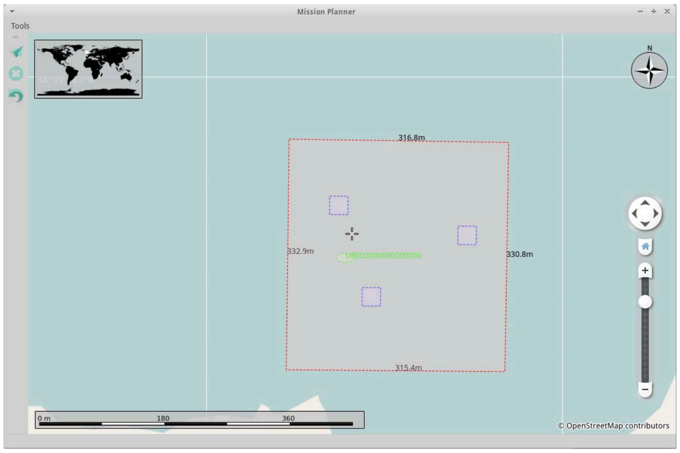

Fig. 3. Mission planning graphical user interface. The red rectangle denotes the area that is required to be searched. The blue squares are manually inserted inspection targets. The green ellipse is the position of an inspection vehicle.

with a world model server was developed. It allows the user to define a search area or individual inspection points. Additionally, it provides feedback regarding the position of each vehicle. Having an integrated world model, the GUI inserts the user provided data into it's world model. Search areas and inspection points defined in the GUI are shared with the vehicles in operation using the world model functionality, eliminating the need for explicit transfer of the information by the user. Position feedback is also received through the world model. The GUI can be seen in Fig. 3.

The next step in the mission execution is performed by the vehicles as they start the area search and inspection. Each type of vehicle has a custom finite state machine executor. It uses this executor to achieve it's goal in the mission by obtaining any relevant information from the world model and deciding it's actions. An overview of the mission execution for a 'search' and 'inspect' vehicle is shown in Fig. 4. Each robot must take a series of actions to successfully complete the mission. The robot can choose it's actions based on it's capabilities that are encoded in the ontology. Additionally, as each action is encoded in the ontology, the robot can infer which steps it should follow and which sensors to use in order to achieve that action. It can use this information to create a plan using a planner such as POPF [14]. Executing a series of plans will eventually allow the successful mission execution.

The search vehicle performs a standard lawnmower area search action. With this action it traverses the area in such a way that exhaustively searches for any potential targets. The inspection vehicle performs an inspect action over a discovered potential artefact or a user defined target. To decide which inspection action it should chose, an efficient method is presented in [9]. There, a centralised method allocates tasks to two inspection vehicles. In this paper this method is extended to be distributed running separately on each inspection vehicle.

A positive side-effect of encoding the action requirements in the ontology is the energy aware planning capability. Using information regarding the sensors that are required for each action the robot can power on and off its sensors on demand. This can lead to energy saving and allow prolonged mission execution.

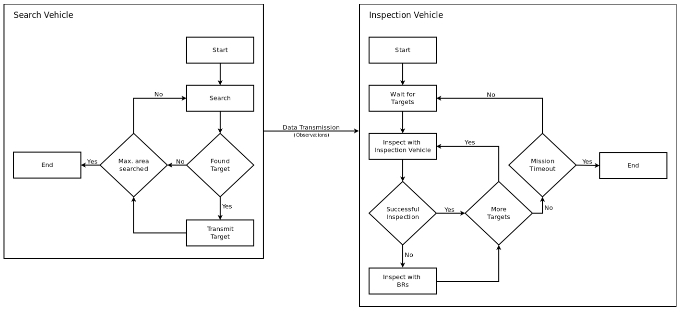

Fig. 4. Mission execution flowchart. On the left is the SAUV mission execution scheme. It searches for targets in the predefined area until all the area is searched. Whenever a target is found it is transmitted to the inspection vehicles. On the right is the IAUV mission execution scheme. It waits for targets to be published and proceeds with inspection when one is received. Execution stops when a maximum allowed time is reached.

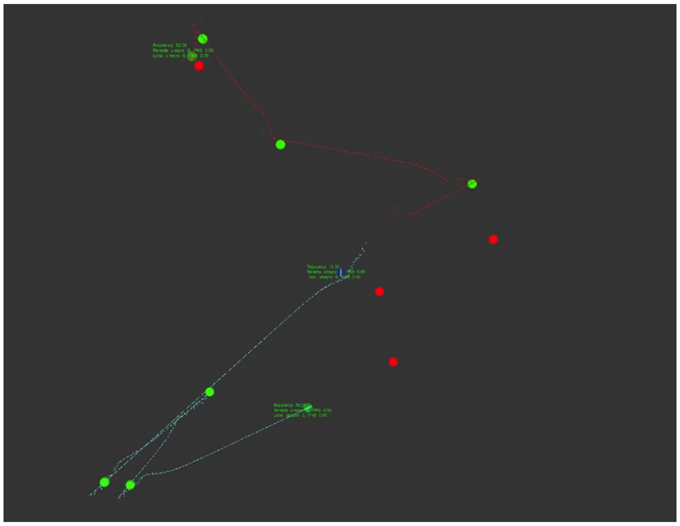

Fig. 5. Simulated mission execution example. The transparent spheres represent the positions of the vehicles. The solid red spheres are potential archaeological artefacts that are still not classified, while, the solid green spheres are classified targets. The lines represent the paths traversed by the inspection vehicles.

III. RESULTS

For the evaluation of the system simulation experiments were performed. The experiments used the distributed world model architecture and the navigation and communication simulators developed by the HWUOSL. A simulated mission execution instance can be seen in Fig. 5.

The experiments studied a k-Means efficient task allocation method, inspired from [15], against a greedy method. It compares the two in terms of time and travelled distance efficiency for different levels of communication errors. Results can be seen in Fig. 6 and 7. The tests involved one SAUV and two IAUVs executing ten inspection missions using 10 different sets of randomly generated targets. Regarding the distance efficiency, the two methods perform the same in lower packet error rates; in higher error rates, however, the greedy method performs better. In terms of mission execution time efficiency the efficient method constantly produces better results. This happens because it achieves a higher vehicle utilisation. In the greedy case there were cases that the mission was mostly

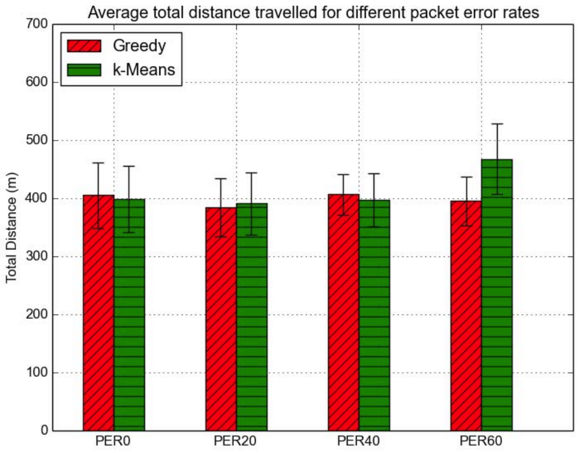

Fig. 6. Average distance travelled by the inspection vehicles for different values of packet error rate. Error bars show one standard deviation. For lower packet error rates the two methods perform equally. In higher error rates the greedy method performs better.

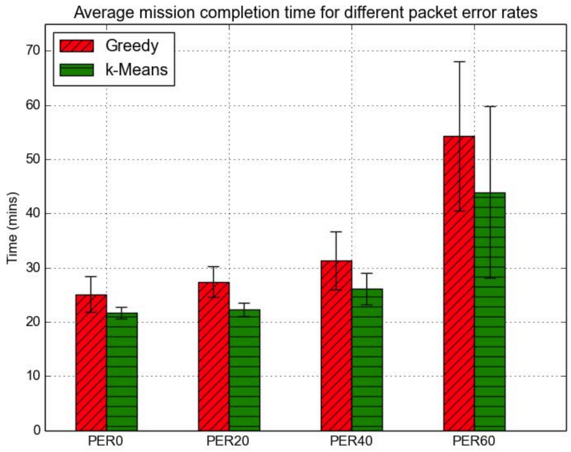

Fig. 7. Average mission execution time for different values of packet error rate. Error bars show one standard deviation. The k-Means based efficient method performs better for all packet error rates utilising the available robot resources better than the greedy method.

executed by one vehicle while the other was idle.

IV. CONCLUSION

In this paper the proposed high level planning and coordination architecture used in the ARROWS project was presented. It allows a multi-robot team to successfully collaborate using unreliable, high latency and low bandwidth communications. Simulation results validate the mission execution feasibility using the distributed world model architecture and propose a task allocation method to be used with the vehicles. Preliminary testing using hardware-in-the-loop testing methods were successfully conducted during the Breaking the Surface workshop in Croatia on October 2014. Extensive sea trials will be performed during the summer of 2015 in Italy and Estonia under the umbrella of the ARROWS project. These trials will validate the proposed architecture in real world conditions and will provide useful information regarding further improvement.

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