Facilitating Cooperative AUV Missions: Experimental Results with an Acoustic Knowledge-Sharing Framework*

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***Abstract*—We describe and experimentally evaluate a decentralised world model for sharing data over limited bandwidth and high loss channels, such as encountered in the underwater domain. This world model service enables information extracted from the environment to be stored and queried using an ontology format. Besides providing an information storage facility, the world model manages all acoustic communications, and ensures that the shared ontology is updated on all robots while minimising transmissions. Using this world model service, a collaborative mission scenario of mine counter-measures is described, where the world model aids in the efficient use of the broadcast medium. In-water experiments conducted in Loch Earn, Scotland, confirmed that the world model functioned correctly with a team of two AUVs. Early results for the efficiency of the system are also presented, which show that the world model can continue to function at relatively high packet error rates, although the error rate increased rapidly with transmission distance in our test environment.**

I. Introduction

Robots are becoming increasingly relied upon to perform complex tasks underwater. This is due to the intrinsic danger of the underwater domain, and the expense of hiring divers and equipment capable of performing tasks at depth. Having a robotic system which can execute a mission autonomously or with minimal user input brings further benefits over remotely-operated robots, as operators are not needed to control the robot, and ships are freed to perform other tasks. Autonomous underwater vehicles (AUVs) also enable cooperative mission scenarios using more than one robot, which gives redundancy in the system as well as enabling tasks to be performed in parallel, thus further decreasing mission time. Missions which benefit from robots working collaboratively include mine counter-measures (MCM) operations, surveying, and many deep-water oilfield inspection and repair tasks.

In order to complete collaborative robotic missions, information must be shared between vehicles (platforms) and the ability to store and query observations must be present. However, in the underwater environment this is complicated by the limited communications bandwidth: electromagnetic waves propagate badly through seawater, ruling them out for robotics communications. Instead, the acoustic channel is generally used, as relatively low-energy sound waves can propagate long distances underwater. However, acoustic communications are still noisy, lossy, and low-bandwidth compared to electromagnetic signals, which makes cooperation between robots in multi-agent AUV missions more challenging than for equivalent land or air robotic missions.

Figure 1. REMUS 100 AUV

Figure 2. Nessie VII AUV

In this paper, we build on a distributed World Model (WM) service developed previously within our lab [1], [2]. The WM service stores semantic information in an ontology, and provides a common and convenient method of storing and querying observations of the surrounding environment. The data in the ontology is transparently synchronised between all platforms in the multi-robot system, using mechanisms optimised for acoustic modems. Ontologies are increasingly common in robotics applications, for example see [3], [4], and provide a structured way of storing information such that it is human-interpretable and standardised across applications.

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Having a shared ontology representation of the surrounding environment allows vehicles to share their observations, as well as vehicle's intrinsic properties, with one another – thus lending itself for collaborative mission scenarios. The architecture of the WM is described further in Section II, and Section III discusses previous work on multi-agent systems and knowledge representation using ontologies.

A key aim of the work presented here was to integrate the WM with real AUV hardware, and demonstrate that the communication and synchronisation systems function correctly. A secondary aim was to experimentally test the efficiency of data transmission by the WM, and compare this with simulated results presented in [1]. An important first step in this was to test the data transmission performance of our acoustic modems in the actual test environment.

Our experimental setup (Section IV) consisted of two AUVs (each with an acoustic modem on-board), a REMUS 100 (Fig. 1) and Nessie VII (Fig. 2). We also used two standalone acoustic modems, and the test site was Loch Earn, in the central Highlands of Scotland. All of the acoustic modems used in this work were Woods Hole Oceanographic Institution (WHOI) Micromodems which are capable of up to 5.3kbps transmission speeds.

The experimental results are presented in Section V, and include: acoustic modem Packet Error Rate (PER) tests; a working real world implementation of the WM architecture; and a real world Ontology Layer Transmission Efficiency (OLTE) evaluation of the WM service. The most significant result was validation-of-concept, i.e. observing the WM working correctly to synchronise ontology data between two AUVs in the field. We also made significant progress toward the secondary goal of measuring the efficiency of the WM, with results showing good performance with increasing PER, although testing was complicated by poor general acoustic performance at our test site.

II. World Model Overview

This section gives an overview of the World Model, which is described in more detail in [1], [2]. The WM is a decentralized knowledge base system that works across multiple AUVs over an acoustic communications channel. It performs two main tasks: firstly it provides an easy interface for storing and retrieving semantic information in an ontology format, and secondly it sends world model updates to other platforms in an autonomous way, without involving the robot's planning and control software. This makes the design and implementation of multi-robot systems significantly easier.

A. Architecture

Fig. 3 shows how the WM, which is primarily a data persistence layer, fits into the architecture of a multi-robot system. The Exchange Manager component shown in the figure performs management of incoming and outgoing data, and selection of data to be sent acoustically, and is described further in Section II-C. The ontology framework used for representing data is covered in Section II-B.

The WM runs on each AUV as a separate server process, and other subsystems of the AUV can access the WM server through a client-side library. The server is responsible for storing information provided by the subsystems of the AUV and communicating the changes of the world model to the AUVs. This method allows each vehicle to concentrate on planning, while the WM service takes care of information exchange among the vehicles. Moreover, the decentralized method enables the seamless operation of a vehicle even if it is temporarily isolated.

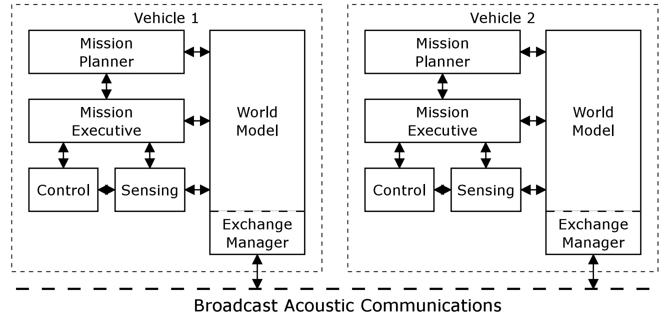

Figure 3. Distributed world model architecture. Figure taken from [1].

On an implementation level, the WM is a ROS stack, so can be easily integrated into any robot architecture using ROS. Clients call into the WM server using a client library, which consists of general-purpose classes for accessing and caching data from the WM, plus application-specific lightweight C++ wrappers that encapsulate domain-level concepts.

B. Ontology

The WM stores its data in an ontology format. Ontologies store both general domain knowledge and knowledge relating to specific scenarios in a human-readable text format. They are defined by two components: a terminological box or `TBox` and an assertional box or `ABox`. The `TBox` stores concepts and the relations between them, and is comparable to the class hierarchy in object-oriented programming, whereas the `ABox` stores instances of these concepts and is comparable to objects in running programs. Recently, the XML-based language OWL [5] has emerged as the most popular ontology format, and is used by the WM.

Ontologies provide several benefits [6], [7], including allowing the re-use of knowledge engineering outputs, improved interoperability between systems, ease of recording information gained from domain experts, and the availability of open-source tools for performing inference and reasoning within the knowledge base. A short review of the use of ontologies within robotics is given in Section III.

In this work, the ontology defines the entities in the world, and this is used as a common language among the AUVs so that they can exchange semantically tagged information. A common issue with ontologies is that there is no built-in mechanism for capturing the history of dynamically changing variables, and yet this is important for many robotics applications. We adopt the solution proposed by [8], where each variable is stored by an instance of the `Attribute` concept. An `Attribute` can have many `PropertyValues`, each representing the value of the variable during a specific time period, and most updates to the WM can simply be captured as new `PropertyValues` for a particular `Attribute`. The WM loads two separate ontologies, and merges them together: a domain-specific ontology, which in our case describes underwater robotics concepts such as AUVs, sonar sensors, mines and so on, and a small WM ontology that contains the concepts `Attribute`, `PropertyValue`, and others necessary to represent observations in the format described by [8].

C. Communications Framework

Information exchange among platforms running the WM is achieved by utilizing a custom information and acknowledgement encoding and a push based broadcast transmission system. The system is optimised for low bandwidth, high latency, high loss transmissions mediums such as acoustic underwater communications. Communication among the robots is coordinated using a time division multiple access (TDMA) scheme, where each robot has a certain time slot to push its local changes of the world model. This requires the clocks of all platforms to be synchronised, so that each knows when its transmit slot starts and ends.

Each platform using the WM has to publish a list of its *information needs* (INs), which are defined by a set of concepts and attributes from the ontology it is interested in receiving updates about. When choosing what to transmit during its time slot, the WM uses the INs of all its peers, together with knowledge of which updates have been successfully received by which peers, to decide the most important updates to send.

Because of the nature of the acoustic communications, a reliable way of understanding when a packet has failed to be delivered and requires retransmitting is needed. In [1], [2] three different acknowledgement methods are presented. The first method is a standard acknowledgement method where each robot uses an acknowledgement vector to indicate which packets it received in the previous TDMA slots, and adds this vector to any packet that is sent in its current TDMA slot. In the second method, called matrix acknowledgement, a matrix is used instead of a simple vector. This matrix holds the acknowledgement messages not only from the robot itself, but from the other robots in the team. The matrix helps propagate the message that a packet is well received from the intended robot even if the acknowledgement fails to reach the transmitting platform. This adds some extra cost because of the increased size of the acknowledgement matrix, but helps reduce the retransmission of packets. The final method, called matrix pseudo-acknowledgement, is the same as matrix acknowledgement, but with the difference that it allows a robot to add its knowledge on the information that another robot has in the acknowledgement matrix.

In simulations it has been shown that the matrix and matrix pseudo-acknowledgement perform almost equally well and always better than the standard acknowledgement method. In this paper we have exclusively used matrix acknowledgements.

The WM uses an efficient mechanism to encode ontology updates into an acoustic packet, which is composed of a acknowledgement block followed by an *inform* block containing one or more attribute updates. The size of the inform block is reduced by firstly using a mapping table of relatively verbose ontology URIs to unique ID numbers, and secondly by putting attribute updates into a stack structure so the IDs of the target objects need not be repeated.

D. MCM Mission Implementation

The WM is well suited to use in complex multi-robot survey and inspection missions, and we chose the mine counter-measures scenario to test it. In this scenario a fleet of AUVs must successfully locate and identify naval mines in a designated area. In order to achieve this task, two types of AUV were used, with different control and planning code developed for each. One type performed a search task, and is known as a search AUV (SAUV), and one performed an inspection and identification task, known as an inspection AUV (IAUV). The SAUV sweeps the designated area and locates mine-like objects, which are then passed to the IAUV (via the WM) for futher inspection. The IAUV then moves to these objects and classifies them as either a mine or a non-mine. Our test mission also included simple conflict resolution methods to avoid two IAUVs trying to inspect the same target.

III. Previous Work

The multi-robot cooperation problem has been studied extensively. Early solution attempts were limited by the technology of the time and were never actually implemented in real robots [9], [10]. Later several multi-robot cooperation platforms were created and successfully tested in different scenarios. In [11] three robots cooperate in a simplified hazard waste clean-up task. In [12] robots cooperate in exploring and mapping an unknown area. In [13] robots perform a box pushing task. In [14] robots cooperate in a mine counter-measures scenario but only simulation results are presented, while in [15] robots perform cooperative tracking. One common aspect of these diverse approaches is that the world representation and communications techniques were specifically created for each particular solution. The viewpoint of this paper is towards a more generic structured world model which is able to be enriched and be applied to the solution of various tasks.

Knowledge representation of the environment is essential for a robot to perform a specific task. In many robotics applications, this knowledge is implicit in the software system, but more robust explicit knowledge representation methods have also been used. An early approach is proposed in [16], where knowledge acquired by sensors is represented in a multi-layered architecture. Unfortunately the detail level is low and no evaluation is given. In [17] a centralized architecture for robots navigating an office environment is presented, and a similar environment is used in [18] to present the use of ontologies in robotics. In [8] ontology world modelling is used to provide battlefield situation awareness, but it is not intended to be used in individual robots, rather it is used in a central command and control computer. An interesting use of ontologies for multi-agent systems performing an urban search and rescue task is presented in [19] but there was not a proof of concept implementation of the proposed methods. More recent work using the combination of ontologies, multi-agent systems and robotics can be found in [20], [21]. Finally [4] discusses the creation of an IEEE standard ontology for robotics, and also provides an excellent review of the use of ontologies in the autonomous robotics domain.

Table I. PACKET TYPES AVAILABLE WITH THE WHOI MICROMODEM (SEE [23])

Packet Type	Max Packet Size (bytes)	Transmission Speed (bps)
0	32	80
1	192	250
2	192	500
3	512	1200
4	512	1300
5	2048	5300

IV. EXPERIMENTAL EVALUATION

The experiments were carried out at Loch Earn, Scotland, in November 2012 and March 2013. The testing site provided a body of water approximately 10km by 1.2km and with depths up to 87m. The Scottish winter outdoor environment adversely affected the trials, in that we were unable to perform experiments to provide as many data points as we desired, but the conditions under which all data were produced were carefully recorded. This paper presents results from PER tests, WM tests between real vehicles, and WM transmission efficiency tests.

A. Equipment

1) Acoustic Modems: For the experiments carried out in this paper, the Woods Hole Oceanographic Institute (WHOI) Micromodem [22] was used for the communication link between the AUVs for full and hardware-in-the-loop tests. The WHOI Micromodem is well known in the underwater robotics field, and is driven from a PC using a serial port connection. It constructs a data packet from several frames of data which is then transmitted acoustically. All frames of a packet must be received successfully for a packet to be received; if any frame of the packet is lost then the whole packet is discarded. The rate of acoustic transmission can be varied by the user and can be changed dynamically; for example, depending on the amount of data wishing to be sent. The available transmission speeds, and their corresponding *packet types* are given in Table I [23]. Packet type 0 is encoded using *frequency-hopping frequency-shift keying* (FSK), and packet types 1-5 are encoded with *phase-shift keying* (PSK). The WM requires the use of PSK packets, as FSK does not provide a fast enough transmission speed to send useful data, but PSK had not been used by the Ocean Systems Lab prior to the experiments described here.

2) AUVs: The two vehicles used for the tests shown are the commercially bought Hydroid REMUS 100, seen in Fig. 1 [24], and Heriot Watt University's Nessie VII AUV, seen in Fig. 2 [25]. Both of these AUVs have a WHOI Micromodem on-board. Using these vehicles allows for a MCM mission scenario to be tested using REMUS as the SAUV and Nessie as the IAUV.

3) Stand-alone Micromodems: For practical testing, two portable Micromodems were used as well as the two vehicles, REMUS and Nessie. These made logistics much easier and allowed more accurate results to be obtained. These acoustic modems are referred to as the "Towfish" (TF, shown in Fig. 4) and "Yellow Box" (YB, shown in Fig. 5) modems and are almost identical setups to REMUS and Nessie, respectively.

Figure 4. Towfish (TF) stand-alone modem

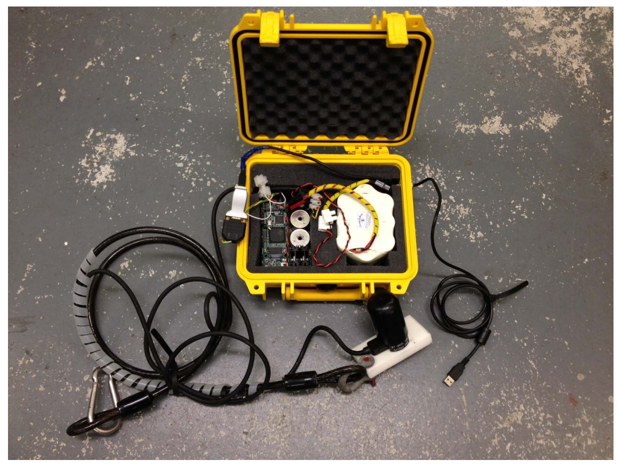

Figure 5. Yellow box (YB) stand-alone modem

B. Packet Error Rate Tests

An important precursor to evaluating the performance of the WM was to establish the baseline performance of the underlying transmission mechanism. We achieved this using packet error rate (PER) tests, where the proportion of packets lost was evaluated at different distances between the sending and receiving platforms. This is an effective experimental strategy because, with the underwater acoustic channel, the available bandwidth decreases significantly with distance [26]. The PER test demonstrates the practical capabilities of the WHOI Micromodem, and PER results are presented in Section V-A, with the effect of increasing PER on the WM's operation shown in Section V-C.

During a PER test, the transmitting modem acoustically sends one packet's worth of data on each timeslot. The data is read sequentially from a text file, and the receiving modem's PER test code has a copy of the same text file, so it can confirm it has received exactly the right data. Further, the clocks of both machines are synchronized prior to the test, and both sides know the start time of the test and the transmission slot period, so the receiver also knows when to expect packets and can work out if a packet is missed completely. PER tests were performed with a slot period of 20s, and using packet types 0, 1, and 3.

C. World Model Test

The WM tests consisted of having the SAUV (REMUS) send the coordinates of a desired point-to-inspect, through the WM service, to the IAUV (Nessie) for it to then move off and inspect it. Although simple, this test validates the practical ability of the WM architecture in real world situations giving visible results of the vehicle's mission execution. This provides proof that the insert/query functionality in the WM service works as well as does the communication coordination of data exchange.

D. Ontology Layer Transmission Efficiency Evaluation

A key issue for the practical usefulness of the WM is how efficiently it encodes and transmits data over the underwater acoustic channel, which is noisy and high-loss [27], [26]. The OLTE test demonstrates the speed and robustness of several aspects of the WM: its storage of observations, its mechanism of choosing which data to transmit, and which transmissions it should repeat. For this test, 25 manually selected points to inspect are inserted into the SAUV's ontology at the beginning of the test. Once stored, the WM determines that the points-to-inspect are an IN of the IAUV so begins sending each of the points-to-inspect acoustically. We recorded the time taken to successfully receive all points-to-inspect at the IAUV.

As will be shown in Section V, it was necessary to carry out the WM OLTE test using stand-alone modems without any vehicles. This was for ease of experimentation as well as issues encountered with the commercial REMUS AUV, which are highlighted in Section V-A. All OLTE tests were performed with a maximum packet size of 512 bytes, which limited the WM to using packet type 0, 1 or 3, and with a TDMA slot of 10s per platform.

E. Hybrid Simulation

In Section V, experimental results from Loch Earn are compared with hybrid simulation results obtained in a similar manor to the results presented in [1]. This simulation used the real WM code and MCM mission client code, but a simulated acoustic exchange module. This acoustic simulator uses pseudo-random numbers to emulate a configurable PER, and the whole simulation runs in accelerated time (using the ROS simulation clock). Experiments were performed with 10 trials at each PER value, each using a different random seed.

V. Results

A. Packet Error Rate Tests

Fig. 6 presents the relationship between the separation distance of the modems and the incurred packet success rate (1-packet error rate) for a fixed transmission speed (packet type 3, 1200bps). Firstly, this figure shows an asymmetric behaviour for the different transmission directions. It should be noted that this is due to the hardware of the TF acoustic modem and that the REMUS AUV exhibits similar behaviour. As a result, the WM tests have to be conducted at much shorter distances due to the increased packet loss in one direction. Secondly, it shows that in these tests in a Loch environment, we achieve

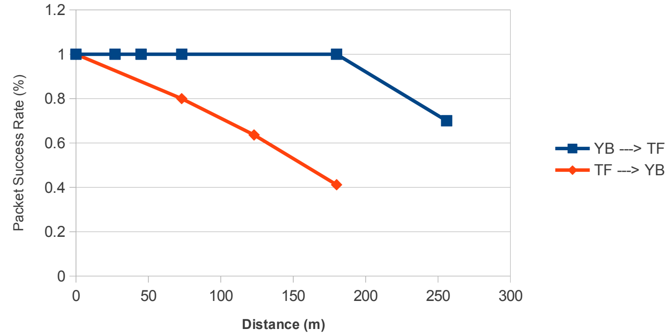

Figure 6. Packet Success Rate Vs Distance between the YB and TF stand-alone acoustic Micromodems, based on results collected from trials in Loch Earn

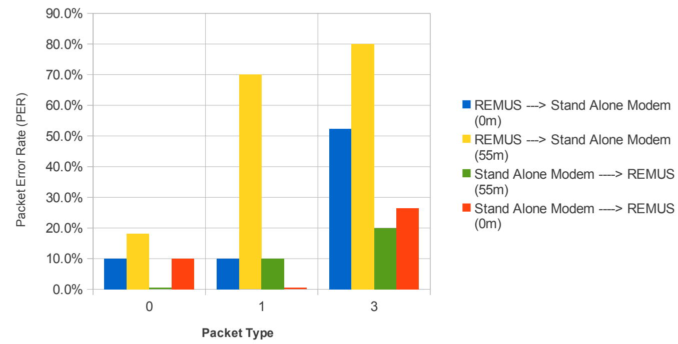

Figure 7. Packet Error Rate vs Packet Type based on experiments between REMUS 100 AUV and a stand-alone WHOI acoustic Micromodem in Loch Earn. Experiments were conducted with the AUV and stand-alone modem next to each other (0m range), and at 55m distant.

much shorter transmission distances than the modem is capable of. From discussions with WHOI during these tests, and their kind analysis of acquired data, the reason for these shorter distances was resolved to the poor acoustic properties of the Loch. In particular, the Loch is, relative to an ideal operating environment, a shallow bowl with a highly reflective, layered hard-sediment bottom, which produces significant multipath.

Fig. 7 presents the relationship of PER against transmission speed (packet type) for two different distances, 0 and 55m. This figure clearly demonstrates the significantly higher PER when the REMUS AUV is transmitting PSK packet types (packet types 1-5). This correlates with the data acquired for the previous graph which used packet type 3 transmission. The cause of this problem is yet to be discovered and is a topic for future investigation. It is, however, thought to originate from how the main vehicle computer of REMUS uses the modem for localisation and keeping the user informed of mission execution which is then conflicting with our use of the modem from a payload computer.

Note that under some conditions, Fig. 7 shows the PER to be worse at 0m than it is at 55m. This is most likely due to clipping, which occurs when the modem transducers are too close to each other and the signal is saturated.

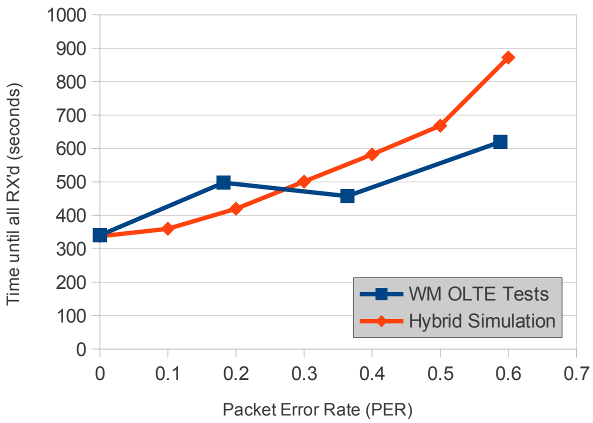

Figure 8. Time to successful reception of all transmitted WM updates, simulation compared to real-world performance. Simulation results were produced using GNU Octave software, while the real-world results were produced in Loch Earn using two stand-alone acoustic Micromodems

B. World Model Test

Although simple, the best measure of determining success with this test was by simply watching the IAUV to see if it moved off to an inspection point, which it did. The vehicle would move if and only if it retrieved an unobserved point-to-inspect from its ontology that had been updated from the SAUV. Once the vehicle started moving towards the first target point, checked with a GPS, this showed that the update process of the WM had been successful in real working conditions. Due to the anomaly in REMUS' transmission as seen in the preceding section, this WM test had to be with very close proximity between vehicles (less than 5m). As a result, the REMUS AUV couldn't be moving, as it would then quickly move out of effective range, and instead it was floated stationary at the surface.

C. Ontology Layer Transmission Efficiency Evaluation

Fig. 8 shows the time until all transmitted target packets were received plotted against the PER, for both simulated results and the experimental results from Loch Earn. The figure shows that the world model remains highly efficient as the noise in the communications channel increases, and in fact performs better than the simulation at high PER.

To replicate the characteristics of the two stand-alone modems, the hybrid simulation was set up to always have a PER of zero for packets received by the SAUV, and use the experimental PER value only for packets received by the IAUV. With a symmetric PER, the shape of the time vs PER graph agreed significantly less well with experimental results, and showed a much faster deterioration in performance with increasing PER. This occurs because until the SAUV receives an acknowledgement that a target has been received by the IAUV, it will continue re-transmitting that target, resulting in significant increases in the mission time.

VI. Conclusions

We have demonstrated a distributed world modelling service running and exchanging ontological data between two AUVs in Loch Earn, Scotland. Testing in real world operating conditions provided insight into the reliability of acoustic information exchange, rather than using pure simulation with associated assumptions, while using the WHOI Micromodem.

Presented first was the WHOI Micromodems performance in terms of packet error rate vs distance and packet error rate vs transmission speed vs distance. The results of which can be seen in Figs. 6 and 7 respectively. The limited attained transmission distance was found to be due to the poor acoustic properties of the Loch. Presented next was a mission implementation of the world model software using real vehicles; one representing a search vehicle with synthetic targets that the other vehicle, of an inspection type, has an "information need" for in order to complete its purpose.

As described in Section II, the World Model software uses a decentralised architecture in its software and system level information exchange. Using a TDMA (time division multiple access) scheme and a matrix acknowledgement policy, it allows the system as a whole to keep operating even in the event of one, or more, vehicles failing (providing there are others of the same vehicle type). This form of mission fault tolerant behaviour is very advantageous to applications where there is high probability of vehicle damage or acoustic communication loss. Further, the WM provides a layer of abstraction which takes the complex task of information exchange between vehicles away from the end user. As a result of this, the WM is not domain specific allowing it to be used elsewhere as a lightweight client interface for storing and querying data in a shared ontology.

Our immediate future aims are firstly to try PER tests in open water, which would confirm that the the limited acoustic range was just a property of the Loch we used for these experiments. Secondly, we would like to further investigate the issues with acoustic transmissions from the REMUS. The REMUS is intended to be a non-user-modifiable product, and we have found it to be an extremely reliable vehicle; while the original design did not envisage using the high data-rate acoustic transmissions used in this paper, we may be able to improve the situation with software or minor hardware modifications.

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