Multiple Communicating Autonomous Underwater Vehicles

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A. ABSTRACT

This paper addresses the problems associated with missions using multiple co-operating autonomous underwater vehicles. In such missions, inter-vehicle communication is an important requirement upon which co-ordination strategy and intelligence decision making functions can be built. This paper presents briefly our current modeling and simulation work on characterizing the vehicle communication performance, together with some of the preliminary results. Even with much simplification of scenario modeling, simulation results exhibit intricate communication characteristics, and they can vary significantly as a function of mission requirements and scenarios.

B. INTRODUCTION

Autonomous Underwater Vehicles (AUVs) are unmanned, untethered, self-propelled platforms. They provide marine researchers with a simple, long-range and low-cost solution with which to gather oceanographic data. Common applications for AUVs include oceanographic sampling, bathymetry profiling, underwater system inspection, and military mine counter-measure (MCM) operations [4] Recent trends in AUV technology are moving towards reducing the vehicle size and improving its deployability in order to reduce the operational costs. It is anticipated that the trend of miniaturizing AUVs will continue in the future. To further capitalize on this output, operations that involve a fleet of small (communicative) AUVs become financially and technologically feasible.

Operations involving multiple AUVs can be broadly categorized into three types: mutual independence, human co-ordination, and complete autonomy. The first type is the simplest in that there is no intended interaction among the vehicles, and the deployment strategy is based on the concept of "conquer and divide". At-sea operations of this type has been demonstrated in the past [15]. To support human co-ordination, vehicle behaviors can be dynamically adapted provided that information about the sensors and commands can be relayed promptly to and from all the vehicles. There has been an increasing focus on this type of operations for military reasons, albeit very little progress has been made due largely to the bottleneck of vehicle perception and communication throughputs to human operators. Nevertheless, at-sea operations which were based on very specific scenarios with pre-defined order of events have been recently demonstrated in recent Navy fleet battle exercises. Complete autonomy requires each of the vehicles to be capable of perceiving the environment, communicating effectively to other vehicles, and making proper decisions in such a way the overall mission objective can be achieved. While there have been previous work done on characterizing the behavioral performance of multiple co-operative vehicles [20], realistic constraints on vehicle communication, perception and intelligence were not considered.

Our research primarily addresses a lack of performance metric with which multiple AUV missions can be quantified and evaluated, subject to realistic sensor and environment constraints. In other words,

- *How can we trade-off single AUV missions against multiple AUV missions*? [1]

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[1] While it is difficult to generalize the trade-offs for all missions, it is believed that the trade-off can be evaluated

- *What trade-off parameters should we consider*?

To answer these questions, a multi-dimensional control study will have to be performed in which each of the parameters is to be perturbed individually. This renders experimentation impractical due to its prohibitive cost and an important fact that the perturbation of parameters tends to be non-deterministic. A more cost-effective approach to begin addressing these issues is through the use of a carefully designed modeling and simulation platform, with an appropriate level of detail or fidelity. Critical attributes are acoustic propagation and communication as co-operative missions are virtually infeasible without any form of inter-vehicle communication. Higher level attributes that can be aggregated include perception, navigation, control and intelligence.

This paper presents our previous work on multiple AUV communication, and our on-going research focus on multiple AUV mission. The next section briefly reviews the problems of underwater acoustic propagation and communication, and models that can be used for simulation. Existing routing techniques for ad-hoc networks of mobile nodes are also reviewed. Section IV describes our approach to designing the modeling and simulation platform, and presents some of the preliminary results. The final section provides both summarizing remarks and future research direction.

C. BACKGROUND

III.1 Acoustic Communication

Acoustic propagation for communication is highly complex because of the inherent variability associated with any acoustic channel [21]. Typically, undersea acoustic channels can exhibit multipath propagation that can be on the order of tens to hundreds of milliseconds, together with ambient noise spectra that are time-varying and have a dynamic range of 30dB or more [7]. In addition, the speed of sound is several orders less than the speed of light, resulting in much lower bandwidth and long turn-around time delay. Furthermore, the propagation paths of sound can be highly asymmetrical due to variability in sound speed profile and bottom characteristics. To maximize the channel utility, one must design an effective communication system such that a proper modulation and channel equalization scheme be chosen, multi-path effects be dealt with. Commonly used signaling schemes include multiple FSK and PSK [11].

Typical communication scenario involves a point-to-point protocol whereby a link is established between any two vehicles, although in some cases, one-to-many connection can be realized with a broadcast mode [6][14]. There are three multiple access methods that enable multiple vehicles to communicate with each other over a shared time and frequency channel. They are frequency division multiple access (FDMA), time division multiple access (TDMA), and code division multiple access (CDMA). FDMA is based on dividing the frequency domain into sub-bands, and assigning each of them uniquely to its matching vehicle. Since the division is fixed, this scheme is not flexible, and is vulnerable to fading effect. Analogous to FDMA in time, TDMA divides the time domain into time slots. Each time slot is assigned to a unique vehicle, and the slot must be long enough to prevent data collision spilled over from adjacent time slots. While TDMA is more flexible in reconfiguring the time slot assignment, it is generally less efficient in terms of throughput. Compared to the former two schemes, CDMA tends to provide graceful degradation, have less timing organization, and is less vulnerable to inter-symbol interference. Details of these multiple access schemes can be found in [17]. Thus far, at-sea operations which involved two AUV communicating with each other has been demonstrated [11]. The communication scheme was based on M-FSK with TDMA with collision avoidance capability.

III.2 Ad-Hoc Networks

An Ad-hoc network is defined herein as a network of AUVs (at least three nodes) with which communication does not require a centralized master for routing vehicle messages [17][19]. In other words, each node can act as a router, if needed. In an co-operative mission, each vehicle determines autonomously its optimal trajectory strategy subject to its high-level mission objective and local environmental constraints. As a result, there tends to be strong variability in its relative range and motion among the vehicles as they compete for the finite resources available. This variability has a significant impact or degradation on the acoustic communication performance, especially when some vehicle is out of acoustic range from another vehicle. In such a case, routing might be the only enabling solution. Figure 1 shows a scenario with five AUVs with circles, each representing an idealized, maximum acoustic range. Note that node *A*, *B* and *C* are all reachable among each other, and point-to-point communication would suffice. Whereas node *E* must require node *D* to route messages to *A*, *B* and *C*.

There are a number of routing algorithms that have been proposed for land-based ad-hoc networks, and their

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more accurately based on the required or expected scaling of temporal and spatial domains for a given mission.

underwater application is currently evaluated by a number of researchers in the field. The routing algorithms can be broadly categorized as 1) flooding, 2) table-driven, and 3) on-demand types. The details are beyond the scope of this paper, although they can be found in [7][13]. The flooding algorithm involves generating and sending a message from a source to other nodes in a network. Whenever a node receives the message, it forwards the message only once to all its neighbors. At the end, each node will receive the message at least once. For an example, a flooding scenario with eleven nodes will require a total of 11 messages to be sent, and 30 messages to be received.

Flooding algorithms do not assume any knowledge about the network topology. Due to the recursive nature of the algorithm, much bandwidth will be needlessly wasted. In table-driven algorithms, each node maintains *some* information in a table about the network connectivity. The information can be number of hops to the next forwardable nodes. Examples include Distance Vector Routing and Link State Routing [18].

Table-driven algorithms require that the tables be updated faster than the change in the network topology. For a moderate size of network, the level of overhead in vehicle communication can still be significant. An alternative to further reducing the overhead needed is to collect routing information for the neighboring nodes only, or to use on-demand algorithms. In these algorithms, routes are provided only for the destination nodes that must be reached. The idea is to generate request messages every time a message is to be sent to a destination for which the route is unavailable. Upon receipt of a request, the destination replies back to the source, and their connection route is established. The latter two algorithms typically assume symmetry of route direction between any two nodes, and this assumption is often violated due to variations in sound velocity profiles and bottom characteristics. In addition, the two algorithms generally require some form of flooding during the initialization process, thereby further reducing the overall efficiency in inter-vehicle communication.

D. METHODOLOGY

Thus far, we have carried out a preliminary simulation study on vehicle communication based on an underwater acoustic propagation model and standard routing techniques [3]. There has been much work done on modeling the acoustic propagation characteristics, and examples of such work include the Gaussian Beam Acoustic Model, and Range-Dependent Acoustic Model. Our main intention is to come up with a statistically relevant model that can capture the typical variability of an acoustic channel, instead of predicting accurately the communication performance associated with a particular acoustic channel.

To that effect, we modeled the acoustic communication characteristics using a uniformly distributed error probability, subject to a threshold function shown in Figure 3. The threshold accounted for the range limitation of an acoustic modem. A message error will occur if the outcome of the uniform distribution exceeds the threshold value. For routing vehicle messages, we have considered both flooding and a localized table-driven routing algorithm called Distance Vector Destination Sequence (DSDV). In DSDV, each node kept a routing table that lists all neighboring destinations, and the number of hops to each of them [13].

This paper presents only one simulation scenario in which three AUVs (referred to *AUV4*, *AUV2* and *AUV5* in the result figures), performed a pre-defined lawn mower pattern [2]. Only one AUV (*AUV4*) sent out messages while the other two were receivers. The simulation performance was evaluated based only on time histories associated with the number of hops used, and routing efficiency (defined as a ratio of the total number of useful messages sent versus the total number of messages sent). The top and bottom plots in Figure 3 show the communication results using flooding and DSDV routing respectively. One can see that flooding used two-hop routing slightly more than DSDV did. Both routing achieved similar routing efficiencies, and the time histories showed intricate dynamics as the vehicle position varied. Results associated with other scenarios can be found in [3].

E. CONCLUSION

In this paper, our approach to address multiple AUV mission and performance has been described, and our preliminary simulation study and results have been presented. Even with much simplification of scenario modeling (with only three vehicles and one sender), the acoustic communication performance exhibited very complex characteristics. Other results that are not shown here in this paper suggest that the performances are highly sensitive to the mission scenarios that require the vehicles to communicate at varying rates and ranges. In other words, there appears to be no general optimal routing technique for all mission scenarios, and equally, any routing algorithm can be optimal in a narrow sense for a particular mission scenario. Our future work includes refinement of the acoustic propagation model that considers the bottom characteristics, selection of *suitable* set of routing mechanisms, development of an analytical framework for characterizing the information

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[2] The vehicle trajectory consists only of positional information. Motion dynamics were not considered.

flow among the vehicles, and development of a performance metric suitable for multiple AUV missions.

F. ACKNOWLEDGMENTS

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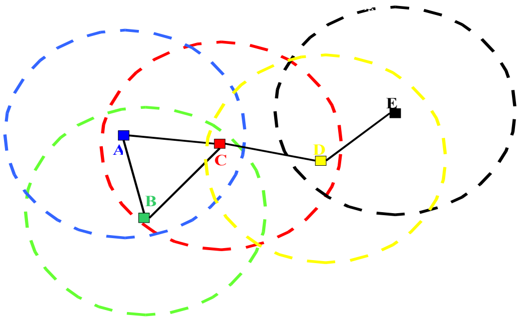


Figure 1 A communication scenario

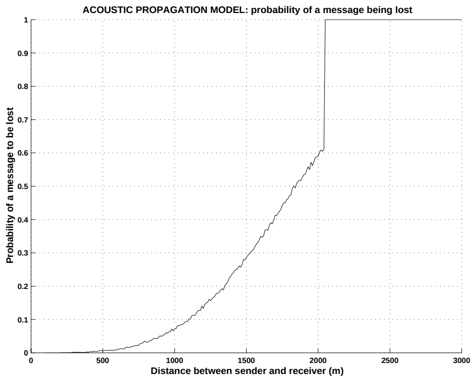
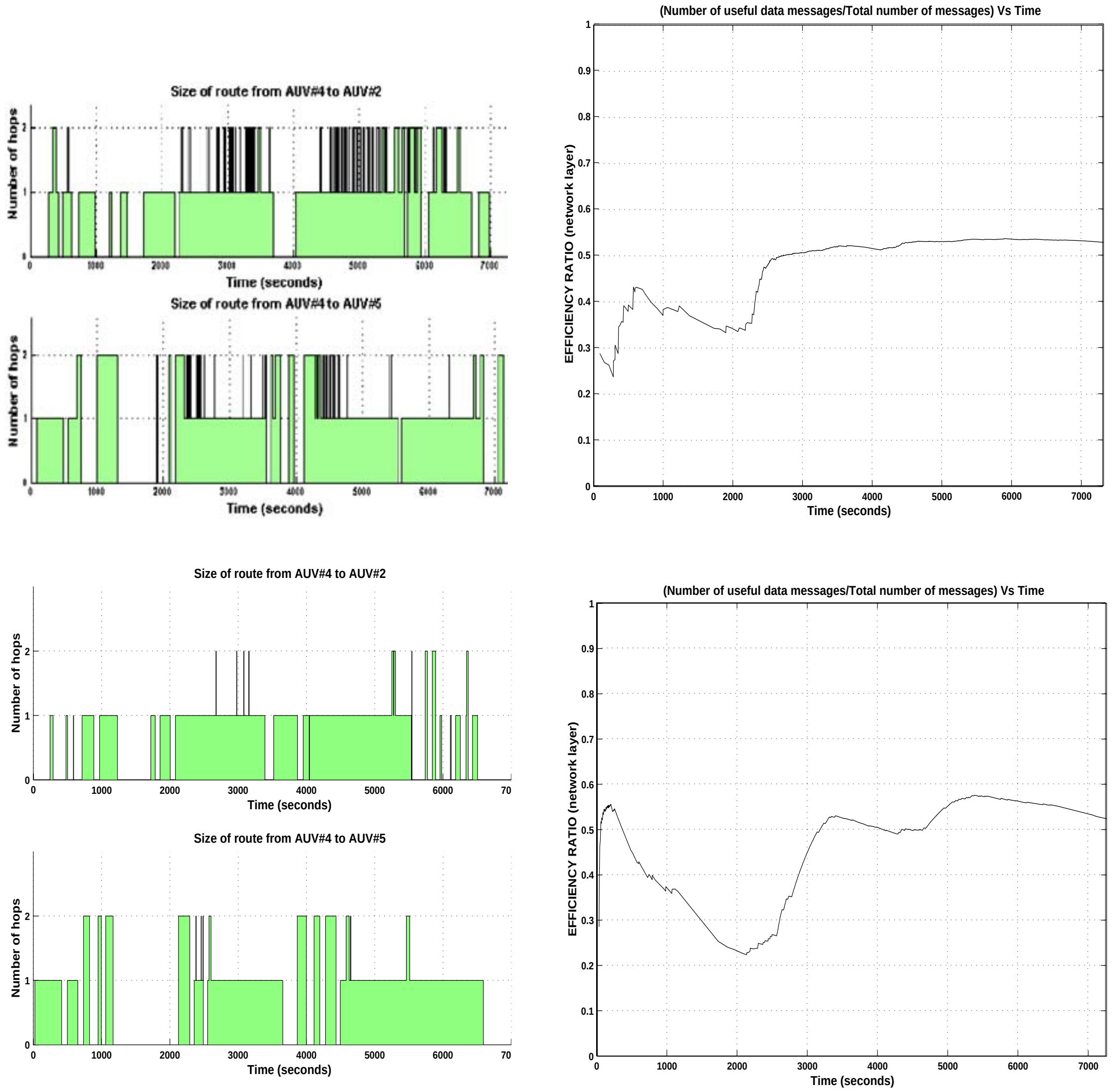

ACOUSTIC PROPAGATION MODEL: probability of a message being lost

Figure 2 Conditional threshold as a


Size of route from AUV#4 to AUV#2

Size of route from AUV#4 to AUV#5

(Number of useful data messages/Total number of messages) Vs Time

Size of route from AUV#4 to AUV#2

Size of route from AUV#4 to AUV#5

(Number of useful data messages/Total number of messages) Vs Time

Figure 3 Simulation results using flooding (top plots) and DSDV routing algorithms (bottom plots)