Task Consensus among a Team of Heterogeneous AUVs under Intermittent Communication

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***Abstract*—Using multiple smaller vehicles to accomplish tasks rather than a single larger vehicle has garnered significant attention in recent years. For these multiple smaller vehicles to operate in unison they need to exchange information frequently. Great progress has been made in this area where communication links are easily established and bandwidth is not a significant issues in modalities such as UGVs and UAVs. In domains where communication is an issue, such as underwater, novel approaches are needed to overcome these limitations. Some of these limitations include range, frequencies and bandwidth. In this paper consensus is defined as the awareness of each team member about its own task as well as the tasks of all the other members of the team. Communication is critical for achieving consensus. Limiting the message size and allowing messages to cascade through the team via multiple coordinated hops are significant challenges that need to be overcome. This paper addresses one such approach.**

Keywords—Multi-vehicle cooperation; UUV; AUV; autonomy; Multi-vehicle coordination; acoustic communication; consensus; auction based

I. Introduction

There has been a paradigmatic shift in many areas where robots are used to complete non-trivial tasks. Rather than using expensive "heavy" vehicles some newer approaches are opting to use many light-weight vehicles to accomplish the same goals. The latter approach has multiple advantages over the former, such as eliminating the single point of failure and being able to execute multiple concurrent missions. Multi-vehicle systems are able to complete tasks that may be time consuming, difficult, or even impossible for a single vehicle. By splitting tasks into sub-tasks and assigning those to different vehicles the multi-vehicle system can take advantage of parallelization.

Because of these advantages multi-robot coordination has been an active and attractive field for robotic researchers during the past decade, especially in military and space applications. Early research has mainly focused on having multiple vehicles fulfill pre-defined missions, but often times these teams work beside each other but not necessarily as a team. Simple solutions to team coordination are accomplished either through a human operator or a single master vehicle that controls the other vehicles. The flaws with these simple approaches are apparent; the human operator makes the system no longer autonomous and the single master vehicle reintroduces the same single point of failure as the "heavy" vehicles.

In order for the vehicles to work autonomously in a coordinated manner, team knowledge must be shared between the vehicles. Spreading team knowledge is accomplished through regular exchange of vehicle status information. Team knowledge allows the vehicles to coordinate with each other intelligently to complete complicated group tasks, but only if there is task consensus among the vehicles. Task consensus is achieved when every vehicle in the team is aware of its own task as well as all other team members' tasks. Although most team missions tend to have an overall goal, during the execution of this goal a single vehicle or a team of vehicles may need to assume new roles. Dynamic re-tasking will lead to vehicles abandoning their previous roles and assuming new ones in order to accomplish emergent tasks. But if the role assignment is done in an ad hoc fashion the original mission could be severely compromised. When one or more vehicles make changes to their task, task consensus needs to be reestablished. Task consensus is critical to maintaining the original mission while accomplishing newly discovered tasks.

It becomes apparent that for multiple vehicles to operate in unison communication is a key component due to frequent and much needed sharing of messages to maintain consensus and team knowledge. Communication becomes an issue over large geographical areas or in volatile environments where regular communication methods do not work, such as in underwater environments. In underwater environments acoustic modems are generally used to transmit messages between vehicles. Factors such as temperature, salinity, and properties of the sea bed impact the range, quality, propagation speed, and bandwidth of acoustic communication. These severe limitations create time delays and gaps in information needed to achieve consensus in a timely manner. Achieving consensus in such a dynamic and constrained environment is difficult.

II. Previous Work

Task management is the backbone of any multi-vehicle system. Even if we cannot perform tasks intelligently or as a team, tasks still need to be done. As mentioned previously, a decentralized approach to task management is necessary in order to avoid a single point of failure [1], [2] and problems associated with intermittent communications [3], [4]. However,

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since the goal of this work is to achieve multi-vehicle cooperation, we must extend task management to include consensus [5]. We have introduced an auction based approach to achieve consensus. Auction based approaches have been studied in general robotics and have been shown to be a reliable way to achieve consensus [6], [7], [8], but communication issues due to the underwater environment make the problem much more difficult [9]. Improving communication would allow for faster spread of team knowledge and reduce the time to reach consensus, but it still remains an open problem [10].

III. Experimental Framework

Tasking, both individually and as a team, is used to determine consensus in our experimental framework. The experimental framework is set up as follows – a team of 6 Autonomous Underwater Vehicles (AUVs) are on a 24/7 surveying mission around a high value asset as shown in Fig. 1. The overall goal of surveying is to detect potential threats to help prevent loss of life or assets.

The small dots represent AUVs that patrol around the High Value Asset (HVA) in a specified pattern for intrusion detection. The highlighted region is a subdivision of the area, and the six AUVs in the wedge are considered part of one team. All six vehicles in each group act together in order to detect intrusions into their designated area. Because of the configuration of all four teams together, it is assumed that threats will come from outside the circle. The AUVs patrol in a bowtie pattern and regularly share status messages through a Time Division Medium Access (TDMA) schedule. The TDMA schedule is an ordered list of time slots that only a designated vehicle can transmit messages during, in order to prevent message collision or loss. Communication inefficiencies arise in a TDMA schedule because there is a fixed order the vehicles transmit in. This can cause redundant sharing of information and delays in receiving replies from vehicles in faraway time slots.

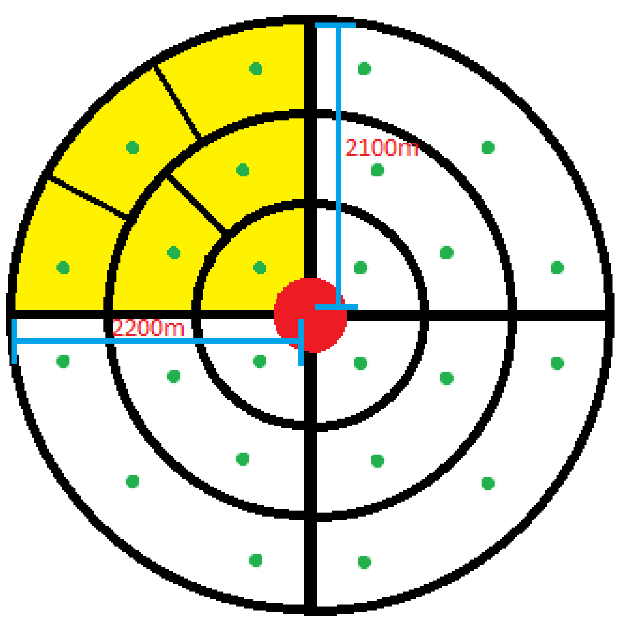

Fig 1. Four teams of six AUVs patrolling around a HVA in the center.

In simulation, 32-byte message sizes were used with a WHOI micro modem, to broadcast status information. When a vehicle needs to broadcast a message, the message is sent to its communication queue. Multiple smaller messages in the queue can be combined into a full size 32-byte message. Due to the small size of the message, it is important that the communication queue is not filled with redundant or useless messages. Situational awareness is used to help better manage the communication queue, as well as address some problems with TDMA scheduling.

The heterogeneity of the team comes from communication and sensing capability, as well as different vehicle speeds and energy consumption rates.

If a potential threat is detected while surveying, a sub-team is formed to further investigate and identify the target. In order to create the sub-team, a modified auction based approach is used to determine its composition. First, a recruiter (the first vehicle that detects the intrusion) announces the mission via broadcast to all other vehicles. Upon receiving an auction announcement, each vehicle creates a bid for the task, as well as re-broadcasts the auction announcement for any vehicle who potentially could not hear directly from the recruiter. The bid consists of information about location and energy of the vehicle, so the recruiter can optimize on both time and energy constraints. After the recruiter receives all needed bids it optimizes the results to create the departing sub-team. Optimization must be considered for both the sub-team performing the new task, and the team continuing on the original survey mission. The recruiter not only takes into account the individual vehicles that can best accomplish the investigation mission but also the ability of the remaining vehicles to maintain survey coverage above a minimum threshold.

The surveying mission threshold is determined by sonar coverage maps, created with vehicle sensor data. Once the sub-team has been picked, the recruiter announces which vehicles were chosen, and the sub-team departs to complete the investigation task. The remaining vehicles reform into a formation to maximize survey coverage. Once the sub-team completes their investigation, they return to the formation, and the full six vehicle team returns to the original formation.

IV. Approach

This auction based approach tests two main consensus points:

1) All vehicles know an auction is going on, and the details

2) All vehicles know if they should reform for the survey mission or depart for the investigation mission

B. Configurations

The time it takes to reach each consensus point is timed for different formations of vehicles in different scenarios. The formations are listed in Table 1, and the layout is with respect to the wedge layout; the first number denotes the amount of vehicles in the outer layer and then moves inward. An example of a formation is shown in Fig. 2.

TABLE I. LIST OF VEHICLE FORMATIONS

Vehicle Formations	
Number of Vehicles	***Layout***
6	3,2,1
5	3,2,0
	3,1,1
	2,2,1
4	3,1,0
	2,2,0
	2,1,1
3	3,0,0

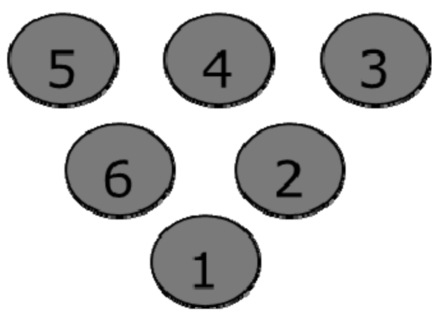

Fig. 2. An example of 6 vehicle 3,2,1 formation.

TABLE II. LIST OF SCENARIOS

Formation Independent Scenarios	
Scenario Number	***Description***
1	All vehicles can communicate with each other
2	All vehicles can communicate up and down the TDMA schedule (e.g. 1 <-> 2 <-> 3)
3	All vehicles can communicate up the TDMA schedule (e.g. 1 -> 2 -> 3)
4	All vehicles can communicate down the TDMA schedule (e.g. 1 <- 2 <- 3)
Formation Dependent Scenarios	
Scenario Number	***Description***
5	All vehicles can communicate with immediate neighbors
6	All vehicles can communicate with their neighbors within a reasonable distance ~750 meters

There are six different scenarios as show in Table 2. Scenarios 1-4 are formation independent, which means the physical layout of the vehicles does not impact the outcome, so it only needs to be run for each different number of vehicles. These scenarios were chosen to test the impact the TDMA schedule has on the outcome the experiments. Scenarios 5 and 6 are formation dependent, and need to be run for each formation, as well for each of the possible recruiters in the formation. As stated previously, it is assumed that the detection will occur outside of the wedge, so all vehicles in the outer layer are possible recruiters. These scenarios are meant to be more realistic in an operational environment.

For base lining purposes, 100% communication rates are used, but since the vehicles are heterogeneous and may have different communication abilities, it is not assumed that there will always be two-way communication.

C. *Experimental Simulations*

Simulation performance is measured by counting the number TDMA slots between the initial auction announcement and each consensus point. TDMA slot time is a configurable parameter that can be adjusted to fit specific needs, in these simulations the slot time was 10 seconds.

The first sets of simulations are 'dumb'. In these simulations the vehicles will continue to only send their bid until they get confirmation that the recruiter has received it, at which point they will start forwarding other vehicles bids. There is no message queue management, they only queue the most recent bid they heard, but will not queue a bid from a vehicle they know the recruiter has heard from. The recruiter maintains and broadcasts a list of vehicles it has bids from. Each vehicle is provided with a list of other vehicles they can hear from, and will ignore messages from vehicles they cannot hear from. This list varies depending on which scenario is being simulated. To remove the effects of randomness and determine a baseline to test against there are no dropped or scrambled messages, see Future Work for more details.

The second sets of simulations are built on top of the previous simulations, but include situational awareness that allows for some level of message queue management. The vehicles are given the communication lists for all vehicles to create a network map of the system. Each vehicle uses the network map to determine which messages they should queue for forwarding to reduce redundant messages. By reducing redundant messages the vehicles are better able to spread team knowledge in a timely manner.

V. RESULTS

The results for the independent scenarios are shown in Fig. 3. Scenario 1 is omitted because the second sets of simulations produced the same results as the first, and in the three vehicles configuration scenario 2 was equivalent to scenario 1. The vertical bars show the overall number of TDMA slots needed for each set of simulations to reach consensus point 2. In all cases, except those previously mentioned, the second simulations outperformed the first by an average of 41% reduction in TDMA slots needed, with reduction ranging from 29% to 54%.

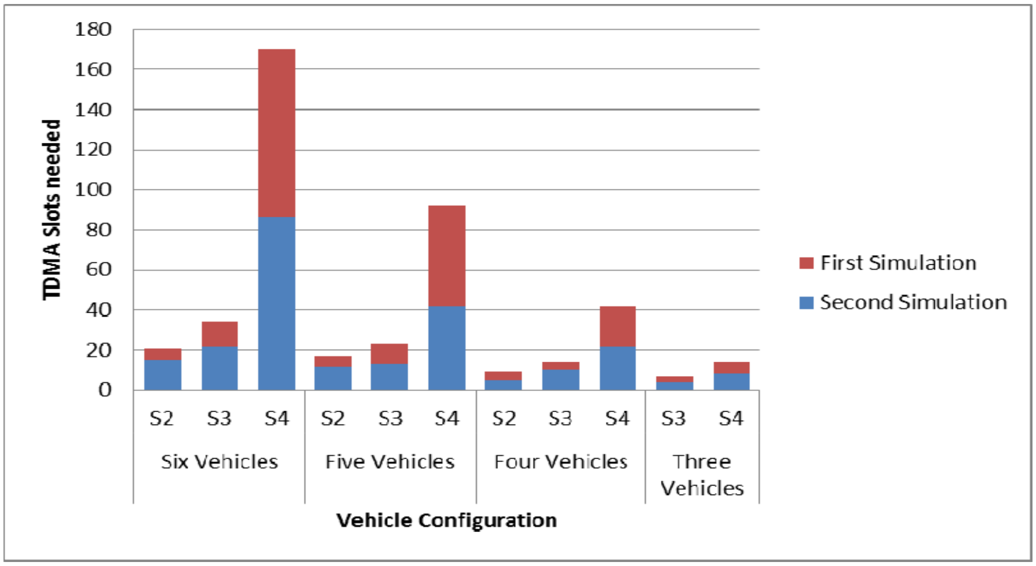

Fig. 3. The total number of TDMA slots needed to reach consensus point 2 for scenarios 2-4.

For the dependent scenarios, there were a total of 28 simulations that were not equivalent to any of the independent runs. Of these 28 simulations 11 resulted in no change in the needed number of TDMA slots to reach consensus point 2. In the remaining 17 runs each of the outcomes resulted in a full cycle reduction in TDMA slots needed. This means that for six vehicles, six less TDMA slots were needed in the second simulation versus the first.

VI. Conclusions and Future Work

Initial results have shown this approach to be a promising method of overcoming range and bandwidth challenges in underwater communication. Many different scenarios were initially tested and results presented. Future work includes:

- Utilizing previous status messages in order to give a 'good enough' view of the system to create a sub-optimal sub-team to meet time constraints
- Excluding specific vehicles from the task assignment process if they are believed to be a non-contender for sub-team selection based on previously gathered data.
- Introducing different percentages of randomly dropped or scrambled messages
- Learning the network map over time based on communication between vehicles

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References

[1] M. Dias, "Traderbots: A new paradigm for robust and efficient multirobot coordination in dynamic environments," 2004.

[2] H. Choi, L. Brunet, and J. How, "Consensus-based decentralized auctions for robust task allocation," Robotics, IEEE Transactions on, vol. 25, no. 4, pp. 912–926, 2009.

[3] D. Eickstedt, M. Benjamin, H. Schmidt, and J. Leonard, "Adaptive control of heterogeneous marine sensor platforms in an autonomous sensor network," 2006 IEEE/RSJ International Conference on Intelligent Robots and Systems, pp. 5514–5521, Oct. 2006.

[4] D. Eickstedt and M. Benjamin, "Cooperative target tracking in a distributed autonomous sensor network," Oceans 2006, pp. 1–6, Sep. 2006.

[5] K. DeMedeiros, R. Balasubramanian, C. Duarte, and G. Martel, "A novel token passing algorithm for management of refueling vehicles in a multi-UUV 24/7 mission scenario," OCEANS …, 2010.

[6] M. B. Dias, R. Zlot, N. Kalra, and a. Stentz, "Market-based multirobot coordination: a survey and analysis," Proceedings of the IEEE, vol. 94, no. 7, pp. 1257–1270, Jul. 2006.

[7] T. Mercker and D. Casbeer, "An extension of consensus-based auction algorithms for decentralized, time-constrained task assignment," American Control …, pp. 6324–6329, 2010.

[8] T. Lemaire, R. Alami, and S. Lacroix, "A distributed tasks allocation scheme in multi-UAV context," IEEE International Conference on Robotics and Automation, 2004. Proceedings. ICRA '04. 2004, pp. 3622–3627 Vol.4, 2004.

[9] S. Sariel, T. Balch, and N. Erdogan, "Naval mine countermeasure missions," Robotics & Automation …, no. March, pp. 45–52, 2008.

[10] J. Partan, J. Kurose, and B. N. Levine, "A survey of practical issues in underwater networks," ACM SIGMOBILE Mobile Computing and Communications Review, vol. 11, no. 4, p. 23, Oct. 2007.