Teamwork among marine robots – advances and challenges

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Abstract. Marine robots are powerful tools that can help us understand our vast oceans. Although much progress has been made in developing robust marine robots, some fundamental challenges such as underwater navigation and dealing with uncertainty still remain. We believe that some of these challenges could be addressed by teams of marine robots. Each member of the team may be low-cost and exhibit simple behaviors, but as a whole the team may be robust and effective in achieving specified goals. We outline the challenges in practical realization of this idea, and the progress made in overcoming some of the challenges. We also provide some insights into possible breakthroughs and future directions for this research.

1 Introduction

Oceans cover more than 70% of the Earth's surface, yet, there is much that remains to be understood about them. Owing to the inaccessibility and harshness of much of the oceans, sensing and monitoring is a difficult and expensive task. The field of marine robotics holds the promise of technology that may make these tasks easier, safer and cheaper. It is a rapidly maturing field, with substantial progress made in the past two decades. Autonomous underwater vehicles (AUVs) are now routinely used for deep water surveys. Autonomous gliders have successfully crossed the Atlantic Ocean, while autonomous surface crafts are currently transiting across the Pacific Ocean.

Despite these advances and successes, some fundamental challenges remain. In particular, the lack of global positioning system (GPS) signals underwater makes long-range underwater navigation a daunting task for AUVs [9]. To deal with long latencies, low bandwidth and low reliability of long-range underwater communication systems [4], AUVs must be capable of making autonomous decisions in face of environmental uncertainties, with only occasional contact with their operators. The conventional solutions to these problems typically involve improved sensors and more complex software. For example, the navigation problem can be partly alleviated through the use of expensive sensors such as Doppler velocity log (DVL) and inertial navigation system (INS). Adding high-quality sonar systems and using techniques such as simultaneous localization and mapping (SLAM), one may perhaps imagine that the challenge of underwater navigation may be overcome. However, these sensors and algorithms add substantial cost and complexity to the AUV, and reduce its reliability. They also increase the power requirements of the vehicle and limit its operational endurance.

While there may be some applications in which these costs and complexity are warranted, we suggest that a very different approach may be useful in other applications. Rather than use a single complex expensive AUV for a robotic task, we could use a number of simpler low-cost AUVs that work as a team to achieve the desired mission. The team may be *homogenous* with each AUV having identical sensors and behaviors, or *heterogenous* with AUVs specializing in different aspects of the mission and adopting different behavioral rules. A team may also benefit from spatial sampling and diversity, and an increased robustness due to redundancy. In this article, we highlight the value in using teams of AUVs and outline some of the steps we have taken towards practical realization of this concept.

2 Technical description

The idea of *teams* is not new. Over millions of years of evolution, nature has discovered that a team is much more than the sum of the individuals that make up the team. This is evident from the numerous examples of teams in nature (e.g., flocks of birds, swarms of bees, colonies of ants, schools of fish, etc). In the field of robotics, the idea of using *swarms* has been gaining increasing traction [13]. Most of that research focuses on large teams of aerial and land robots. We believe that practical teams of underwater robots are likely to be small, and therefore focus our research on small teams of underwater robots.

We draw our inspiration from a specific example of a team in nature. To avoid being eaten, coral fish spawn several kilometers away from the reef. When the larvae hatch, they have to find their way back to the reef to seek shelter and food. It has been shown that noise from the reefs may help guide the larvae to the reef [14]. Yet, with only a few millimeters of acoustic aperture size, how does a fish larva reliably estimate the direction of the reef? It is possible that a school of fish larvae is able to harvest team synergy to locate the reef. This possibility has been demonstrated through numerical simulations with a simple set of behavioral rules combined with schooling [12, 5]. By designing simple behavioral rules for a team of low-cost AUVs based on these principles, we are currently exploring the efficacy of using the team to locate underwater sources of sound. We aim to experimentally demonstrate such a team next year. Although the research currently assumes a sound source to be the target of interest, it is easily extended to localize other signals such as chemicals, temperature, etc. This research essentially invokes the idea of *emergence* to obtain useful and robust team behaviors from a set of simple individual behavioral rules [7].

The research described above focuses on using homogenous teams of simple AUVs to create useful emergent team behaviors. Although we are able to numerically demonstrate that this is achievable with teams as small as 10–20 AUVs, as one would expect, the emergent properties of such teams disappear as the teams become smaller. With very small teams of AUVs, we advocate the use of heterogenous sensing capability and carefully designed behaviors to achieve team synergy. A specific example of this is a 2–3 AUV team used for surveys, where one AUV has better navigational sensors than the others. This AUV adopts a specially designed behavior that helps the other survey AUVs achieve good positioning accuracy through acoustic ranging. In some cases, this behavior is designed using an optimization criteria [1], while in other cases, it is 'learned' from a large number of Monte-carlo simulations [15, 16].

To implement a homogenous or heterogenous team of cooperating AUVs, we require an AUV that can easily be reconfigured with sensors needed for a specific mission. Under the STARFISH ('small team of autonomous robotic fish') program [10], we have developed a number of small modular AUVs for such missions. While our algorithms try to minimize the necessary communication between AUVs, to achieve cooperation, we require some communication. Communication between AUVs, bottom-mounted sensor nodes, autonomous surface vehicles, and surface control station are achieved using acoustic modems developed as part of the UNET (underwater networks) project [3].

3 Key challenges

There are several challenges, both theoretical and practical, that we need to overcome before this vision of marine multi-robot teams can become reality.

The primary theoretical challenge is in the design of behavioral rules for the individuals in the team. Given a set of rules, it is possible to run a large number of Monte-carlo simulations to understand how the team would behave. However, given the desired team behavior, how does one design individual rules to achieve that behavior? As teams become larger and emergence plays a role in the overall behavior, this inverse problem of rule design poses a major challenge.

Cooperation requires communication. Achieving reliable communication between underwater robots can be challenging in many environments. At very short ranges, optical or electromagnetic communication may be possible. However, at longer ranges most communication is acoustic. The acoustic channel can vary significantly with temperature, depth, bathymetry, etc and is known to be one of the more challenging channels for communication systems.

There are several more practical challenges – these are more mundane, but nevertheless important. Safe deployment, recovery and management of a large number of marine robots can be difficult, especially in poor weather conditions. There is a need to develop automated deployment and recovery systems that can work is fairly high sea states. Extensive hardware and software testing is required to make marine autonomous robots robust enough for general use. In general, such testing is expensive and time-consuming, and only a few research facilities have the resources to undertake it. Without tens of thousands of hours of testing, one cannot confidently deploy large number of robots and expect most of them to complete a given mission and return successfully.

4 The future

Although the challenges are formidable, we do not believe that they are unsurmountable.

The problem of inferring behavioral rules from collective behavior is a topic of intense research in many disciplines [11]. Of particular interest is some recent work on inferring rules in fish schools [6, 8]. We are applying the findings from this research into teams of AUVs. We foresee development of robust theoretical and simulation tools that will allow us to decompose a team goal into a set of behaviors for each member of the team. This is likely to be computationally intensive and therefore best done offline, in advance of a mission. An online locally optimal version of these tools may run onboard the robots to adapt the behaviors in case of unforeseen changes to the mission.

Underwater communication systems have been slowly but steadily improving in performance and robustness. However this often comes at the cost of high power requirements and larger size. As the technology matures, there is no doubt that these systems will become more power-efficient, smaller and cheaper. A trade-off of communication range and data rate against power and size is possible. This will enable AUV teams that require minimal communication over short ranges to adopt small and low-power communication systems. We also expect that as command & control systems for AUV teams mature, communication needs of AUVs will be considered while planning AUV behaviors and routes [2]. This will ensure that communication links are more likely to be available when they are required by the AUVs to coordinate their tasks.

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