Teamwork among AUVs

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Abstract We believe that the future of marine sensing lies in teams of cooperative autonomous assets working together to provide a coherent picture of the operating environment. The assets may be fixed or mobile platforms, both underwater and on the surface. Although several different research projects at ARL contribute important technologies towards achieving this vision, the STARFISH research program was our first significant step towards integrating the systems into a cooperative "team". The program was aimed at understanding the challenges faced in cooperative underwater robotics, exploring ways to overcome the challenges, developing missing component technologies, and demonstrating cooperation in a small team of autonomous underwater vehicles (AUVs). In this paper, we present a brief overview of the research undertaken, the key technologies that have been developed, and some of the future research directions.

Introduction

It has been shown that teams are often capable of better performance than any individual in the team (Woolley et al., 2010). Swarms of bees, flocks of birds, schools of fish, colonies of ants and termites are just a few examples in nature where individuals come together to harness the synergy in teams (Resnick, 1997). Of particular significance in marine research is the possibility that emergent behavior in schools of fish larvae allows them to locate coral reefs (Potter and Chitre, 2006). Inspired by nature, researchers have successfully developed algorithms that use interaction between a number of simple *agents* to solve problems (Bonabeau and Theraulaz, 2008). Although many studies have focused on teams of homogenous agents, there is evidence that teams can benefit from a minority of more capable agents (Reebs, 2000). With this in mind, we wanted to explore if a small team of AUVs with heterogenous capabilities could benefit from emergent behavior to accomplish useful tasks. To allow us to go beyond numerical simulations, in 2006, we embarked on a project to build a small team of *autonomous robotic fish*[1], or STARFISH for short.

Figure 1: Two STARFISH AUVs at the surface during a field trial.

STARFISH AUVs

In order to deploy and test teams of heterogenous AUVs, we needed each AUV to be low-cost, easily reconfigurable and have underwater communication capability. The reconfiguration could involve physically adding or removing sensor or actuator modules. We desired minimal changes to the AUV software when the sensing or actuation capability of the AUV changed. The guiding principle was that hardware (be it sensors, actuators or processing units) should be coupled with the necessary software that knows how to use the hardware, to form a module. When the module is added to the AUV, the software should integrate itself into the AUV guidance, navigation & control (GNC) system.

Most commercially available AUVs are based on proprietary interfaces & architectures and have limited modularity. As we could not easily implement the desired degree of "plug-and-play" modularity with off-the-shelf AUVs, we developed STARFISH AUVs to meet our needs (Koay et al., 2010). Two currently operational STARFISH AUVs are seen in Figure 1. Another three similar AUVs are currently being assembled.

Open Architecture

Since the lack of modular architecture and open interfaces drove us to develop our own AUVs, we wanted to ensure that the STARFISH AUV has an open architecture that allows other researchers to easily integrate their sensors, actuators and software modules into the AUV. In the following sections, we will elaborate on how this is achieved.

[1]The term "fish" here simply refers to an AUV and does not imply biomimetic body or propulsion.

Mechanical modularity

The STARFISH AUV has a torpedo-shaped modular hull with a diameter of 20 cm. The mechanical coupling between sections is standardized, allowing modular sections to be developed independently and inserted into the AUV. The coupling consists of a set of interlocking teeth, O-rings and a rotating electrical connector with guiding pins as shown in Figure 2. The mechanical drawings of the inter-section coupling are made available to researchers who wish to build new STARFISH AUV sections.

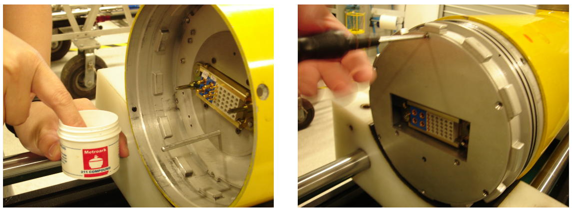

Figure 2: Male and female inter-section connectors showing the interlocking teeth, O-rings, electrical connector and guiding pins.

Simple electrical interface

The inter-section electrical interface primarily provides power and Ethernet communications. The power bus allows power to be drawn by a section, and for a section with batteries (or other forms of power sources), power to be supplied by the section. The Ethernet lines allow the section to communicate with other sections in the AUV to provide or consume appropriate services from other sections. A few additional electrical lines are available on the connector for AUV health status and battery information – however many useful sections can be implemented without using these lines explicitly.

DSAAV

The benefits of hardware modularity can only been realized to their full potential if the software is able to easily support the new sensors and actuators added to the AUV. Software frameworks such as the mission oriented operating suite (MOOS) provide a potential solution to address this requirement (Newman, 2001). MOOS adopts a *star* architecture with all components connecting to a central database in order to deposit or retrieve information from sensors and actuators. This architecture can potentially lead to a data bottleneck and a single point of failure. Moreover our modular hardware architecture is most effectively used with a distributed software framework with peer-to-peer communications between AUV sections, rather than a centralized architecture provided by MOOS. We therefore developed a distributed software architecture for autonomous vehicles (DSAAV) to address this need (Chitre, 2008).

DSAAV has been designed with modular AUVs in mind. Each AUV module provides a uniform software interface that other AUV modules can access. This interface allows configuration of the module, logging of critical information, discovery of services, access to sensor & actuator services, health monitoring and automated software update functionality. The interface is rich in functionality, yet lightweight and portable to ensure that even low power micro-controllers can easily implement it. The interface is easily extensible through remote procedure call (RPC) constructs and therefore provides forward compatibility. DSAAV can be implemented on any underlying communication backbone – in the STARFISH AUV, the communication backbone used is Ethernet. The software components running under DSAAV are independent of the underlying communication backbone.

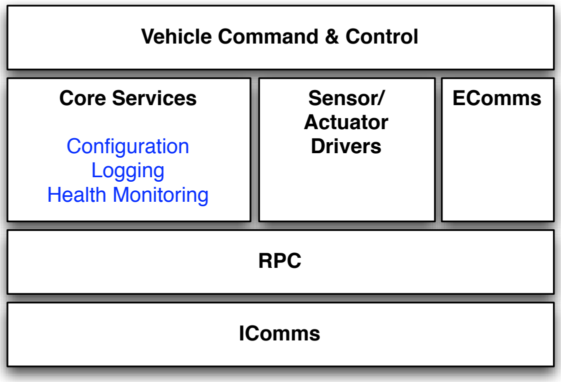

Figure 3: DSAAV 4-layer architecture.

DSAAV is a four-layer architecture as depicted in Figure 3. The bottom-most layer (IComms) provides an implementation of an unreliable messaging service (similar to UDP/IP) over the communications backbone available. The next higher layer is the RPC layer which implements remote procedure call semantics using the IComms messaging service. The third layer consists of framework and sensor/actuator services implemented using the RPC framework. This includes core services for vehicle configuration, logging and health monitoring. It also includes hardware drivers for all the sensors and actuators as well as inter-vehicle communications. The top layer houses the GNC components which utilize the services provided by lower layers to achieve the mission of the vehicle. A typical deployment of software components in the STARFISH AUV using the DSAAV framework is shown in Figure 4.

The DSAAV software implementation is portable and provides C/C++ as well as Java API. The implementation is made freely available for researchers interested in developing modules for STARFISH, as well as researchers interested in implementing DSAAV in their own autonomous vehicles.

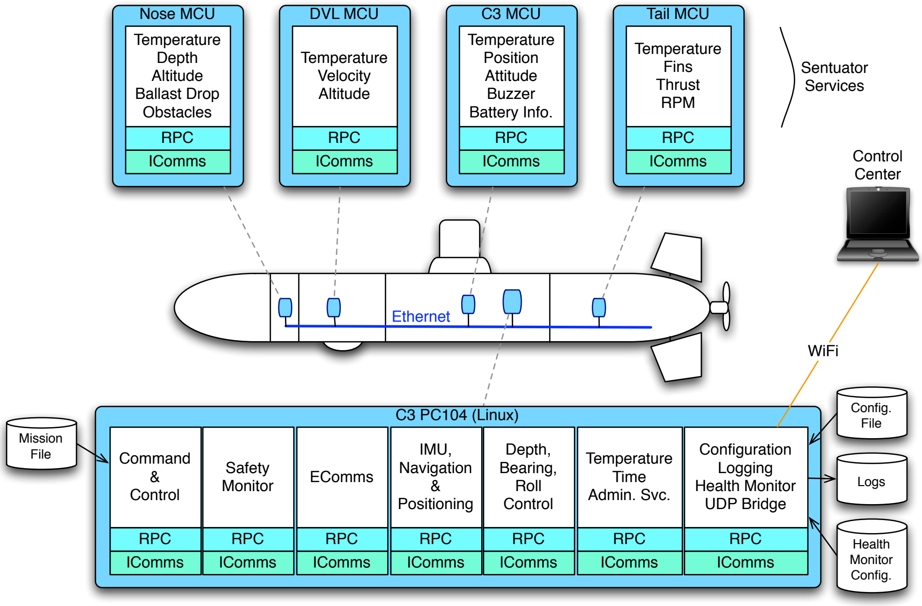

Figure 4: Deployment of DSAAV-based software components in a typical STARFISH AUV.

Command & Control

The idea of a team of interacting heterogenous individuals is also applied to the GNC of the STARFISH AUV. Each AUV is controlled by a team of interacting software *agents* (Tan et al., 2010). As shown in Figure 5, the roles and responsibilities of each agent are modeled on the hierarchical command structure of navies.

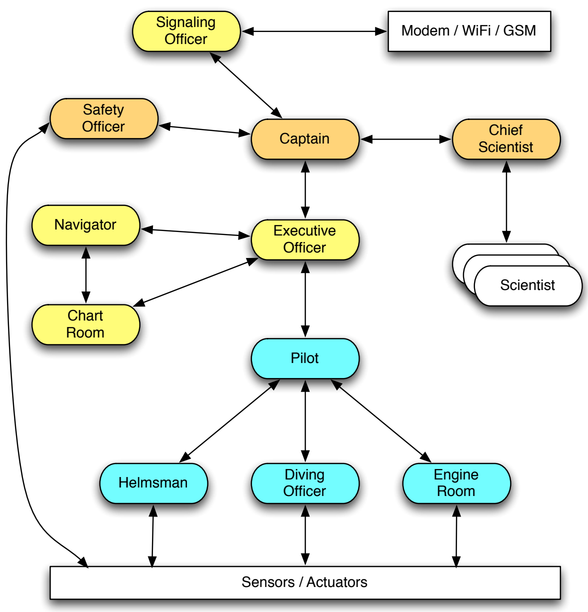

Figure 5: Software agents responsible for the command & control of the STARFISH AUV.

The *Captain* is responsible for interpreting the mission file and providing high-level commands to the *Executive Officer*. The *Executive Officer* works with the *Navigator* and the *Chart Room* to plan a path for the AUV, and then instructs the *Pilot* to steer the AUV down the planned path. The *Safety Officer* observes the health of the AUV and the incoming data from various sensors to ensure that the AUV is operating within safety limits. Should there be a safety concern, *he* can advise the *Captain* accordingly. If *he* suspects that the command & control system is malfunctioning, *he* can execute an emergency procedure to safely bring the AUV to the surface. The *Chief Scientist* works closely with the *Captain* to coordinate between various *Scientists* responsible for different scientific sensor payloads on the AUV. The *Signaling Officer* is in-charge of coordinating all communications with other AUVs in the team.

The interaction between these software agents determines the overall behavior of each AUV. It is the interaction between agents across AUVs that determines the overall behavior of the team of AUVs. The overall team behavior is thus a complex function of the behaviors and interactions of simple agents. These are precisely the conditions that support novel team behaviors to emerge. The study of the emergent behaviors and ways to ensure that the behaviors that emerge are desirable and robust is an active area of research.

Underwater Communications

In order for AUVs in a team to cooperate, they need to communicate. On the surface, they are able to communicate over WiFi and GSM networks. However, once submerged, the only effective means of medium-to-long range communications is acoustic. Although advances in acoustic communication techniques have made point-to-point communications feasible, effective underwater networking among multiple AUVs is still in its infancy (see Chitre et al. (2008) for a review of state of acoustic communications & networking technology). Optical communications systems may be able to augment acoustic communication systems for applications requiring high-speed short-range data transfer (Doniec et al., 2009).

ARL Modems

Most commercially available acoustic communication modems yield poor communication performance in snapping shrimp dominated shallow waters around Singapore. Hence we developed a set of communication modems based on robust signal detection and error correction techniques that have been shown to work effectively in Singapore waters (Chitre et al., 2006, 2005; Chitre, 2006; Chitre et al., 2007). The STARFISH AUVs are equipped with these modems that enable them to communicate with each other, a control center, and other fixed and mobile assets.

Medium Access Control (MAC)

Owing to five orders of magnitude difference in propagation delays, MAC protocols developed for wireless (electromagnetic) networks do not work well underwater. Hence underwater MAC protocol design has been the subject of intense research in recent years. Originally the STARFISH AUVs adopted a TDMA MAC. This has now been superseded by a MACA based protocol that has recently been tested (Shahabudeen et al., 2009; Shahabudeen and Motani, 2009).

Although large propagation delays have often been cited as the reason for poor network throughput in underwater networks, the opposite is in fact true! The large propagation delays provide an opportunity to have multiple transmissions simultaneously without colliding. By careful scheduling of transmissions, this opportunity can be exploited to achieve a much higher throughput in underwater networks, as compared to wireless networks with the same number of nodes (Chitre et al., 2010). Although the currently known algorithms assume static nodes, protocols to accommodate ad hoc mobile nodes are currently being researched.

Synchronization & Ranging

Since the propagation delay incurred during communication encodes information about the range between the nodes, a measurement of this delay can give us valuable information that can be used for position estimation and tuning of networking algorithms. To measure the propagation delay accurately, we need timing synchronization between the communicating nodes (AUVs, or other fixed and mobile nodes)[2].

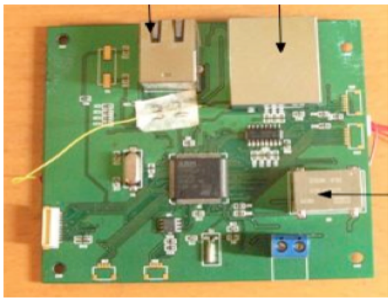

Figure 6: Timing synchronization unit.

It is possible to achieve synchronization between the clocks at all nodes when the nodes are at the surface and have access to a common GPS clock. However, synchronization is usually rapidly lost due to non-linear clock drift once the nodes submerge and do not have access to the GPS clock for regular re-synchronization. To combat this problem, we have developed a timing synchronization unit (Figure 6) consisting of a GPS, a high accuracy oven (temperature) controlled crystal oscillator (OCXO) and a micro-controller. If the timing synchronization unit is connected to the ARL modem, it provides a low drift clock reference to the modem. The modem is then able to measure accurate range between communicating nodes. We use this feature for cooperative positioning as described in the next section.

Cooperative Missions

Since accurate positioning underwater is a challenging task, we focused our initial efforts on developing algorithms for cooperative positioning of AUVs in a team. Accurate navigational sensors such as Doppler velocity log (DVL) and inertial navigation systems (INS) are expensive, and therefore the cost drivers for AUVs. Without these sensors, an AUV either needs to surface often to get GPS position fixes or has to be supported by acoustic positioning systems that require beacons to be deployed prior to the AUV operations. In our sample application scenario, we assumed that only one AUV in a team is equipped with accurate navigational sensors – we call this AUV the *beacon AUV*. All other AUVs (we call them the *survey AUVs* as they are typically equipped with other payload sensors) navigate using dead reckoning based on thrust estimates and heading measurements, but are able to make frequent range measurements to the beacon AUV. In a cooperative survey mission, we

[2]Without synchronization, we can measure two-way propagation delays; however, this reduces the robustness, accuracy and frequency of the measurement.

need the AUV team to accurately track the positions of all survey AUVs, although only the beacon AUV is equipped with accurate navigational sensors. We have shown that this is indeed possible if the beacon AUV chooses its path smartly, with an aim to minimize the expected error in the survey AUVs' position estimates (Chitre, 2010; Gao-Rui and Chitre, 2010). The beacon AUV is not given a pre-determined path, but rather chooses its path in real-time using the cooperative positioning algorithm. Sample paths taken by the beacon and survey AUVs during a simulated run of a two-AUV survey mission are shown in Figure 7. Without cooperative positioning, the positioning error of the survey AUV grows unbounded as a result of accumulation of errors in dead reckoning. However, with the cooperative positioning, we see that the error can be bounded and small. The algorithm has been shown to successfully keep the error of the survey AUV's position bounded during field trials (Gao-Rui and Chitre, 2010).

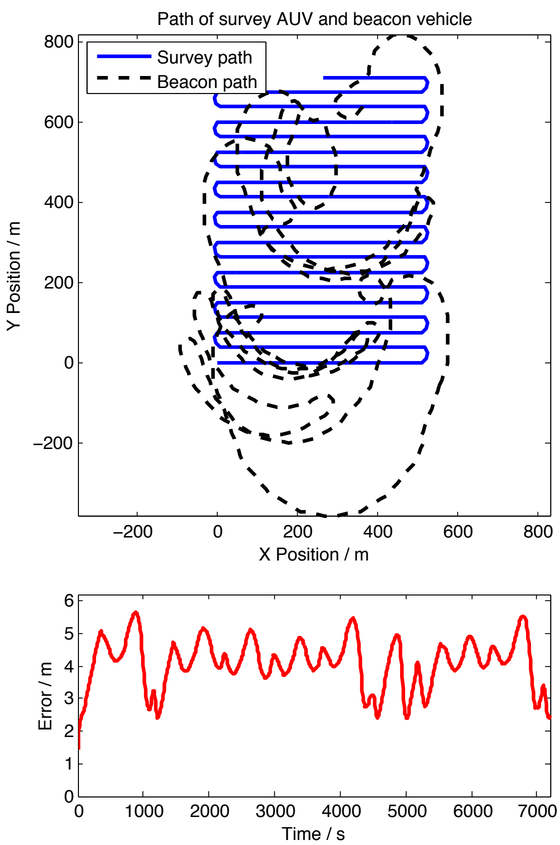

Figure 7: Sample paths taken by the beacon and survey AUVs.

Apart from cooperative positioning algorithms, we are currently also investigating the use of teams of AUVs for adaptive surveying as well as target detection & tracking.

Expanding the STARFISH Team

At present we have two operational STARFISH AUVs that we use in field tests. In order to get a better understanding of the emergent behavior in teams of AUVs, we need to start working with larger teams. We are currently assembling three more STARFISH AUVs to join the team. However, we do not want to limit the team members to only STARFISH AUVs. Fixed sensor nodes, other AUVs and unmanned surface vessels (USVs) can also be part of the STARFISH team if they are able to communicate with the STARFISH AUVs. This is accomplished by integrating the ARL modem onto other fixed and mobile platforms.

The Folaga is a hybrid glider/AUV developed by GraalTech in Italy (Caffaz et al., 2009). We collaborated with the NATO undersea research center (NURC) and GraalTech to develop an enhanced Folaga (eFolaga) that is able to support payload modules to extend its functionality. We then developed and tested an ARL modem payload module on the eFolaga, that allows it to communicate with other AUVs using the same modem. We currently have two eFolagas at ARL, which we intend to use as additional members of the STARFISH team.

The center for environmental sensing and modeling (CENSAM) is a research program at the Singapore MIT alliance for research and technology (SMART). As part of the marine sensing component of CENSAM, we are currently exploring the use of STARFISH teams for environmental sensing. To augment the STARFISH team with more heterogenous assets, researchers at CENSAM have integrated the ARL modem onto a USV (autonomous kayak) and the Iver AUV from Ocean Server. Other researchers at CENSAM are also developing novel environmental sensing modules that can be installed on the STARFISH AUVs.

The PANDA is an underwater anchored sensor node that can be deployed and recovered easily without diver support (Koay et al., 2002). The currently available version of the PANDA has limited sensing and communication capability. We are currently developing a new version of the PANDA that has the ARL modem integrated into it. This will allow the PANDA to function as a fixed sensor node in the STARFISH team. It may also function as an acoustic relay node to extend the communication range, and as a beacon node to help improve position accuracy of the mobile members of the STARFISH team.

We envision that many missions may benefit from the range and speed of USVs but the underwater exploration capability of AUVs. Such missions could use USVs to transport AUVs over long distances, autonomously deploy them to accomplish their mission, and then recover them. The automated recovery of the AUVs by the USVs is a key technological component that is hard to accomplish. To achieve this, we are currently working on the development of an automated launch and recovery (AutoLARS) system in collaboration with NURC (Pai et al., 2009).

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