STARFISH – A Small Team of Autonomous Robotic Fish

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***Abstract*—Autonomous Underwater Vehicles (AUVs) have gained popularity in various research, commercial and military applications in the past decades. In recent years, research into multi-vehicle cooperative mission control has gained interest in the AUV community. Most commercially available AUVs are either complex and expensive, or too limited to be effectively combined into multi-AUV teams. Therefore, in 2006, we embarked on a project to develop a modular low-cost AUV specifically designed to be used for research in heterogenous small teams of AUVs. The project was named "Small team of autonomous robotic fish," or STARFISH for short, and the AUV developed is known as the STARFISH AUV.**

In this paper, we present an overview of the open architecture used in the STARFISH AUV. The architecture exhibits a high degree of modularity with well defined mechanical, electrical, and software interfaces that are open for other researchers to use. The use of this architecture allows us to keep the basic AUV simple and low-cost, while allowing it to be extended with various sensor and actuator sections. This then facilitates the creations of teams of low cost, heterogeneous AUVs that can be reconfigured based on the mission requirements. At the present time, we have two fully functional STARFISH AUVs, and more are being added to the team.

To support this open architecture, we have also developed a flexible vehicle command & control (C2) system that is capable of handling various configurations of AUVs. Thus the same C2 system can be used to control all the team members of a heterogenous AUV team. The C2 system is loosely based on the C2 hierarchy in submarines, with software agents such as Captain, Executive Officer, Navigator, etc interacting to control the behaviors of the AUVs.

A number of field trials have been conducted in coastal Singapore waters and some initial trial results are presented. A cooperative positioning experiment using two heterogeneous AUVs demonstrated that a single AUV with good positioning accuracy was sufficient in a team of two AUVs to keep the position errors of both AUVs bounded. We present the results from this experiment to illustrate how the capabilities of multiple STARFISH AUVs can be effectively combined in cooperative missions.

I. Introduction

Over the past decades, a number of successful AUVs have been developed, initially as scientific research tools, and later as commercially available AUVs. AUVs such as Hugin [1] and Urashima [2] were designed for long range missions. Although they provides excellent endurance, these vehicle are large, costly and require enormous logistics support to operate. In order to reduce the ownership and deployment costs, a number of small vehicles such as REMUS [3], GAVIA [4], Bluefin-9, Iver [5], etc were developed. Many of them are still fairly expensive, while others have limited capability. The lack of open architecture in most AUVs limit the user to payloads available from the same vendor.

The "Small team of autonomous robotic fish" (STARFISH) project was started in 2006, with a goal to develop a low-cost open-architecture AUV platform for collaborative AUV research. The STARFISH AUVs provides a high degree of modularity, reconfigurability, and well defined interfaces which make them excellent research platforms. New scientific modules and functionalities can be easily added and tested. The modularity also makes them attractive field operation vehicles where the users are able to quickly configure a team of heterogeneous vehicles based on situational requirements. The modularity comes at two levels – section compatibility, and internal component modularity. The former makes multi-section AUV re-configuration feasible, while the latter reduces the number of component types and eases maintenance. Micro-controller units (MCU), components and electronics stacks are identical among various sections, allowing ease of replacement and reconfiguration.

The hardware modularity has to be coupled with a plug-and-play software capability. The STARFISH AUVs employ the distributed software architecture for autonomous vehicle (DSAAV) to provide flexible software reconfiguration [6]. DSAAV makes extensive use of a remote procedure calls

(RPC) construct to allows distributed deployment of software components within the AUV, making re-deployment of software components very easy. DSAAV also provides a deployment framework that allows migration of software component across platforms (such as from PC104 to MCU) easy. It also allows flexible data "plumbing" where the data flow between subsystems can easily be configured during deployment. For example, the C2 algorithm can easily select positioning data from the GPS provided by a MCU, a DVL based dead-reckoning subsystem, or a complex data fusion algorithm that combines multiple positioning cues. When a new section with advanced sensors is added to the AUV, data plumbing can easily allow the new high-quality data to replace lower quality data that may be otherwise used in the base AUV. In the current STARFISH AUVs, an altimeter provides altitude data to all subsystems that require it. When an optional DVL section is added to the AUV, the higher quality altitude measurements from the DVL can instead be used by all subsystems without any change to their source code.

II. STARFISH AUV

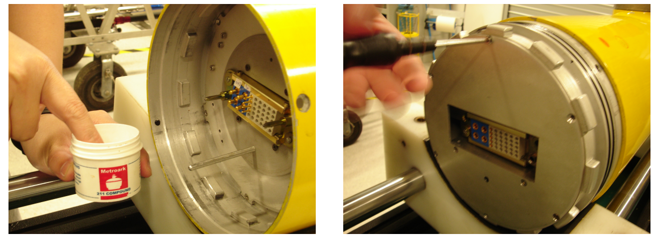
The baseline STARFISH AUV weighs less than 45 kg and is about 1.6 m long. It consist of a nose section with an altimeter, a forward-looking sonar (FLS) and a depth sensor, a tail section providing propulsion and control surfaces, and a command, communications and control (C3) section that provides positioning, navigation and communication capability. Although the baseline AUV is fully functional, it has limited positioning accuracy and does not carry any scientific payload. Additional sections based on an open section interface can be added to increase the capabilities of the AUVs, if required by a mission.

The STARFISH AUV is powered by a number of 110 Wh, 48 V Lithium Polymer battery packs distributed across various sections. Different configurations of the STARFISH AUV typically carry between 9 to 12 battery packs, providing an energy capacity between 990 Wh and 1320 Wh. The battery packs are designed to be safely charged from an external battery charger using a tether connection on the communication tower. The tether also carries Ethernet lines from the connector, allowing data to be downloaded while the batteries are being charged. Data download, mission upload and software updates can be also be effected over a WiFi connection.

A. Modular design

Section modularity is realized through a unified mechanical, electrical and software interface specification. The interface specification is freely available to the scientific community upon request, to promote third-party development of payload sections and encourage collaborations.

The mechanical interface (coupling) uses a male-female interlocking mechanism with locking teeth (see Fig. 1). The assembly process involves inserting the male interface to the female interface follow by a rotation to engage the locking teeth. Four screw are then used to avoid unintentional disengagement of rotational interlock. In order to ensure the integrity of the vehicle assembly, the tolerance of the intersection locking mechanism is kept very small. A consequence, however, is that a support fixture is required for ease of alignment during section assembly and disassembly.



(a) Male coupling (b) female coupling

Fig. 1. Section interface (mechanical)

The electrical interface consists of a pair of hybrid connectors (which can be clearly seen in Fig. 1) configured to carry four high-current power lines and a number of small signal communication lines (see Table I for details).

TABLE I
SECTION INTERFACE (ELECTRICAL)

Connection	Description
48V battery bus	Connects to common battery pool; all the batteries in various sections connects to this bus.
48V system bus	Connects to common system power; all the electrical modules collects power from this bus
48V power return	Serves as power return bus for battery and system power bus
Ethernet bus	Serves as inter-section communication bus
Run Level	Serves as vehicle wide status indicator
Fuel gauge	Provides a means to interrogate battery status across all sections

All communication within the vehicle (except some local communication between sensors and actuators) is carried using Ethernet packets; this makes it extremely lightweight, even for MCUs. This allows us to extend the modularity within the section, where electronics are grouped into function-specific modules, governed by a MCU and connected to the rest of the system using the common electrical interface. All the details of the communication protocol are abstracted from user by a set of application programming interfaces (APIs) provided by DSAAV. This allows the engineers to concentrate on payload development without having to worry about system compatibility.

Communication to the external world, however, is carried out with a number of standard interfaces to ensure compatibility to various off-the-shelf systems. These interfaces include TCP/IP over Ethernet or WiFi, acoustic modem, and GSM modem. In the event when the primary communication modes are unavailable, the vehicle's GPS location and limited vehicle control commands can be relayed using SMS messages through the GSM cellular network in coastal waters, once the vehicle returns to surface.

B. AUV configuration for heterogeneous teams

Heterogenous teams of AUVs can easily be set up, by adding appropriate payload sections to the baseline STARFISH AUVs. Two different configurations of STARFISH AUVs – a BlueStar AUV configured with Doppler Velocity Log (DVL) payload for accurate positioning, and a RedStar AUV configured with side-scan sonar payloads for seabed imaging, are shown in Fig. 2. Both vehicles were assembled using the same basic components and operate using identical firmware/software. The only difference between the AUVs is the payload sections, the configuration files and the mission files. The modularity also enables easy reconfiguration of the sections and modules within a single vehicle. For example, the locations of both payload sections in RedStar can be readily interchanged without any software changes.

Fig. 2. BlueStar with DVL payload (right) and RedStar with side-scan sonar payload (left)

1) BlueStar - the beacon AUV: The BlueStar AUV is special configuration of the STARFISH AUV designed to play the role of a positioning beacon in cooperative missions. It consists of a baseline vehicle enhanced with a DVL section, providing it high-accuracy positioning capability. The DVL allows measurement of vehicle speed over ground, which is then integrated to yield as estimate of vehicle position. In multi-vehicle cooperative missions, the BlueStar broadcasts its position regularly. By measuring range to BlueStar, other AUVs are then able to refine estimates of their own positions. The BlueStar AUV has evolved from the first generation design [7], with the acoustic modem transducer located at the communication tower.

2) RedStar - the sidescan AUV: The RedStar AUV is a specially configured member of the STARFISH team with the task of object detection. It extends the capability of the baseline STARFISH AUV with an Imaginex OEM sidescan sonar unit in order to capture acoustic images of the sea bottom. RedStar employs an upgraded internal design with improved modularity and system robustness. The changes have been realized without effecting the control software – a benefit of the software modularity provided by DSAAV. The acoustic transducer of RedStar is located at the bottom of the vehicle, allowing acoustic communication to be tested even when the vehicle is at the surface. As the RedStar AUV is usually not equipped with a DVL section, it does not have high-accuracy positioning capability. It instead works in tandem with the BlueStar AUV to keep its positioning error small.

III. AUV Control System

The yaw controller in STARFISH uses the top and bottom rudders for steering. The controller is a simple P-controller (Fig. 3a) with the rudder angle clipped below the stall angle of the fins (about 15°). Although very simple, this controller worked very well in lake as well as sea trials, as we shall see shortly.

The AUV control can only be decoupled under the assumption that the AUV roll is negligible. Although we have a good metacentric height to stabilize the AUV from rolling, an active roll control is needed to ensure that the roll is kept small. The roll controller is a P-controller with a compensating filter. This filter accounts for the phase lag due to the dynamics of the AUV. The output of the roll controller is an offset between the elevators that leads to a rolling moment. The elevators are also used for pitch/depth control. To avoid using the full range of the elevators for roll control, the elevator offset is clipped to a smaller value (about 5°) than the stall limit of the fins.

The AUV thruster torque induces a rolling moment on the AUV. To avoid having the fins work against this moment through the entire mission, the AUV is preloaded with a small roll angle in the opposite direction of the thruster torque. At nominal cruising speed, the roll caused due to the thruster torque balances the preloaded roll, leading to an AUV with minimal roll for the roll controller to correct.

As shown in Fig. 3b, the depth controller in the AUV uses a P-controller which drives a inner pitch controller. The pitch controller is a sliding mode controller (SMC) that uses the estimated velocity of the AUV to determine the control parameters for the inner pitch controller. This allows the controller to be stable and perform well over a range of operating speeds rather than being tuned for only a single optimal cruising speed. The detailed control synthesis for depth controller can be found in [8].

Fig. 4 shows a typical yaw, pitch, roll and depth response of the STARFISH AUV during a simple navigational mission. From the yaw response, one can see that the yaw set point was followed closely by the yaw response despite the use of only a simple P-controller. During the straight run, the yaw error was less than 1°.

The roll of the AUV over the entire duration of the mission is shown in the bottom left of Fig. 4. The roll controller tries to ensure a zero-roll whenever the AUV is thrusting. On the surface (time interval 2950-3000 and time interval 3300-3400), the surface waves and wind cause significant roll (up to about 10°). However, once the AUV was underwater, the roll was less than 2°.

The plot of pitch response shows that the AUV was pitched down at about 1.5° in both 8 m and 12 m constant depth runs.

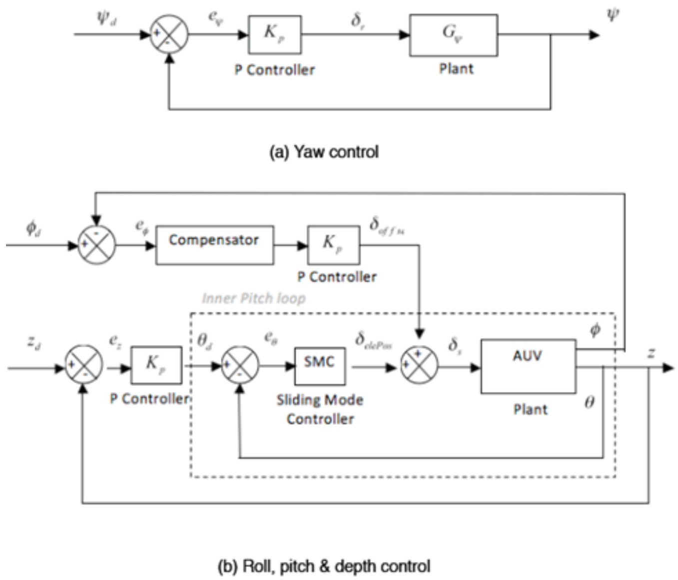


Fig. 3. STARFISH AUV: Vehicle control system

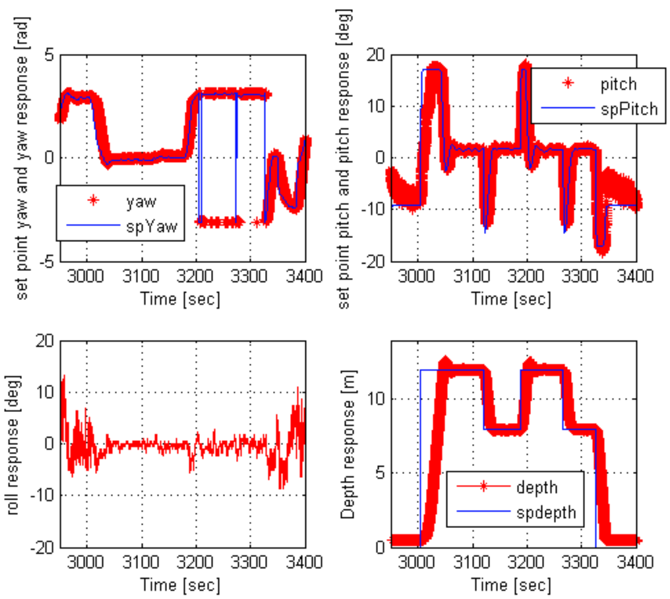


Fig. 4. Yaw, pitch, roll and depth response for a round trip mission at Selat Pauh, Singapore

The AUV is trimmed to be slightly positive buoyant (0.2 kg) in order for the AUV to float to the surface in the event of system failure, and also to keep the WiFi, GPS, and GSM communication antennas well above the water surface during surface missions. So, in order to travel at a constant depth, the AUV needs to pitch down at a small angle to cancel the buoyancy force.

During the mission, the AUV was commanded to alternate depth set points between 8 m and 12 m. A switching algorithm is implemented in the outer P-controller to change the controller gain depending on whether the AUV is diving or surfacing. This is essential as the diving pitch dynamics and surfacing pitch dynamics are different. The differences are caused by asymmetry in geometry between top and bottom of the AUV and also by the positive buoyancy. The effectiveness of the controller in handling this discrepancy was demonstrated in the depth response of Fig. 4. The steady state depth error is bounded within 0.15 m.

From the above sea experiment results, we conclude that the controller is effective in controlling the yaw, pitch, roll and depth of the AUV with a satisfactory degree of accuracy.

IV. Command and Control of the AUV

A C2 system performs tasks ranging from planning, coordinating, directing and controlling various activities in an AUV. It receives the processed data from the sensors as inputs and then outputs the control commands to the AUV's actuators or control systems to generate desired maneuvering behavior to achieve the mission objective while keeping the AUV safe throughout the mission execution.

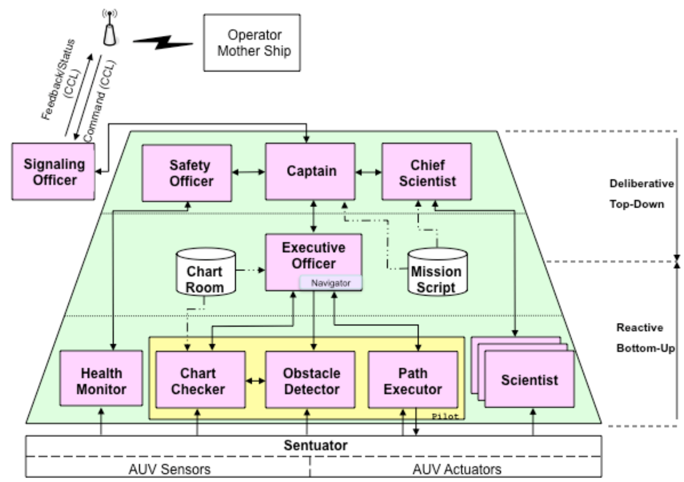


Fig. 5. Hybrid Control Architecture for the AUV.

In the STARFISH project, we have developed a novel C2 system based on a hybrid hierarchical model as shown in Fig. 5 [9], [10]. It adopts a deliberative-reactive architecture and consists of a set of interacting agent components arranged in hierarchical order to depict different level of command responsibilities. Our architecture consist of three levels: Supervisory level, Mission level and Vehicle level. The Supervisory level is in charge of monitoring the high level mission and vehicle status as well as corresponding and sending the information to the operator/mothership. The Mission level is responsible for mission/tasks planning and finally, the Vehicle level carry out the mission tasks and perform obstacle avoidance by utilizing different Sentuators (sensors and actuators) to generate the desired maneuvering behaviors. A communication component (Signaling_Officer) also is designed to provide a communication link with the mothership/operator or with another AUV. Chart Room is the database where a map of the mission areas are stored while Mission Script consists of different mission files identified by their mission numbers. This approach offers many benefits. The hybrid architecture allows deliberative high level mission control while decouples the low level reactive vehicle control. Moreover, the breaking down of C2 tasks into individual agent components presents an explicit view of the clearly defined control responsibilities at different level of control hierarchy.

Each agent component has its private data and implements its own algorithms depending on the assigned tasks. All the components are self-contained and have a uniform software interface to facilitate inter-component communication by using a message passing mechanism. The vehicle's C2 tasks are achieved via the interaction and cooperation among the involved agent components. The agent component design provides flexibility in terms of software implementation and alternation. Instead of modifying the existing software components, new components with identical interfaces but different algorithms can be built and loaded when necessary. Besides that, the Scientist component can be configured to adapt to the AUV's final payload setup without affecting the overall control structure. This can be done easily by changing the entries in the configuration file.

An agent component's internal activity is governed by a finite state machine which processes its tasks continuously depending on the current state of the component. The transitions between states are triggered by commands from components higher up in the control hierarchy and/or the component's internal events. The current state of a particular component can be monitored and controlled by another component. This is particularly important in a C2 system where supervisory components at the high level control architecture can monitor and command the behavior of low level components.

Besides that, since the components are self-contained and the inter-component communication is carried out through message passing, the internal operation of the components do not interfere with each other. This provides fault tolerance if errors occur in one component, as they do not cause the whole C2 system to malfunction.

V. Cooperative Positioning Experiment

Several field trials have been carried out at Selat Pauh, an anchorage area south of Singapore (see Fig. 6). In this section, we present data from an autonomous cooperative mission carried out using multiple STARFISH AUVs to test a cooperative positioning algorithm. The mission involves the use of two AUVs – the BlueStar beacon AUV equipped with the DVL payload, and the RedStar survey AUV equipped with a side-scan sonar payload. While on the surface, GPS signals serve as position updates for both AUVs. However, when underwater, each AUV finds its position by integrating velocities from different navigation sensors (i.e. DVL, compass, etc). The beacon AUV utilizes accurate DVL velocity measurements over the seabed for its position estimation. The survey AUV estimates its body-frame velocity from its expected thrusting force. It is, however, unable to factor in the water current. Due to lack of DVL, the dead-reckoning accuracy of survey AUV is poor, necessitating position updates through other means to keep the position error low. In a cooperative survey mission with two AUVs, the survey AUV serves to survey an area of interest. The role of beacon AUV is to aid the survey AUV in positioning by providing it with regular range updates using 2-way acoustic travel time measurements between the modems on the AUVs. The path of beacon AUV is planned to minimize the error accumulated by the survey AUV.

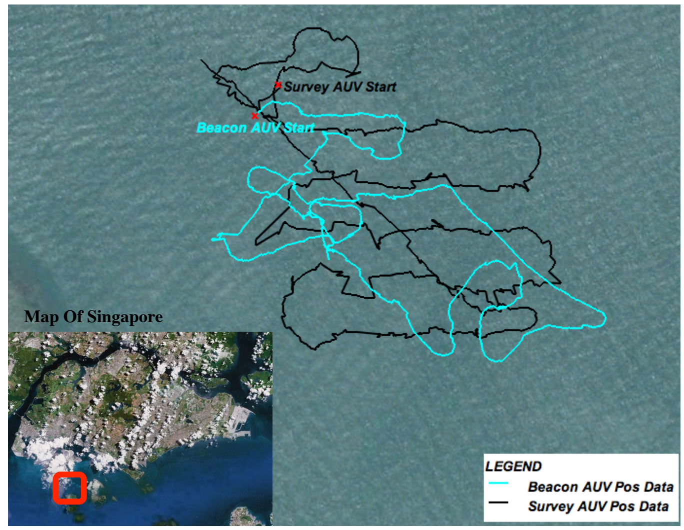


Fig. 6. Plot of Cooperative mission paths around Singapore coastal area.

A. Path planning and position estimation

The survey AUV executes a lawnmower path to survey an area with its sidescan sonar payload. The beacon AUV's path is planned through a series of sequential decisions made by the onboard command and control system during the mission. It is shown that the error estimate of survey AUV position is reduced in the radial direction of the ranging circle centered at beacon AUV. The error in the tangential direction remains the same. Hence the beacon AUV aims to move such that the next range measurement occurs along the direction of the major axis of the error ellipse of survey AUV. The decisions are made with an optimization criteria that minimizes the error of the survey AUV, avoids collisions between AUVs, maintains good communication range, enforces geofencing constraints and etc. The details are explained in [11].

An Extended Kalman Filter (EKF) is implemented on the survey AUV to fuse the range updates from the beacon AUV. With state vector containing the AUV position at the east, north and depth in navigation frame, the system estimates the positioning using dead reckoning from thruster modeling. The observation comes from range measurement computed by a 2-way propagation delay of underwater signals. The predicted measurement is the Euclidean distance between the survey AUV position predicted and beacon AUV position obtained. The details are explained in [12].

B. Experiment setup and results

Several field trials (both in lake and sea) have been conducted to explore the effectiveness of the cooperative positioning between two AUVs. The AUVs were running on the surface so that a GPS fix was available as the ground truth. Since the acoustic modem does not work well at the surface, the range measurements in this experiment were simulated using the known GPS positions. The range information was fed to the survey AUV every 20 seconds.

Fig. 7 shows the cooperative mission from the trials at Selat Pauh in January 2010. The planned lawnmower path for survey AUV is shown as a solid line. The beacon AUV path was chosen automatically during the mission. Without range measurements, dead reckoning (dotted line in Fig. 8) was based on the thrust-induced velocity without inputs on the strong currents. Thus, although the survey AUV assumed it is on the correct track, it has a significant eastward drift. The position updates are clearly seen at the discontinuities in the survey AUV position estimates (in dots) when EKF is fed with range measurements. The command and control system was able to use the updated positions to better direct the survey AUV to follow the designated survey path. In Fig. 9, the position error was compared with GPS positions. The position error of survey AUV using range measurements was significantly lesser and also bounded as compared with a single AUV relying only on dead reckoning.

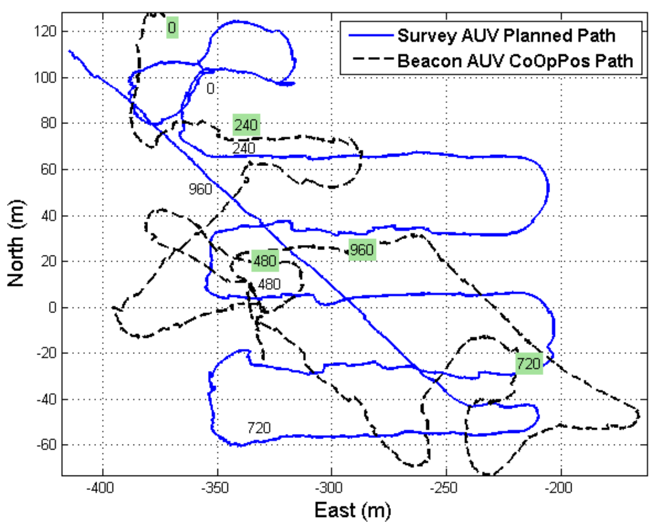


Fig. 7. AUV paths for lawnmower mission survey during sea trials

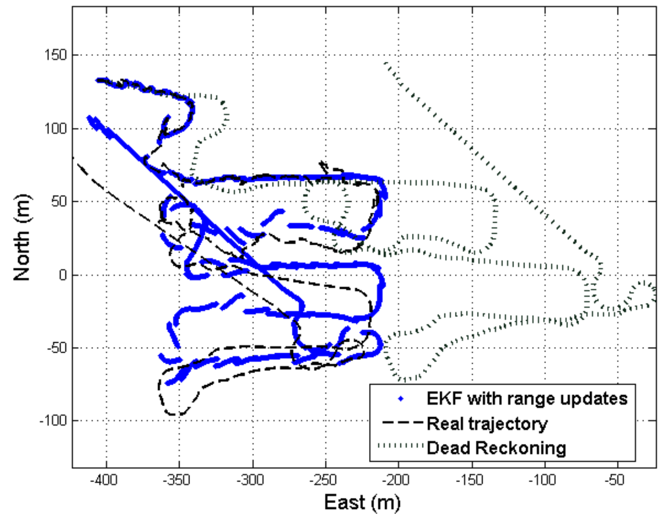


Fig. 8. Comparison EKF with ranging (cooperative positioning) and dead-reckoning (single AUV positioning) during sea trials

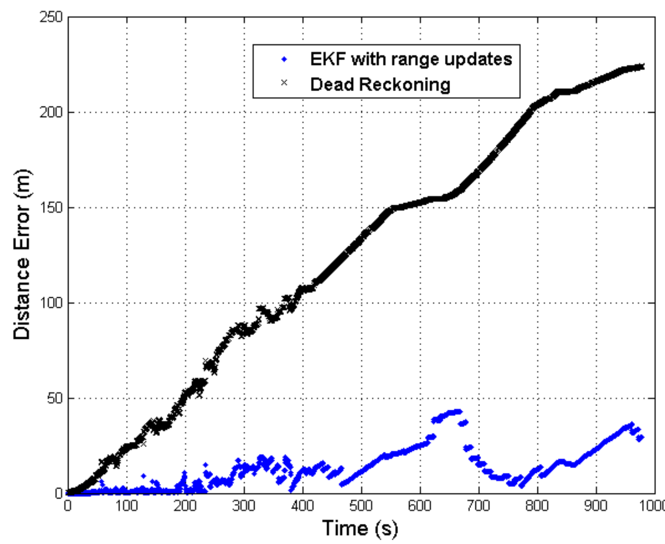


Fig. 9. Position error of EKF with range updates (cooperative positioning) as compared with dead reckoning (single AUV positioning) during sea trials

VI. Conclusion

We presented the modular and open architecture of the STARFISH AUV. The architecture was designed to allow a fleet of heterogeneous, collaborative, low-cost AUVs to be easily used in real applications. The section modularity in the hardware design and distributed software architecture allow easy migration of functionalities and control algorithms across different platforms. The clearly defined section architecture, both in terms of mechanical and electrical interfaces have provided an easy way to implement new sections with novel functionalities to extend the basic AUV.

The vehicle control system uses a dual-loop depth controller with an inner SMC pitch controller and an outer proportional controller. The control scheme has been found to work well with the different vehicle configurations that exhibit different buoyancies, structural protrusions, and lengths. Experimental results show that the controller is effective in controlling the depth, heading of the AUV with negligible steady state error.

The AUV employs a novel C2 framework based on command chains in submarines operations. Multiple software agents such as Captain, Executive Officer, Navigator, Safety Officer, Communication Officer, Pilots, Scientist, etc work together to control the STARFISH AUV.

Two different STARFISH AUVs have been configured and extensively tested in open sea experiments. More vehicles are currently being developed to increase the number of team for a more complex cooperative experiments. A sample cooperative positioning mission demonstrated how these AUVs could be used in tandem for a survey mission when the survey AUV is not equipped with accurate positioning sensors.

Acknowledgment

The authors would like to acknowledge DSTA for their funding support for the STARFISH project. We would also like to acknowledge SMART for their funding of the collaborative CENSAM project that provided numerous opportunities for testing the STARFISH AUVs at sea.

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