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STARFISH – A small team of autonomous robotic fish

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STARFISH AUVs (Autonomous Underwater Vehicles) are a group of open architecture vehicles with high degree of modularity and well defined mechanical, electrical, and software interfaces. This enables the baseline AUV configuration to be simple and low in cost, while allowing its capabilities to be extended with various specialized modules depending on the need. Various AUVs can easily be configured in different ways to form a team of heterogeneous AUVs tailored to a specific mission. STARFISH AUVs employ a flexible Command and Control (C2) architecture that is capable of adapting to various configurations of AUVs. The vehicle command is loosely based on the C2 hierarchy in submarines, with software agents such as Captain, Executive Officer, Navigator, etc interacting to each other to control the AUV's behaviors. Numerous field trials have been conducted in open waters. Results from some of these trials are presented in this paper to illustrate the capability of deploying a heterogeneous team of cooperative AUVs. Specifically, the mission illustrated shows how a single AUV with high positioning accuracy can be used to reduce the positioning error of one or more AUVs with poorer navigational sensors.

[**Keywords**: AU V, Teams, Cooperation, vehicle]

Introduction

Over the past decades, a number of successful AUVs have been developed, initially as scientific research tools, and later as commercially available AUVs. Many AUVs such as Hugin[1] and Urashima[2] were designed for long range missions. Although they provide excellent endurance, these vehicle are large, costly and require enormous logistics support to operate. In order to reduce the ownership and operating 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 of these AUVs limits extension of capabilities to vendor specific payloads.

The 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 provide 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, with minimal modifications to existing systems. The modularity also makes them an attractive field operation vehicles where the users are able to quickly configure a team of heterogeneous vehicles based on mission 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 vehicles (DSAAV) to provide flexible software reconfiguration[6]. DSAAV makes extensive use of a remote procedure calls (RPC) construct that 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 provides a flexible data “plumbing” capability to allow data flow between subsystems to be easily 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 by various subsystems in the baseline 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.

This paper is organized as follows. We first describe the general AUV features, the open architecture interfaces, and some example configurations the AUVs. The AUV control system and its control performance is presented. This is followed by description of the C2 architecture that allows flexible swapping of control algorithms and supports the hardware modularity. Lastly, we presents the operation of two heterogeneous AUVs built on this architecture, demonstrating a preliminary field trial involving cooperative positioning.

Materials and Methods

Architectural Overview of the AUV

The baseline STARFISH AUV weighs less than 45 kg and is about 1.6 m long. It consists 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.

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.

Mechanical interface (coupling) uses a male-female interlocking mechanism with locking teeth (Fig. 1). 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 the rotational interlock. In order to ensure the integrity of the vehicle assembly, the tolerance of the inter-section locking mechanism is kept very small. A consequence, however, is that a support fixture is required for the ease of alignment during section assembly and disassembly. Electrical interface consists of a pair of hybrid connectors (Fig. 1) configured to carry four high-current power lines and a number of small signal communication lines (Table 1).

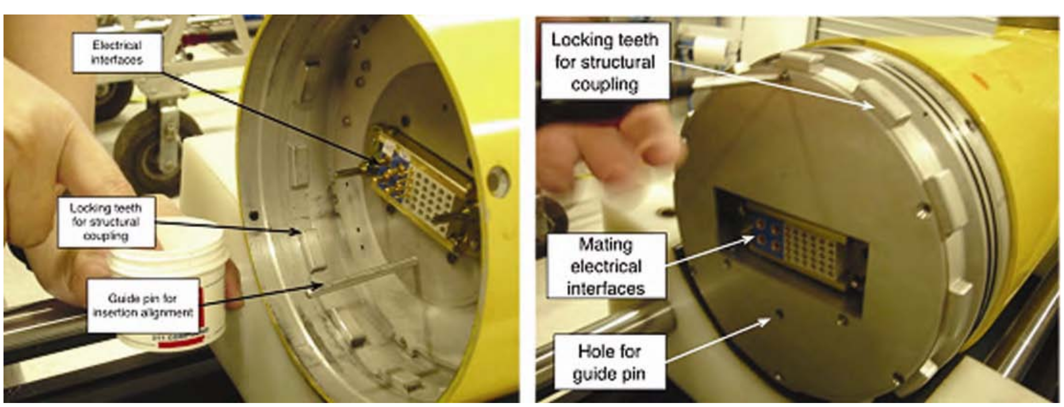

Fig. 1—Physical section interfaces includes both mechanical and electrical couplings in male female physical configuration

All communications 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 helps us improve 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 with minimal effort required to ensure system compatibility.

Fig. 2 shows the various subsystems deployed throughout the STARFISH AUV, over the common backbone interface. The square labels above the vehicle indicate different hardware modules deployed within the vehicle, while the rounded square labels below the vehicle indicate the Sentuator (sensors and actuators) services that each section provides to the user. These services can be easily re-deployed over different MCU or even PC104 when necessary.

Table 1—Section interface (electrical)

Connection	Description
48V battery bus	A common bus for the vehicle's battery pool; Battery packs in all sections are connected here.
48V system bus	A common bus that provides power to electronics; All the electrical modules collect power from this bus; A power management module will connect it to battery bus when powered on
48V power return	Serves as power return bus for both battery and system power bus
Ethernet bus	Serves as communication backbone between sections
Run Level	Provides instantaneous vehicle status to all sections
Fuel gauge	A bus for inquiring battery status across all sections

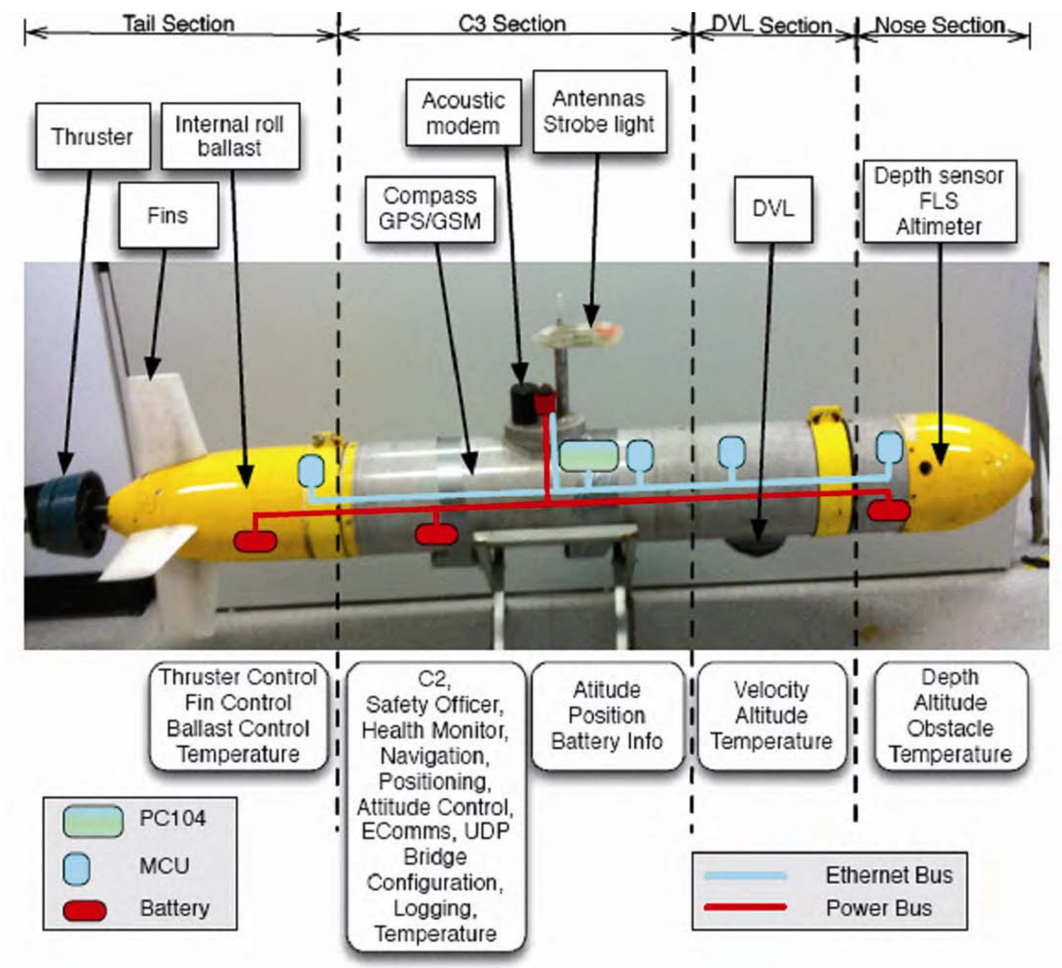

Fig. 2—Distributions of subsystems within the STARFISH AUVs

Fig. 3 shows the internal within C3 section, where different electronics were arranged in stacks based on their functionality. The same inter-section electrical interfaces have been extended to these stacks implementation. Power is drained from the standard 48V bus, communications between stacks are carried out over Ethernet packets, while local communications within the stack are specialized to the needs from respective sensors or actuators in it. Power management are done locally within each stacks.

Communication to the external world 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.

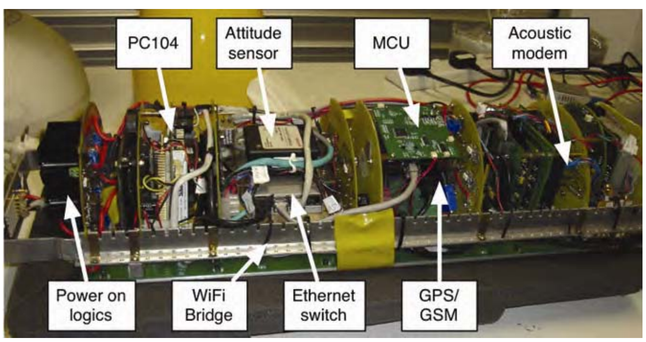

Fig. 3—Internals of the C3 sections

Fig. 4—Two heterogeneous STARFISH AUVs configured from the same basic vehicles. BlueStar with DVL payload (right) and RedStar with sidescan sonar payload (left). Fishing lines were attached to the AUVs in the initial trials to safe guard them.

Configuration for a team of hetrogenous AUVs

Heterogenous teams of AUVs can be easily set up, by adding appropriate payload sections to the baseline STARFISH AUVs, Two different configurations of STARFISH AUVs a BlueStar AUV configured with the Doppler Velocity Log (DVL) payload for accurate positioning, and a RedStar AUV configured with the sidescan sonar payload for seabed imaging, are shown in Fig. 4. Both vehicles were assembled using the same basic components and operated using identical firmware/software. The only difference between the AUVs is with 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 or hardware modification.

The BlueStar AUV is a special configuration of the STARFISH AUV designed as a dynamic positioning beacon to assist AUVs with poor navigational sensors in the position estimations. It consists of a baseline vehicle enhanced with a DVL section, providing it with high-accuracy positioning capability. The DVL allows measurement of vehicle speed over ground, which is then integrated to estimate the position of the vehicle.

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.

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 hardware changes have been realized without affecting 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 minimize its positioning error. However, a DVL section can be added to the RedStar AUV if required by the mission.

Results and Discussion

AUV Control System

The yaw controller in STARFISH uses the top and bottom rudders for steering. Yaw dynamics is modeled as a second order transfer function G_ψ. The top and bottom rudder have same angle of deflection, δ_r which is commanded by a controller based on the yaw error e_ψ. The controller is a simple P-controller (Fig. 5a) 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.

AUV control can only be decoupled under the assumption that the AUV roll, φ is negligible. Although we have a good metacentric height to

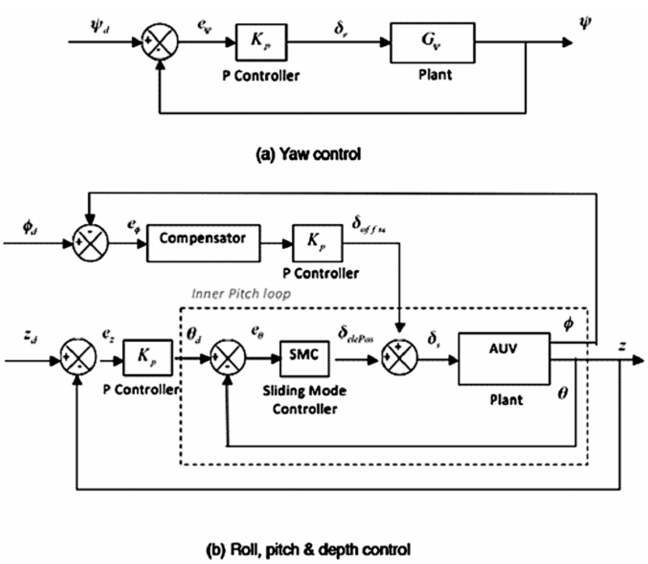

Fig. 5—STARFISH AUV: Vehicle control system

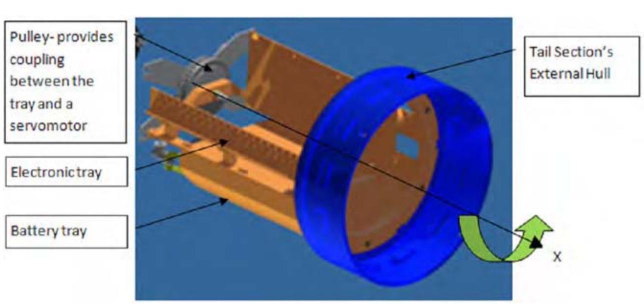

Fig. 6—Mechanical design of internal rolling mass for active roll compensation of STARFISH AUV

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. Output of the roll controller is an offset between the elevators, δ_{offset} that leads to a rolling moment. 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.

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 (about 7°) in the opposite direction of the thruster torque. At nominal cruising speed, the roll caused by the thruster torque balances the preloaded roll, leading to an AUV with minimal roll for the roll controller to correct.

As shown in Fig. 5b, the depth z of the AUV is controlled using a P-controller which drives an inner pitch controller. Under this dual loop design, the outer depth controller generates the desired pitch angle θ_d, to the inner pitch controller. The pitch controller is a sliding mode controller (SMC)[13] 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 is described by Eng. et. al.[8].

The total elevator deflection δ_e is the sum of δ_{elePos} from SMC controller and δ_{offset} from roll compensator. As the maximum deflection angle of the elevators are limited to 15°, it left only small room of deflection angle for pitch/depth control. In order to free up the elevators for pitch/depth control, we have designed an internal rolling mass mechanism at the tail section of Redstar. A battery tray with about 1.5kg weight is located at the bottom part of the assembly (orange portion in Fig. 6). The tray is attached to a pulley which is driven by a servomotor. This mechanism allows us to rotate the battery along the longitudinal-axis of the AUV. Such rotation motion changes the center of gravity of the AUV and thus able to create a net roll moment for active roll control. The implemented system is shown in Fig. 7 and the control algorithm is currently being tested.

Fig. 8 shows a typical yaw, pitch, roll and depth response of the STARFISH AUV during a simple navigational mission. From the yaw response, one can

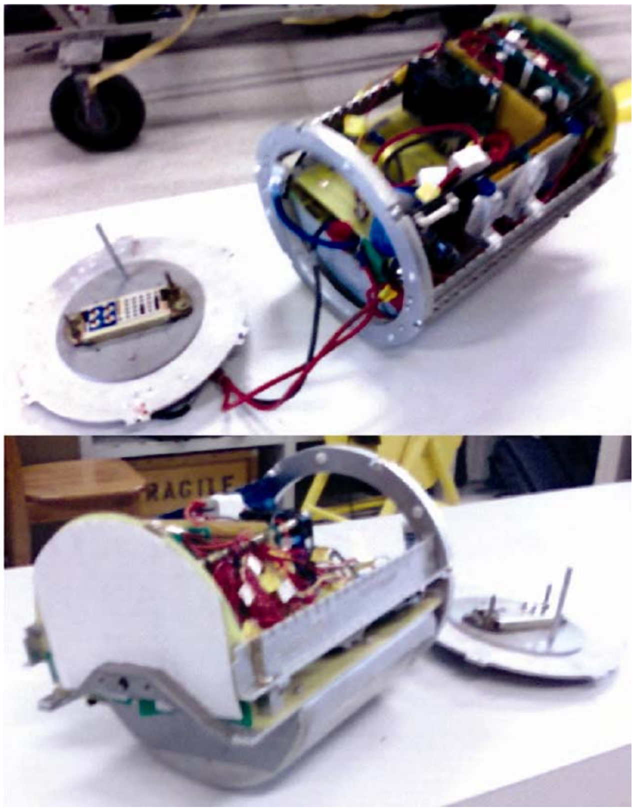

Fig. 7—Picture of internal rolling mass located in the tail section of STARFISH AUV

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°.

Roll of the AUV over the entire duration of the mission is shown in the bottom left of Fig. 8. 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 caused significant roll (up to about 10°). However, once the AUV dives underwater, the roll was less than 2°.

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. 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 out 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

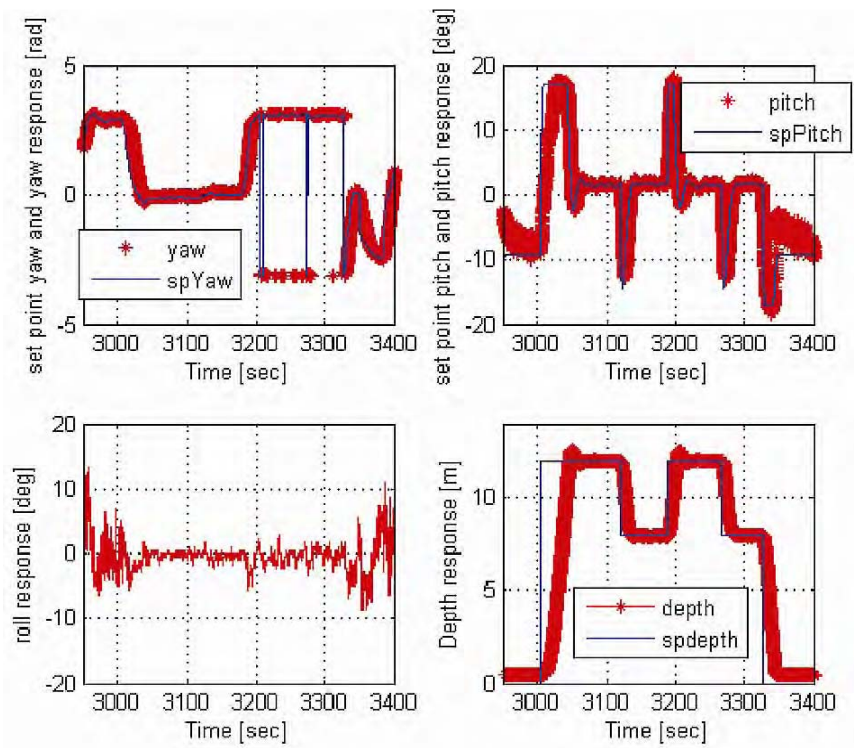

Fig. 8—Yaw, pitch, roll and depth response for a round trip mission at Selat Pauh, Singapore

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. These differences are caused by asymmetry in geometry between top and bottom of the AUV as well as its net positive buoyancy. Effectiveness of the controller in handling this discrepancy was demonstrated in the depth response of Fig. 8. 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.

Command and Control of the AUV

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

In the STARFISH project, we have developed a novel C2 system based on a hybrid hierarchical model as shown in Fig. 9[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 consists of three levels: Supervisory level, Mission level and Vehicle level. 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. 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 to generate the desired maneuvering behaviours. A communication component (Signaling Officer) is also 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 decoupling 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

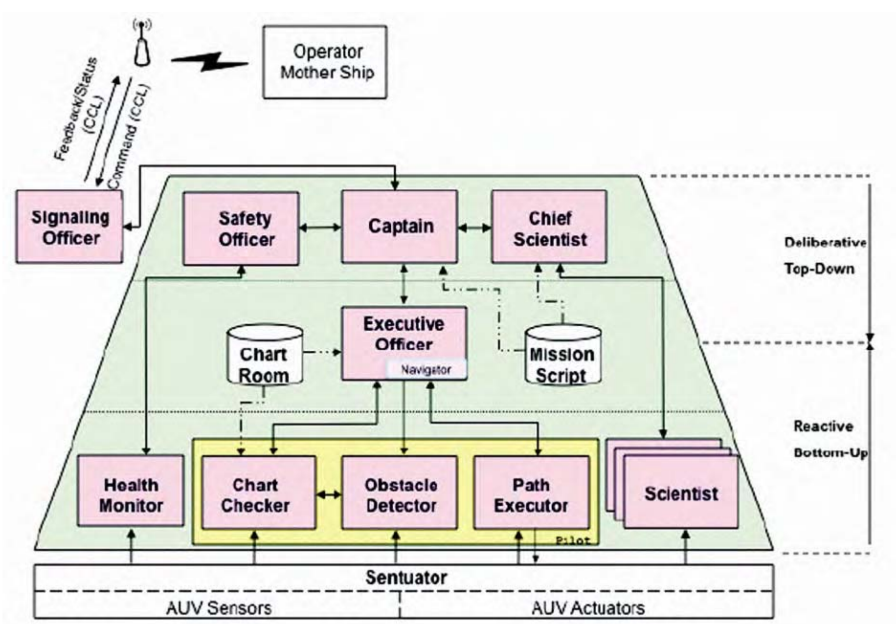

Fig. 9—Hybrid Command and Control Architecture of STARFISH AUV with software agents adapted from command architecture in naval vessel

interaction and cooperation among the involved agent components. The agent component design provides flexibility in terms of software implementation. 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 behaviour 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.

Cooperative Positioning Experiments

Several field trials have been carried in a lake, and open sea area at Selat Pauh, an anchorage area south of Singapore (Fig. 10). 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 sidescan 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, unaware of the water current induced drifts. Due to lack of DVL, the dead-reckoning accuracy of survey AUV is poor, necessitating position updates through other means to keep the error of position estimates low. In this cooperative survey mission, the survey AUV serves to survey an area of interest. The role of beacon AUV is to aid the survey AUV in position estimates by providing it with regular range updates using onboard acoustic modems on the AUVs. The path of beacon AUV is planned to minimize the error accumulated by the survey AUV.

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, and enforces geofencing constraints. The details are explained in a separate paper[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[12].

Experiment setup and trial result

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. It has been shown that ranging between AUVs can be used to bound positioning error during survey, whereas dead reckoning incurs estimation drift with time[12].

After the trials, a fixed-interval offline smoothing using the Rauch-Tung-Stribel (RTS) algorithm is performed to further improve the position estimation. With range updates as nonlinear measurement by EKF, the RTS smoothing algorithm filters backwards and re-estimates the position at time t_k with the prediction and measurement at time t_k+N where N > 0. Although this does not provide realtime estimation capability, it is useful for post-processing of data collected, especially during the case of dive missions where no other positioning information is available.

Fig. 10 shows the cooperative mission from trial at Selat Pauh in January 2010. The black solid line is the planned lawnmower path for the survey AUV. The GPS of the survey AUV was cut off after 7 minutes. Fig. 11 shows the position estimation starting from the time that GPS was cut off. Without range measurements, dead reckoning (dotted green line) was based on the thrust-induced velocity model without information related to the velocity induced by the ocean currents. Thus, although the survey AUV assumed it is on the correct track, it has a significant eastward drift. The position estimation is significantly improved by range updates by EKF (trajectory in blue dots). The position updates are clearly seen at the discontinuities in the survey AUV's position estimates 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. An offline RTS smoothing (red dashed line) gets even better estimation of survey AUV's position by incorporating all the prediction and measurement throughout the whole mission. In Fig. 12, the position error was compared with GPS positions, which are considered as ground truth and plotted in black dashed line in Fig. 11. With dead reckoning alone, we expect the error to grow unbounded over time; the position error of survey AUV using range measurements was significantly lesser as compared with a single AUV relying only on dead reckoning. The RTS smoothing utilizes the future information to further optimizes the position estimates giving better and smoother estimates of positions, see Fig. 13. However, smoothing needs a two-way pass filtering, namely, the forward Kalman filtering and the backward smoothing. The later process requires a track of all the filtering in the past, which introduce heavy load to

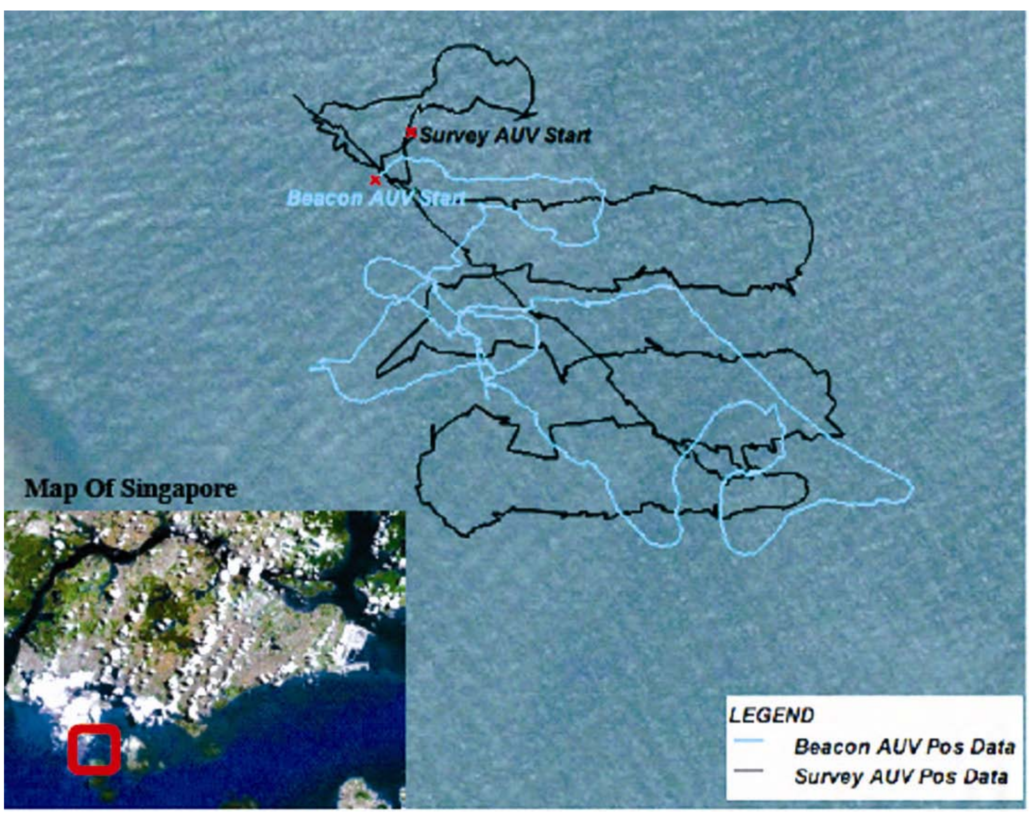

Fig. 10—Plot of Cooperative mission paths around Singapore coastal area

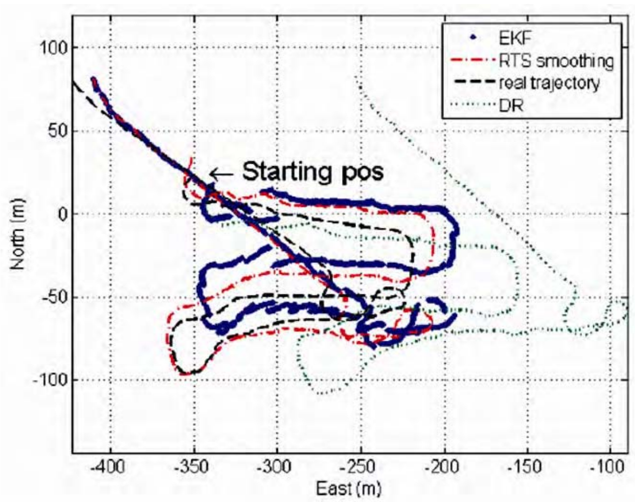

Fig. 11—Comparison of EKF with ranging (cooperative positioning), RTS smoothing (cooperative positioning by Offline smoother) and dead-reckoning (single AUV positioning) during sea trials

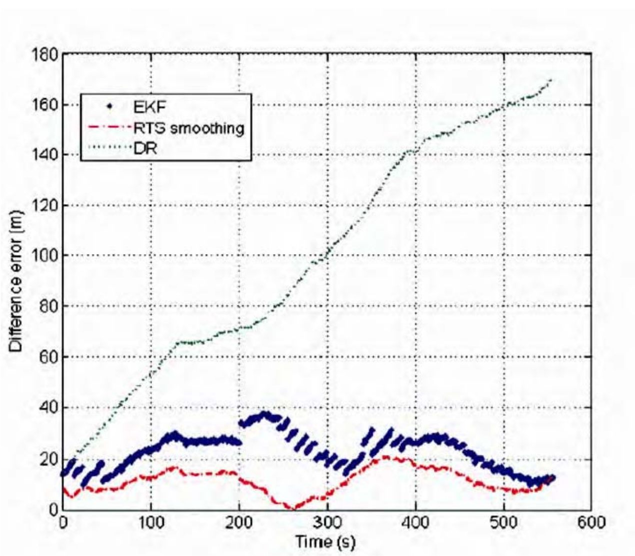

Fig. 12—Position error of EKF with range updates (cooperative positioning), RTS smoothing (cooperative positioning by Offline smoother) as compared with dead reckoning (single AUV positioning) during sea trials

both memory and computation. While the RTS smoothing can't be used in mission run-time, it is still useful for post mission analysis, performance evaluation and target re-acquisition.

Conclusion

Modular and open architecture of the STARFISH AUV had been presented. The architecture was designed to allow a fleet of heterogeneous, collaborative, and low-cost AUVs to be easily used in

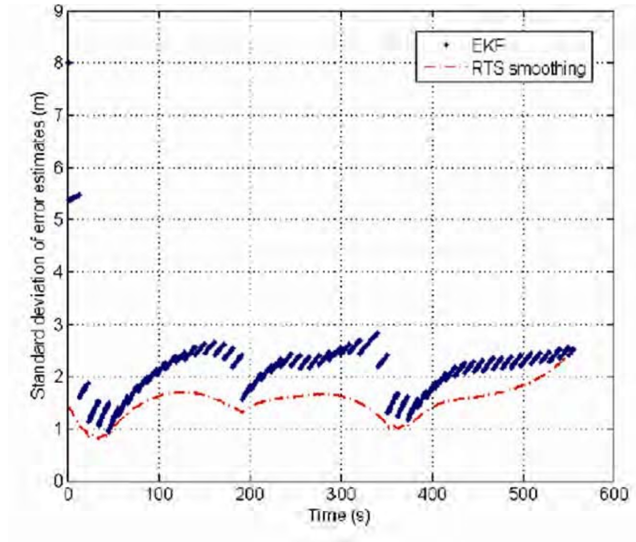

Fig. 13—Comparison of the standard deviation of the error estimates between EKF and RTS smoothing

real applications. Section modularity in the hardware design and distributed software architecture allow easy migration of functionality and control algorithms across different platforms. The clearly defined section architecture, both in terms of mechanical and electrical interfaces, has provided an easy way to implement new sections with novel functionalities to extend the baseline AUV.

Vehicle control system uses a dual-loop depth controller with an inner SMC pitch controller and an outer proportional controller. 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 has demonstrated how these AUVs could be used in tandem for a survey mission when the survey AUV is not equipped with accurate positioning sensors.

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