Distributed Software System Architecture for Autonomous Launch and Recovery System of Autonomous Underwater Vehicles

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Fig. 1. AutoLARS used in the Experiments

Fig. 2. AutoLARS intercepts AUV

Abstract— **In this paper we discuss the software system architecture that is developed for the autonomous launch and recovery platform (AutoLARS). The architecture comprises of several components distributed across physical processing units. The architecture handles the real time data from the hydrophones and subsequent processing of that data to guide the AutoLARS to intercept the autonomous underwater vehicle (AUV) for subsequent recovery. The architecture is built to be distributed to facilitate the load balancing of the system resources. The architecture is modular and makes it easy to deploy based on the system resources**

Index Terms— **Distributed,Software Architecture, Autonomous, AUV, LARS, AutoLARS**

I. INTRODUCTION

Underwater vehicles are increasing their autonomous capabilities more and more in order to carry out more complex and longer missions. The ability to safely launch and recover an autonomous underwater vehicle (AUV) is critical to any mission involving AUV operations. As AUV gets larger and operations move to higher sea states, the current practice is to use larger surface support with high load rated lifting equipment [1]. However, when any vessel motions are present the operation can become hazardous to personnel and equipment, thus limiting AUV operations.More recently, researchers have been working on subsea capture systems that have great potential where are AUVs are customized to home into the subsea capture system [2], [3]. We have been working on an elegant alternative called the AutoLARS, that facilitates the automatic launch and recovery of AUV [4], [5], [6].

The AutoLARS system fig. 1 is designed to facilitate the recovery of AUV's which are not equipped to dock into docking stations. The only requirement for the AUV is to be able to proceed between two waypoints at a nominal heading and depth. The AutoLARS will triangulate the AUV and proceed to intercept it for subsequent recovery. Since the interception takes place subsea the AutoLARS can operate at elevated sea states. In this paper we will be describing the detailed software architecture and its interaction with system hardware to achieve the goal of AutoLARS. The AutoLARS system comprises of the subsea capture and interception hoop and a surface unit for power and control. The hoop is connected to the surface unit with a tether capable of supplying power and data. The AutoLARS is equipped with a free running commercial off the shelf (COTS) pinger, a set of four hydrophones on the periphery of the hoop, a compass and a depth sensor. The AutoLARS will triangulate towards the COTS transponder installed on the AUV see fig. 2.

The paper introduces the distributed software system architecture used in the design of the AutoLARS system. The requirements for the system architecture is the ability to perform in real time a myriad of tasks to enable the interception of the AUV. The system performs a set of pipelined tasks encompassed in software modules each with a well defined interface. The distributed system architecture used in AutoLARS allows for load balancing the software modules on the hoop and the surface units. The system also allows for the playback of captured data from the trials between various submodules for subsequent analysis. The system allows the remote monitoring of the capture process if the system is mounted on the Unmanned Surface Vehicle (USV). The distributed nature of the system allows for the operator to be in the loop in case on a manual intervention in the recovery process. The design also caters for a completely

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autonomous system with all the processing being done in the hoop. The paper discusses the System architecture in section II, the equations for finding the AUV position in section III, the experimental setup and results in section IV.

The development of AutoLARS was started in collaboration with NATO Undersea Research Center (NURC), now Center for Maritime Research and Experimentation (CMRE) and trials were performed at the NURC facility in La Spezia. A few challenges in development of AutoLARS were realized in the trials [5]. In order to address these challenges a scaled version of AutoLARS with same mechanical geometry was developed at Acoustics Research Lab (ARL), NUS. The final tracking system and path planning experiments were performed on the ARL prototype. The scaled prototype developed is for demonstration of capability and it does not have a capture mechanism. In the experiments, only interception and homing of AUV were performed.

II. System Architecture

A. Overview

The fig. 3 shows the different components of the architecture used in the development of the AutoLARS. The components are defined below

1) *Acoustic Acquisition System* manages the capture of the acoustic data in real time from the set of four hydrophones mounted on the hoop.
2) *Navigation Sensor Interface* manages the capture of data from the navigation sensors.
3) *Control System* completes the interception loop, the loop is finally closed by the Path Planning System commanding the control system to direct the AutoLARS system for interception of the AUV.
4) *Signal Processing System* handles the correlation and signal processing of the data. This system also logs the raw data for analysis.
5) *AUV Positioning System* calculates the AUV position by triangulation of the transponder signal received by the four hydrophones on the hoop.
6) *Path Planning System* executes the trajectory planning of the AutoLARS system with respect to the AUV position data.

The components of the system architecture follow a producer consumer paradigm. The consumers register with the producers. The producers send a notification to the consumers on the availability of data. At the system boundaries the producers run an asynchronous TCP/IP client. The consumers run a TCP/IP server to receive the client requests. The asynchronous nature of the connection allows the producers to fulfil realtime obligations while using the TCP/IP protocol.

B. Acoustic Acquisition System

The hydrophones on the AutoLARS are arranged as shown in fig. 4. The four hydrophones are connected to a 24 bit sigma delta Analog to Digital Converter (ADC). For improved fault tolerance, we included a heartbeat mechanism to monitor the system health as shown in fig. 5. The Acoustic AcquisitionSystem is a multi threaded software component.

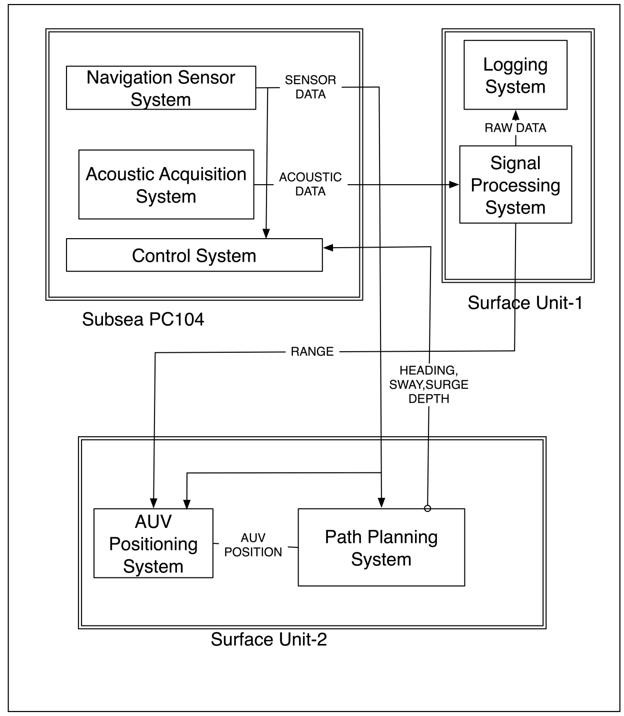

Fig. 3. System Component Overview

The Card Interface thread reads the data from the ADC in blocks of 655.36ms per channel.This corresponds to a 1MB storage in memory. The data from the ADC is converted from EBDIC format and is stored into a buffers that is retrieved from a pre-allocated circular buffer pool by the Signal Conditioning thread. The buffer is then sent by asynchronous TCP/IP connection to the TCP/IP server in the Signal Processing System in Surface Unit 1 see fig. 3. If an connection to the Signal Processing server cannot be established the buffer is immediately returned to the circular buffer pool.This is possible due the asynchronous client which reports that the connection state is not established instead of waiting for the connection to complete. In the case where the connection is established the Signal Conditioning thread returns the buffer to the pool after the socket write by the TCP/IP client.This system runs in a real time constraints. It is fatal failure if the Card Interface thread cannot get a buffer from the circular buffer pool. The size of the pool itself is adjusted to account for a transient nominal load on the CPU.

C. Navigation Sensor System

The Navigation Sensor System runs a thread per sensor which reads the navigation sensors in the AutoLARS on a periodic basis. The data from the sensors is filtered and stored in a cache. This cache is then queried by the clients. The data of the navigation sensors is the current heading, depth , pitch and roll of the AutoLARS system. The Navigation Sensor Systems is a TCP/IP server which waits for the data requests from the AUV Positioning System, the Path Planning System and the Control System which are the TCP/IP clients to the server.

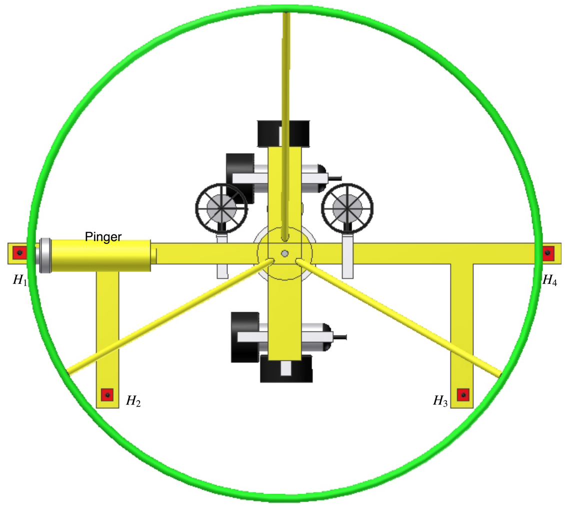

Fig. 4. Hydrophone placement on the AutoLARS system

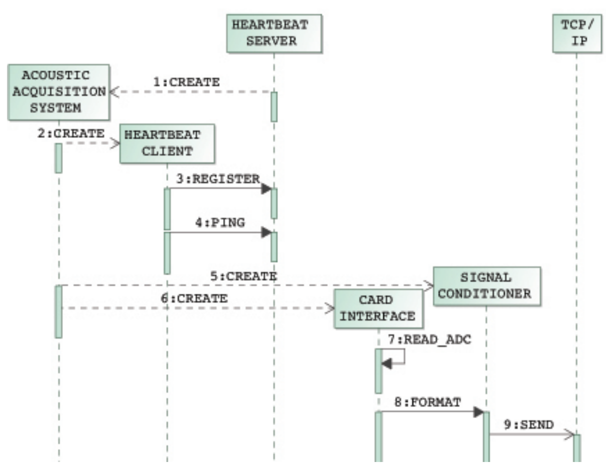

Fig. 5. Acoustic Acquisition System Sequence Diagram

D. Control System

The Control System for the AutoLARS uses a Proportional Integral Derivative (PID) controller. The Control System of the AutoLARS takes the required heading, depth and the sway and surge distances as set points from the Path Planning System. The Control System then uses the six thrusters to satisfy the commands of the Path Planning System. The Control System uses the data from the Navigation Sensor System to close the feedback loop. The Control System runs a TCP/IP client thread to connect to the Navigation Sensor System. The Control System runs a TCP/IP server thread to interface with the Path Planning System.

E. Signal Processing System

The AutoLARS fig. 4 uses four commercial off the shelf (COTS) Reson TC4013 hydrophones. One COTS pinger operating at 20kHz frequency is fixed butting hydrophone one. The transponder on the AUV is a COTS chirp based transponder with a frequency range of (23-27)kHz. The pinger has a signal duration of 4ms and the transponder has a signal duration of 10ms. The Signal Processing System runs as a server to the Acoustic Acquisition System fig. 6. The Signal Processing System starts the Range Aggregator thread. This thread starts the Pinger Detector and the four Transponder Detector threads for each of the hydrophones in the system. The data from all the hydrophones is read by the server for processing. The Signal Processing System uses the same circular buffer interface used in the Acoustic Acquisition System. This ensures that the cost of memory allocation is paid upfront and not during the processing of the signal. The Pinger Detector thread and the Transponder Detector threads process the acoustic data in blocks. This method of processing should be able to handle scenarios where the signal is spilt between two consecutive blocks of data. The goal of the signal processing by the detector threads is to find the start of the signal from the transponder and pinger by correlation. The detector threads prepends to the current block, the data from the previous block for finding the correlation. The data prepended from the previous block should be at least the size of the signal. The AutoLARS system prepends the previous block data of 20ms. The detectors uses a running index over the blocks. The correlation index chosen is the one with the larger magnitude of the correlation when the detection is within the ambiguous zone striding two blocks. This zone is detected by the two correlation index delta being less than the size of the signal under consideration. The detector threads inform the range aggregator on the detection of the transponder and the pinger signals. On a detection of a pinger signal i the range aggregator sends the range information between the previous ping $i-1$ and the transponder signals corresponding to pinger signal $i-1$ to the AUV Positioning System

The Logging thread is a consumer of data from the Acoustic Acquisition System. The acoustic data is stored with the meta data which include timing parameters and channel numbers. The data is stored in the same block format as was sent by the Acoustic Acquisition System. This facilitates the subsequent testing of the Signal Processing System with the stored data as the input. The processing from the data acquired from a specific sea trial can be repetitively processed by the Signal Processing System to refine the process of detection.

F. AUV Positioning System

The AUV Positioning System receives the range data form the Signal Processing System on the TCP/IP Interface fig. 7. The range data is the filtered to remove outliers and the Triangulation thread is notified. The Triangulation thread gets the telemetry data from the Navigation Sensor System fig. 3. The Telemetry data is the depth, the heading, the roll and pitch of the AutoLARS. The hydrophone positions are transformed from the Body coordinate System to the NED coordinate system see fig. 8. The details of the solution are

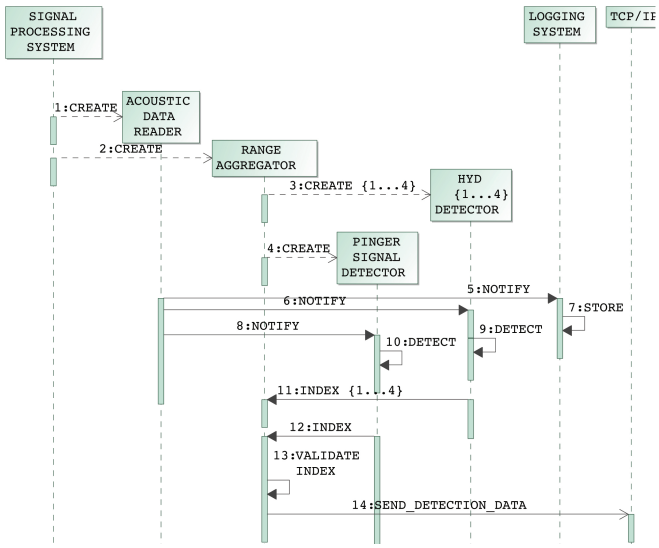

Fig. 6. Signal Processing System Sequence Diagram

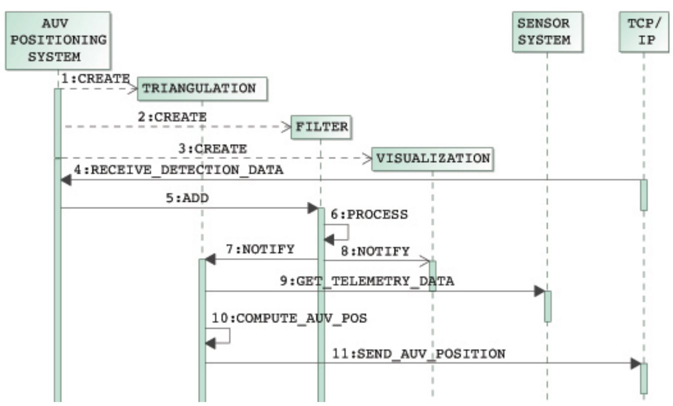

Fig. 7. AUV Positioning System Sequence Diagram

explained in section III. The AUV Positioning System is a client to the Path Planning System. The Path Planning System receives the AUV position in polar co-ordinates from the AUV Positioning System.

G. Path Planning System

The Path Planning System runs as a server to the AUV positioning System and is a client to the Control System. The Path Planning System receives the AUV coordinates from the AUV Positioning System and this data is input to the Finite State Machine (FSM). The FSM states direct the AutoLARS on a state specific strategy for intercepting the AUV. The strategies would include commands to the Control System to proceed in sway or surge for a specific distance. It could also tell the Control System to change the heading of the AutoLARS. The Navigation Sensor System will provide the sensor parameters of depth,pitch,roll and heading to the Path Planning System. The Path Planning System will utilize this data along with the data from the AUV Positioning System to effect the interception of the AUV.

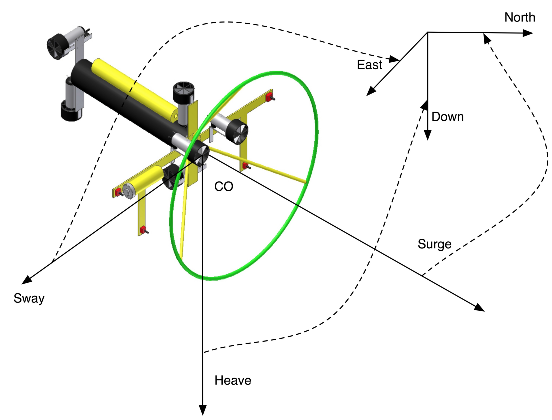

Fig. 8. Body Fixed Coordinate System

III. Solution for AUV position

The input to the AUV positioning system is the number of samples corresponding to the time difference of transmission of the pinger and the receipt of the transponder signal by the hydrophone. The pinger mounted adjacent to the hydrophone H_1 (fig. 4) is a free running pinger operating at 20kHz. The distance between the hydrophone H_1 and the transponder (τ) on the AUV is half of the roundtrip time from the pinger to the transponder and back to the hydrophone H_1. After receiving the signal from the pinger the transponder (τ) responds after a predefined time given by the manufacturer datasheet. The fig. 4 shows the placement of the hydrophones and the pinger on the AutoLARS system.

List of Symbols

(x_n, y_n, z_n)	Location of hydrophone $H_n; n = \{1,\ldots,4\}$
(x_τ, y_τ, z_τ)	Location of the transponder τ
s_n	Number of samples from the start of the pinger to the detection by hydrophone H_n at position (x_n, y_n, z_n)
t_n	Time corresponding to the samples of hydrophone $H_n; \frac{s_n}{s_r}$
u	Speed of sound in water
$\hat{\rho}_{cn}$	Distance between the hydrophone H_n and the assumed position of the transponder τ
ρ_{etat}	Distance corresponding to the error for the turn-around time in transponder
ρ_{tat}	ut_{tat} is the distance corresponding to the turn-around time
ρ_n	Distance from the hydrophone H_n to the transponder τ
o_b	Origin in the BODY coordinate system. The origin is chosen to coincide with the point at the centre of the hoop on the AutoLARS
o_n	Origin in the NED coordinate system
s_r	Sampling rate of the ADC
t_{etat}	Error in turn-around time(in seconds). This is the delta between the actual time and the expected time of transmission

t_{tat} Turn-around time (in seconds)
v^t $R^t_f v^f$ where v^t,v^f are the positions in the two coordinate systems and R^t_f is the Rotation Matrix to convert from one coordinate system to the other
Z_a AUV depth
Z_l AutoLARS depth

The heading information is used to orient the AutoLARS system towards the AUV. The roll (ϕ) and pitch (θ) induced by the motion of AutoLARS are considered as mere disturbance in the system. The Hydrophone H_n locations need to be transformed by the rotational matrix R^n_b for the roll and pitch from body frame to North East Down (NED) coordinate system. While the heading is calculated by numerical methods described later.
The depth of the AUV and AutoLARS system are known apriori. The AUV is programmed to maintain a specific depth with an expectation that it is capable of having a good depth control.

The difference in depth between the AUV (corresponds to the transponder τ depth) and the AutoLARS is given by

$$z_\tau = Z_a - Z_l \tag{1}$$

- **For** H_1**:**

$$\begin{aligned} us_1 &= 2\rho_1 + \rho_{tat} + \rho_{etat} \\ \rho_{c1} &= \frac{us_1 - s_r\rho_{tat}}{s_r 2} \\ \rho_e &= \frac{\rho_{etat}}{2} \\ \rho_1 &= \rho_{c1} - \rho_e \end{aligned} \tag{2}$$

- **For** $H_n, \quad n = 2, \ldots, 4$**:**

$$\begin{aligned} us_n &= \rho_n + \rho_1 + \rho_{tat} + \rho_{etat} \\ \rho_{cn} &= \frac{2us_n - us_1 - s_r\rho_{tat}}{2s_r} \\ \rho_e &= \frac{\rho_{etat}}{2} \\ \rho_n &= \rho_{cn} - \rho_e \end{aligned} \tag{3}$$

The following non linear equations $\forall n = \{1..4\}$ give the distance between the AUV and the hydrophone n.

$$\rho_n = \sqrt{(x_\tau - x_n)^2 + (y_\tau - y_n)^2 + (z_\tau - z_n)^2} \tag{4}$$

Assuming initial values of $x_\tau, y_\tau, z_\tau, \rho_e$ which is the estimated position of the transponder τ.

- **For** H_1**:**

$$\hat{\rho}_{c1} = \sqrt{(x_1 - x_\tau)^2 + (y_1 - y_\tau)^2 + (z_1 - z_\tau)^2} + \rho_e \tag{5}$$

  The distance using the measured values by the Signal Processing System is given by

$$\rho_{c1} = \frac{us_1 - s_r\rho_{tat}}{2s_r} \tag{6}$$

- **For** $H_n, \quad n = 2, \ldots, 4$**:**

$$\hat{\rho_{cn}} = \sqrt{(x_n - x_\tau)^2 + (y_n - y_\tau)^2 + (z_n - z_\tau)^2} + \rho_e \tag{7}$$

  The distance using the measured values by the Signal Processing System is given by

$$\rho_{cn} = \frac{2us_n - us_1 - s_r\rho_{tat}}{2s_r} \tag{8}$$

The error between the measured and computed distance is

$$\delta\rho_{cn} = \rho_{cn} - \hat{\rho}_{cn} \tag{9}$$

Using Taylors series to address the non-linearities. For Hydrophones H_n.

$$\delta\rho_{cn} = \frac{(x_n - x_\tau)\delta x_\tau + (y_n - y_\tau)\delta y_\tau + (z_n - z_\tau)\delta z_\tau}{d_n} + \delta\rho_e \tag{10}$$

$$d_n = \sqrt{(x_n - x_\tau)^2 + (y_n - y_\tau)^2 + (z_n - z_\tau)^2} \tag{11}$$

The equations are formed with the form $A\mathbf{x} = B$ where the solution is of the form $\mathbf{x} = (A^T A)^{-1} A^T B$.

- **Shallow Water** In the experiments with shallow waters of a lake there was a noticeable error in the turn around time while the AUV depth was stable. For this scenario with z_τ is known from (1).

$$\delta\rho_{cn} = \frac{(x_n - x_\tau)\delta x_\tau + (y_n - y_\tau)\delta y_\tau}{d_n} + \delta\rho_e \tag{12}$$

$$\begin{bmatrix} \frac{(x_1-x_\tau)}{d_1} & \frac{(y_1-y_\tau)}{d_1} & 1 \\ \frac{(x_2-x_\tau)}{d_2} & \frac{(y_2-y_\tau)}{d_2} & 1 \\ \frac{(x_3-x_\tau)}{d_3} & \frac{(y_3-y_\tau)}{d_3} & 1 \\ \frac{(x_4-x_\tau)}{d_4} & \frac{(y_4-y_\tau)}{d_4} & 1 \end{bmatrix} \begin{bmatrix} \delta x_\tau \\ \delta y_\tau \\ \delta\rho_e \end{bmatrix} = \begin{bmatrix} \delta\rho_{c1} \\ \delta\rho_{c2} \\ \delta\rho_{c3} \\ \delta\rho_{c4} \end{bmatrix} \tag{13}$$

  Iteration is repeated till δe is less than some predetermined precision.

$$\delta e = \sqrt{\delta x_\tau{}^2 + \delta y_\tau{}^2 + \delta\rho_e{}^2} \tag{14}$$

- **Sea Water**
  In experiments in the sea waters the error in turn around time was not noticeable, then with $\delta\rho_e = 0$ and assuming z_τ is unknown.

$$\begin{bmatrix} \frac{(x_1-x_\tau)}{d_1} & \frac{(y_1-y_\tau)}{d_1} & \frac{(z_1-z_\tau)}{d_1} \\ \frac{(x_2-x_\tau)}{d_2} & \frac{(y_2-y_\tau)}{d_2} & \frac{(z_2-z_\tau)}{d_1} \\ \frac{(x_3-x_\tau)}{d_3} & \frac{(y_3-y_\tau)}{d_3} & \frac{(z_3-z_\tau)}{d_1} \\ \frac{(x_4-x_\tau)}{d_4} & \frac{(y_4-y_\tau)}{d_4} & \frac{(z_4-z_\tau)}{d_1} \end{bmatrix} \begin{bmatrix} \delta x_\tau \\ \delta y_\tau \\ \delta z_\tau \end{bmatrix} = \begin{bmatrix} \delta\rho_{c1} \\ \delta\rho_{c2} \\ \delta\rho_{c3} \\ \delta\rho_{c4} \end{bmatrix} \tag{15}$$

  Iteration is repeated till δe is less than some predetermined precision.

$$\delta e = \sqrt{\delta x_\tau{}^2 + \delta y_\tau{}^2 + \delta z_\tau{}^2} \tag{16}$$

Fig. 9. AUV with transponder strapped to its bottom

IV. Experiment Setup and Results

The experiments were carried out in shallow waters of Pandan reservoir in Singapore to test the path planning and the positioning systems. A transponder was attached to the small AUV for the tests see fig. 9. The AutoLARS system used in the tests did not have a capture mechanism. The objective of the experiment was to validate the AUV tracking and the trajectory employed for interception.

The AUV towed the transponder at a constant depth of 0.75 meter. The AUV maintained a constant speed of one knot and constant heading while towing the transponder. The AutoLARS was set up at approximately 30 meter from the starting point of AUV. The AutoLARS has umbilical of 12 meter. The Path Planning System received the heading delta from the AUV Positioning System. This is the heading of the AUV with respect to the LARS as shown in fig. 10. The Path Planning System uses this delta along with the actual heading of the AutoLARS from the Navigation Sensor System to compute the heading that the AutoLARS should turn towards for an interception. The plot as shown in fig. 11 shows the heading difference vs distance between the AUV and AutoLARS for three distinct interceptions. The interception of the AUV is at the point when the difference in distance between the AUV and AutoLARS is zero. The AUV transponder is a point source and at the time of interception there may be a heading difference due to the point of entry of the AUV into the hoop see fig. 10 and the placement of the hydrophone constellation see fig. 4. This is true when the AUV does not enter at the center (o_b) of the hoop.

V. Conclusion

The experiments were successfully carried out by using the system architecture described above. The distributed model leveraged on the high bandwidth of the TCP/IP interfaces to move the large volume of the acoustic data between the different subsystems while meeting real time constraints. This allowed us to handle the data on the surface platforms without constraints imposed by the embedded systems. By using overlapped block data we were able to handle the signal processing with block based functions provided by the standard signal processing libraries in real time.In the future work in order to further exploit the distributed architecture, we plan to provide fault tolerance in the system. We will be using the TCP/IP interfaces for providing the fault tolerance. We will also be looking at using the redundancy in the hydrophone constellation to achieve robustness in the solution of the AUV position in presence of error of detection in one or more hydrophones.

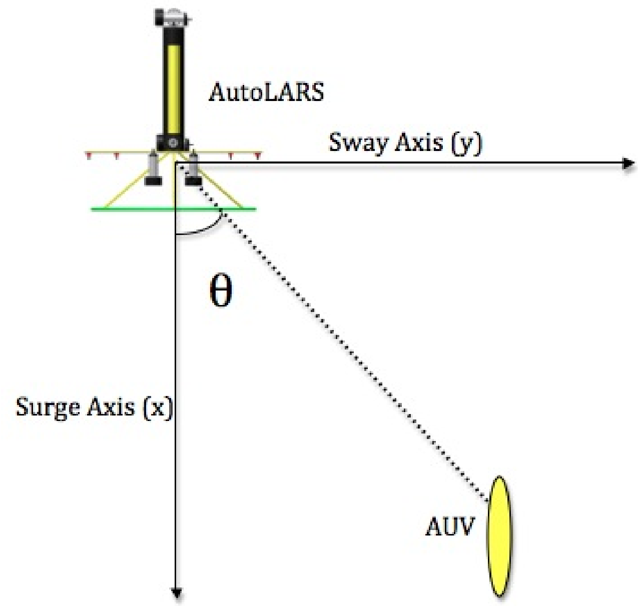

Fig. 10. Heading of the AUV with respect to AutoLARS

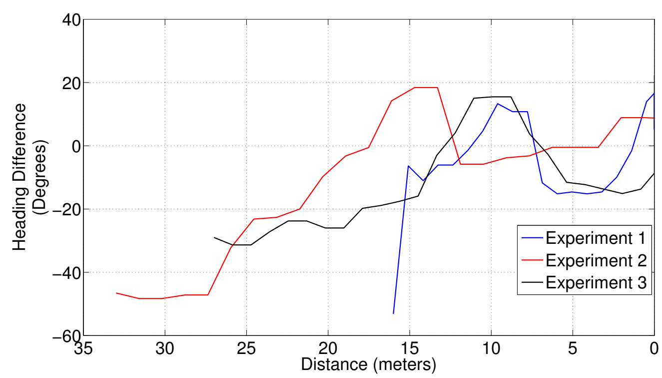

Fig. 11. AUV heading with respect to AutoLARS and the distance between the AUV and AutoLARS

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