A Path Planning System for Autonomous Launch and Recovery System of Autonomous Underwater Vehicles

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***Abstract*—In this paper, a path planning system for mobile Autonomous Launch And Recovery System (AutoLARS) is presented. The unique AutoLARS is capable of tracking an AUV eqipped with a commercial off the shelf transponder. Path planning system uses the information of position and commands the AutoLARS control system with motion set points. The real time tracking of the AUV is used to build approximate trajectory or intercept strategy directly. The path planning system uses a graph building method for filtering the tracking data of AUV and Finite State Machine (FSM) to compute motion set points for control system. The path planning incorporates motion that allows the AutoLARS to align with the AUV and intercept it. The AutoLARS does not require to be equipped with velocity sensors or high grade navigation sensors and assumes that AUV is coming at a nominal heading between two way points at a known depth.**

Keywords*—*AutoLARS, AUV, Tracking, Path Planning, Transformation, Filtering

I. Introduction

LAUNCH and recovery system (LARS) have a great potential in operation of Autonomous Underwater Vehicles (AUVs) due to the inherent nature of challenging underwater environment. Autonomous launch and recovery system is a step further in LARS. However, an autonomous retrieval would require either a mobile or a stationary platform and an accurate tracking system on the platform or the AUV. In case of a mobile platform, it will have to navigate towards the direction of motion of the AUV and will require to have a small turning radius and hovering capability to intercept it. We are working towards the development of a mobile and autonomous launch and recovery platform called Autonomous Launch and Recovery System (AutoLARS). There is significant amount of research directed towards docking of an AUV in to stationary hoop [1] [2]. However, the major drawback of such a system is the substantial modifications needed on AUV's to facilitate the docking. An elegant alternative is proposed here, in the form of AutoLARS that requires only a small and lightweight transponder to be strapped on the AUV. The AutoLARS has tracking capabilities [3]. AutoLARS concept requires last stage of AUV's mission planned as submerged at a nominal heading and know depth. Also most of the discussion in this paper pertains to recovery of AUV.

A. AutoLARS

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. A few challenges in development of AutoLARS were realized [4]. But eventually a scaled down version of AutoLARS with same mechanical geometry was developed at Acoustic Research Laboratory, National University of Singapore (NUS). The final positioning system and path planning experiments were performed on NUS prototype.

AutoLARS is a remotely operated vehicle that has six thrusters for navigation, four hydrophones for acoustic data collection and related electronics [5]. AutoLARS does the job of tracking the AUV and positions itself in front of incoming AUV to initiate its retrieval. CAD drawing of AutoLARS is shown in Fig. 1.

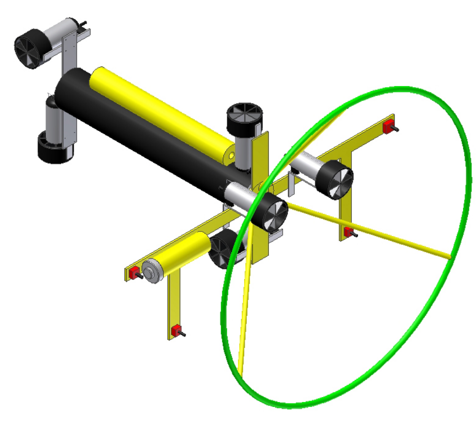

Fig. 1. AutoLARS CAD model

The presence of six thrusters produces broadband noise and makes the tracking of AUV difficult [4]. To solve this problem,

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chirp transponder is used on AUV. The features of positioning system that affect the path planing approach is discussed in the next section. The details of path planning, AutoLARS experiment and results are also presented.

B. AUV

The AUV used in the demostration of AutoLARS is Thunder tiger Neptune SB-1 [6] . The electronics and software were modified to suit the need of experiment. This AUV is capable of moving at 1 knots at a certain prespecified heading.

II. Method

A path planning is vital for Autonomous launch and recovery of AUV. The target tracking is done without any stationary frame of reference. The transducer arrangement for tracking the AUV is shown in Fig. 2.

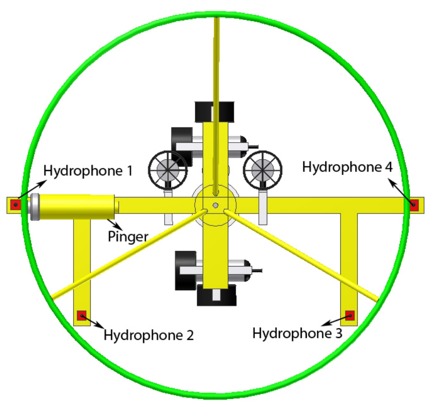

Fig. 2. Transducers and Pinger on AutoLARS

Hydrophones 1-4 are the transducers and a pinger is used to query a chirp transponder on the AUV. Due to this arrangement with transducers in one plane facing the same direction, there are certain concerns for tracking of the AUV. The quantitative analysis of error in tracking when the AUV is stationary at 30 meters pointing from 0 to 90 degrees towards AutoLARS is plotted in Fig. 3.

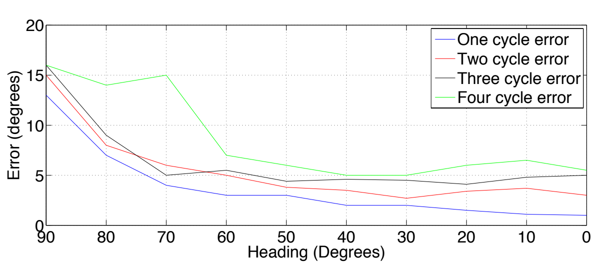

Fig. 3. Error vs angle plot when there is error on hydrophone 2

The plots are for error of 1 to 4 wave length in detection of start of transponder signal (frequency = 25Khz, middle freqecy of chirp) on Hydrophone 2, chosen randomly. There are various other error analysis with error on two or more hydrophones, that can be performed but this paper restricts itself to error in detection on hydrophone 2. The results from other analysis show similar trend. It can be concluded that there are two factors that affect the accuracy of positioning system.

- The positioning accuracy is best when baseline connecting AutoLARS and AUV is normal to AutoLARS transducer plane and it decreases as the absolute value of azimuth angle increase on both the sides of the baseline. See Fig. 3.
- In general, the positioning system accuracy increases as the distance of AutoLARS from AUV decreases due to improved Signal to Noise Ratio (SNR).

The path taken by AutoLARS must take these salient features of positioning system into account.

The flowchart in Fig. 4 depicts the various sub systems in AutoLARS. It can be seen that there is provision of manual input that can be used to send manual commands. It is useful in initial deployment of AutoLARS to align it at certain heading and depth.

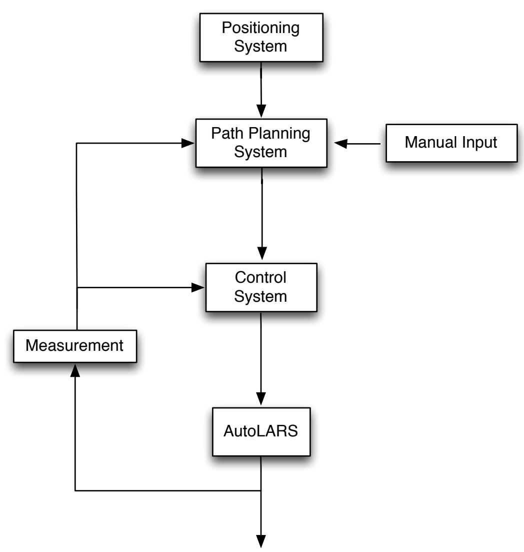

Fig. 4. A complete system configuration of AutoLARS

The Path planning system's role is central to the working of AutoLARS system. It serves two purpose of filtering the data and implements a Finite State Machine (FSM) for set of motions of AutoLARS. The FSM state shifts are based on range of AutoLARS relative to the AUV. Path Planning system executes certain set of guidance laws to facilitate the interception of the AUV.

The positioning system computes range and azimuth of the AUV in the non inertial local reference frame of AutoLARS.

The positioning data is transformed from local frame to geographical or North-East-Down (NED) frame using compass and depth sensor. As there are no inertial sensors on-board, motion estimation in surge and sway direction is done based on predetermined AutoLARS and AUV velocity. Filters are applied on the data in NED frame to remove the outliers. Based on this information it commands the control system with set points.

III. Details of path planning system

The path planning system has three primary sub systems i.e. compensation of positioning data in the frame of reference of AutoLARS, filtering of positioning data and finally to set motion set points implemented as states. The flowchart in Fig. 5 depicts the flow of data in path planning system.

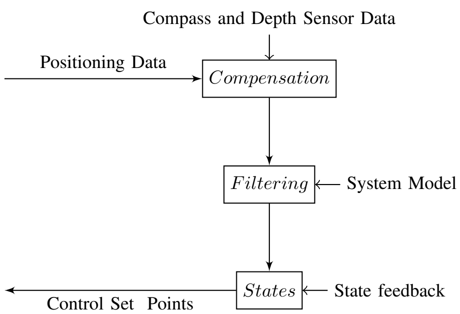

Fig. 5. A flowchart describing the overall path planning system

The path planning system assumes that the AUV is coming at a nominal heading between two way points at a known depth. The positioning system provides a good heading, range data. The depth data from the positioning system is noisy. In general the AUV typically maintains a good depth control with the errors in the range of centimeters. This is true when the AUV is operating at sufficient depth from the surface. The path planning system will use this knowledge of the depth for interception. The path planning system also ignores the currents and surface action. The interception has to be planned against the direction of current to facilitate the ease in interception. In the following subsections, the sub systems are explained.

A. Compensation

Before doing any filtering on the positioning data (range, azimuth and depth), it must be compensated in NorthEastDown (NED) frame of reference as the AutoLARS might be at some pitch or roll when positioning data was calculated. The data can be transformed to a non inertial frame attached to the moving AutoLARS NED reference frame. The data from compass as heading, pitch and roll is required for this compensation.

If the rotation matrix about the euler angles roll (ϕ), pitch (θ) and yaw(ψ) are denoted by $R_x(\phi)$, $R_y(\theta)$ and $R_z(\psi)$ respectively then the transform for body frame (b) to NED(n) frame is

$$R_b{}^n = R_z(\psi)R_y(\theta)R_x(\phi) \tag{1}$$

B. Filtering

After the compensation of data, the outliers must be recognized. The AutoLARS path planning system builds a graph of valid data points for filtering. In this method, the current value from positioning system is used to evaluate the next incoming data. The relative speed of AUV with AutoLARS is used to create an imaginary circle around the received point, refer 2. If the next point is outside this circle, another node is created shown in the Fig. 6.

$$R = S\delta t \tag{2}$$

where, R is radius of imaginary circle, S is maximum relative speed of AUV with respect to AutoLARS, δt is duration between received points.

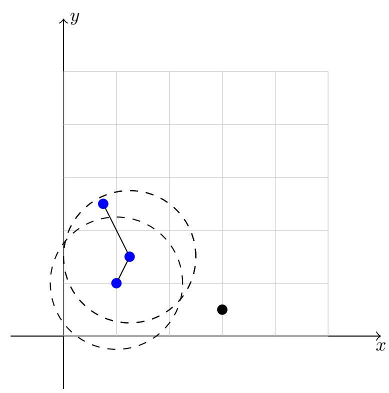

Fig. 6. Selection criteria for determining node

Thus a grid is created which is collection fo received points mapped on to a specific node based on this selection criteria as shown in Fig. 7. This grid is for depiction of method only.

In the Fig. 7, the different nodes are represented by n^1, n^2, n^3, n^4. The one that grows longest is used in path planning system. In this case, it is n^1. In an unlikely, ambiguous situation where two nodes are of same size, the node with latest point is selected. In general, a low pass filter is also implemented on azimuth data to get rid of extreme fluctuations in the acceptable band.

C. States

There are five states and each state comprises of sub states. The shift in state is based on distance of AUV with respect to AutoLARS and the states shifts are only possible in forward direction. Inside a state, the AutoLARS can go into various sub states.

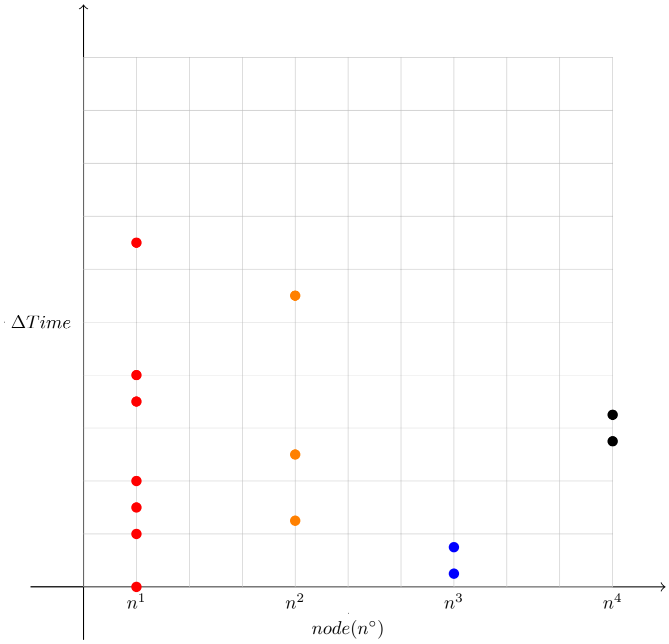

Fig. 7. Grid mapping of the received points to respective nodes based on the selection criteria

The various sub states inside a state are Head to target State, Point to AUV State, Slope State, Sway State, Surge State, Heading State, Intercept State, Capture State and Missed State. The sub states are described below.

1) **Head to target State:** This is the initial deployment of AutoLARS. The AutoLARS is deployed in the direction AUV is supposed to come from. It is the opposite of known nominal heading of AUV path. A timer is path planning system shifts AutoLARS from this state to point to AUV state. If target heading of AutoLARS is H_t and AUV heading is Y_t, then target heading is given by

$$H_t = (180 + Y_t) \bmod 360 \tag{3}$$

where mod is an operation that computes the remainder when divided by the number.

2) **Point to AUV State** In this state, the AutoLARS points to the AUV with a baseline ambiguity. A baseline ambiguity helps in ascertaining the direction of Sway for AutoLARS. This stage helps in deducing the initial direction of motion for AutoLARS and building a reliable node in filtering. If the value of range is 150 % more than the length of umbilical of AutoLARS, it shifts into slope state, else it attempts an interception by surge state. In this state the calculation of slope using 2 point method is also carried out. A buffer of slope values are generated and it moving average and standard deviation is computed.

3) **Slope State:** In this state the slope of AUV trajectory is computed and AutoLARS tries to align itself with slope and sway in the direction AUV coming.
The slope calculation method is explained in 4.

$$\Delta S_t = \tan^{-1} \frac{y_t - y'_{t-1}}{x_t - x'_{t-1}} \tag{4}$$

where, ΔS_t is slope at time t, y_t, x_t is AUV sway and surge position at time t, y'_{t-1}, x'_{t-1} is AUV sway and surge position at time $t-1$, compensated with velocity of AUV with respect to AutoLARS.

$x\prime$ and $y\prime$ positions are calculated by 5 and 6 respectively.

$$x'_{t-1} = x_{t-1} - \left|\vec{V}\right| cos(\delta\theta)\delta t \tag{5}$$

$$y'_{t-1} = y_{t-1} - \left|\vec{V}\right| sin(\delta\theta)\delta t \tag{6}$$

where, δt is the time duration between $t-1$ data and t, $\delta\theta$ is the change in heading of AutoLARS from time $t-1$ to time t, $\vec{V}$ is the velocity of AutoLARS with respect to a stationary frame, y_{t-1}, x_{t-1} is the position of AUV at time $t-1$.

It can be seen that velocity of AutoLARS is important to calculate the slope. Dead reackoning estimates are performed because of absence of velocity sensor. This could lead to erroneous slope calculation. A moving average of slope values and its standard deviation is calculated. A criteria is established to stay in slope stage. The criteria is given by 7.

$$\Delta S_{t+1} < \mu_{\Delta S_T} \pm 2\sigma_{\Delta S_T} \tag{7}$$

where, ΔS_{t+1} is the current computed slope, $\mu_{\Delta S_T}$ is moving average of five previous slopes, $\sigma_{\Delta S_T}$ is standard deviation of five previous slopes, T is $(t-4, t-1, .., t)$.

If this criteria is not satisfied, the AutoLARS shifts to Sway state. It may shift to Heading state also if the value of sway is zero, which will happen if AutoLARS is aligned in the motion of AUV.

4) **Sway Stage:** A sway state is a state in which AutoLARS moves along its sway axis while maintaining a certain specified heading. Heading to incoming AUV with a baseline ambiguity and swaying helps the AutoLARS in getting closer to AUV trajectory. The sway is stopped once a change is value of azimuth is observed.

5) **Heading State:** A state in which AutoLARS points to a certain specified heading. This state can be sway state or surge state when the value of sway and surge is zero respectively. A bound of 1 m which is the diameter of AutoLARS hoop, is used in sway and

surge direction of signify zero.

6) **Surge State:** A surge state is a state in which AutoLARS moves along its surge axis while maintaining a certain specified. The AutoLARS can surge forward or surge backward. AutoLARS has an umbilical and it should be rolled back if it is coming in direction of deployment vessel to avoid entanglement with umbilical.

7) **Intercept State:** This sub state is the last state till interception. The greatest accuracy in positioning data demand is associated with Intercept stage and AutoLARS must respond to set points swiftly. The low pass filter on positioning data is removed and AutoLARS is allowed to move corresponding to the positioning data. The requirement of intercept stage goes well with the positioning system as its accuracy increases when distance between AUV and AutoLARS decreases.

8) **Captue State:** This state is the successful interception of AUV. AutoLARS and AUV are retrieved.

9) **Missed State:** If the AutoLARS misses the AUV, it orients itself in direction opposite to target heading waiting for the AUV. For autonomous recovery, it is assumed that AUV is doing lawn mover mission.

The state and sub state flow and interaction are shown in the Fig.8.

The states are cluster of sub states. During the interception and homing experiment AutoLARS maintains the known AUV depth. The description of each state is below.

1) **State 1**: This is the primary launch state. The AutoLARS is deployed at target heading and after some time it shifts in to point to AUV state. In the point to AUV state, the AutoLARS points at AUV with baseline ambiguity. During this stage, slope data is also computed. The shift out of this state is based on distance. And it can either shift to 2nd state or directly to 3rd state based on value of range.

2) **State 2**: This state has sub states that incorporate motion of AutoLARS along sway axis. The AutoLARS either points to the AUV and sways or maintains heading parallel to slope and sways.

3) **State 3**: This state has sub states that incorporate motion of AutoLARS along surge axis. The AutoLARS points to the AUV and surges towards or away from it.

4) **State 4**: This the terminal state. Swift motion of AutoLARS is required in this state. It is the final surge towards the AUV to intercept it or to pull back with a reduced relative speed.

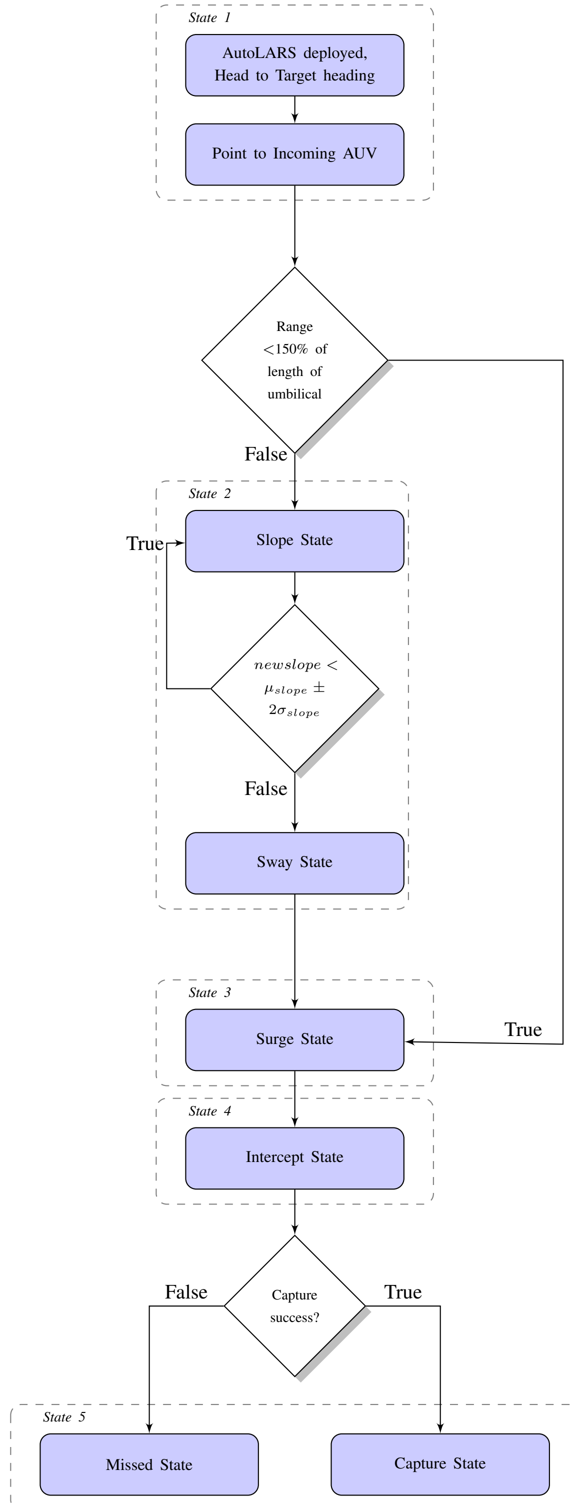

Fig. 8. A flow diagram detailing multiple states of the implemented path planning system

5) **State 5**: This state concludes the operation of AutoLARS. In this, it is either a successful capture or a missed state, in which case a retry is required.

The following section describes the experimental set up and results.

IV. Experiment Setup And Results

The trials were performed at Pandan reservoir, RC pontoon, Singapore. A transponder mounted AUV is programmed to maintain a constant heading and a constant speed of 1 knot at 0.75 meter depth. The AutoLARS is set up at approximately 30 meters from the starting point of AUV. The AutoLARS has umbilical of approximately 12 meters. The experiments were intended to demonstrate the performance of the proposed path planning system by intercepting the AUV, and hence the capture mechanism was not installed on the AutoLARS, as shown in Fig. 9 .

Fig. 9. AutoLARS

The heading difference, $\delta\theta$ (as shown in Fig. 10), is the angle of baseline connecting AutoLARS and AUV with normal of AutoLARS transducer plane.

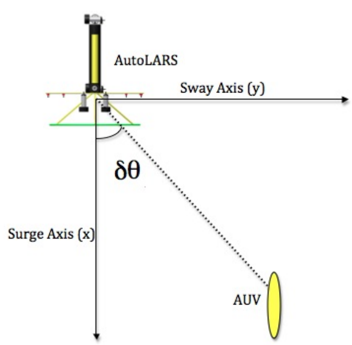

Fig. 10. Heading difference representation

Fig. 11 shows $\delta\theta$ as a function of time for positioning and path planning system. Any deviation in path planning set points from positioning set points is due to filtering stage as shown in Fig. 5.

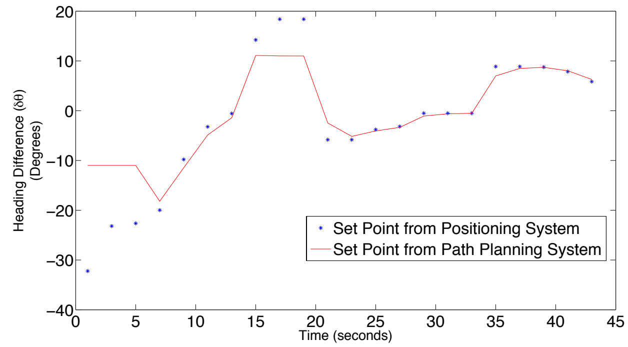

Fig. 11. Plot of azimuth from positioning system and path planning system

The Fig. 12 shows the AutoLARS response to heading set point data. The control system is given heading set point in global NED frame of reference. A deviation between the set heading and AutoLARS's heading is desirable to resolve baseline ambiguity. The Fig. 15 shows $\delta\theta$ as a funtion of distance between the AutoLARS and AUV during three different experiments. The interception happens when the relative distance between the AUV and AutoLARS is approximately zero.

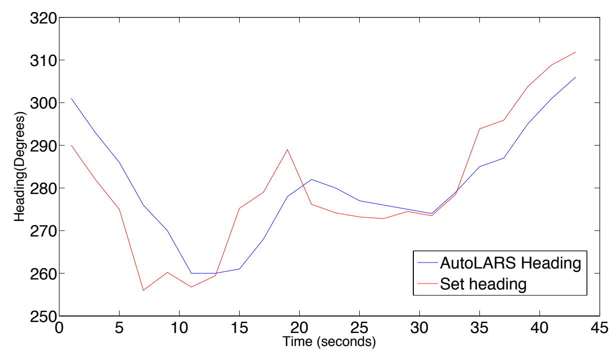

Fig. 12. The AutoLARS heading set point compensated to global frame comparison with actual heading

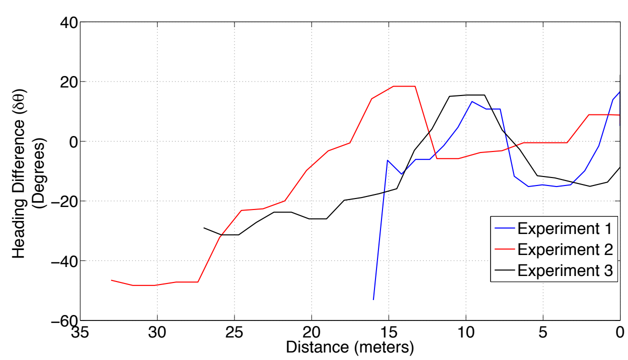

Fig. 13. Plot of Heading difference Vs Distance

Fig. 14 and 15 shows AutoLARS doing the homing and interception of AUV respectively.

Fig. 14. AutoLARS homing on to an AUV

Fig. 15. AutoLARS intercepting an AUV

V. Conclusion and Future Work

In this paper, a path planning system for AutoLARS has been presented. The path planning system helps in homing on to an stationary AUV on surface or intercept an AUV. The results of lake trials were presented. This approach does not require any real time velocity instrument, thereby greatly reducing the cost of the docking platform. Though possible benefit from a velocity sensor on AutoLARS is realized. As indicated in the work that it is difficult to compute the slope of trajectory of incoming AUV with respect to stationary reference frame. If AutoLARS position with respect to the deployment ship/vessel can be computed by using ultra short baseline system (USBL) or velocity sensor, the trajectory of AUV can be calculated more accurately. An autonomous launch and recovery attempt with this capabililty is worth exploring.

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