

# Relative localisation for AUV swarms

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**Abstract** – In most robotic swarming applications each individual needs to know the positions and orientations of at least its near neighbours. One way of achieving this local estimate underwater is by means of wide-bandwidth acoustic signals of specific statistical characteristics (maximum length sequence – MLS). The principal capability of local posture estimation has been demonstrated in [6, 7]. While previous results have been achieved off-line, e.g. have not been available to the vehicles while being in the swarm, this article reports about the first on-line evaluation test-runs.

## I. INTRODUCTION

The Serafina project [1, 2, 10] aims to have many small autonomous submersibles (55cm in length) in swarms. Given the high degree of manoeuvrability and agility of the individual vehicles as well as the provision to allow a large number of members [3] mean the spatial configuration of the swarm changes frequently.

The requirements of the relative localization system are to provide estimation of the relative angular bearing, relative pose and distance to near neighbours. This information needs to be updated at a reasonable rate with respect to the motion of the swarm. Given the nature of the application, constraints are imposed on available energy and space by the small size of the vehicle in addition to the need to produce a solution with a low cost implementation.

As discussed in [6, 7], a system for relative localisation for submersibles utilising wide-band acoustics have been developed incrementally. However, in the previous cases, all the processing and estimation was carried out off-line. This paper would discuss an on-line implementation of the localisation system with additional experimental procedures carried out to measure relative bearing, relative pose and range of neighboring submersibles as well as introduce a novel scheme of calculating the relative pose and range.

### A. Relative localisation

For swarming behaviour each submersible needs to know the positions and orientations of at least its near neighbours. Even for a large swarm with many members in a local neighbourhood, the measurements can be generalised to two members at a time – the observing member and the observed member.

The main quantities involved with relative localisation – bearing  $\theta$ , pose  $\alpha$  and range  $r$  are shown in figure 1. Considering the coordinate frames fixed to the robots, with re-

spect to the observing robot  $R_1$ ,  $\theta$  is the angular bearing of the neighbouring robot  $R_2$ . The range  $r$  is the distance between the origins of the coordinate frames of the observing ( $R_1$ ) and neighbouring robot ( $R_2$ ) while  $\alpha$  is the rotation of the coordinate frames attached to the neighbouring robots relative to the coordinate frame attached to the observing robot.

## II. TECHNICAL APPROACH

This section gives an overview of the employed technical setup and evaluation procedure.

### A. MLS signals

The system utilises wide-band acoustic pulses comprising of Maximum Length Sequence (MLS) signals as described in [7]. An MLS signal which is essentially a binary sequence, have a quasi-flat frequency spectrum up to the Nyquist frequency, similar to white noise but with the advantage of being deterministic, hence accurately reproducible.

Out of many candidate signal types considered for the acoustic localisation system, MLS signals [4] exhibited the best performance at producing a single sharp peak at zero in

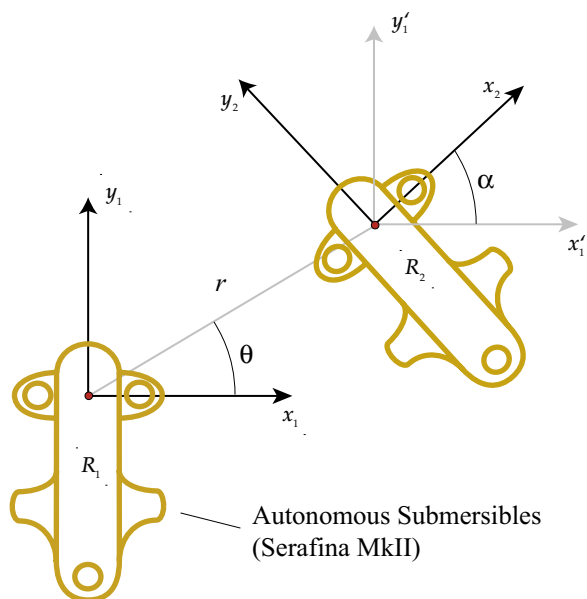


figure 1: Bearing, pose and range definition

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the auto-correlation graph in acoustically harsh underwater environments (with noise, fading, reflections, reverberations and multi-path propagation as described in [8, 9]).

With the use of different generating polynomials, MLS signal sets of different length can be generated. In general the degree  $n$  of the MLS signal gives the length  $l$  of the sequence as  $l = 2^{n+1} - 1$ . An MLS signals of degree 6 (length 127) was calculated using a computer program to be used in the localisation system.

### B. System overview

MLS pulses are sent out with projectors from two extremities of a Serafina vehicle. Each sending event generates four signals on the receiving side as each pulse (one sent from the front, the other from the rear) is received by two hydrophones. Cross-correlation of pairs of these signals provides the relative delays between the channels and these values are used in estimating the bearing, pose and range.

The deployment and capture methodology of the acoustic signals was significantly changed from the previous setups described in [6, 7] for the current online implementation. Instead of using a computer and sound card, for timing accuracy, a microcontroller is used to store and send out the precalculated MLS. One sending event comprises of the 127 bit sequence first being sent out from the projector at front of the submersible – wait for 20ms – send the same sequence from the projector at the rear of the submersible. The sending sampling rate of approximately 96kHz makes the duration of the 127 bit sequence 1.3 ms (figure 3). The binary sequence at TTL voltage levels (0V to 5V) is stepped up using a MOSFET driver (-12V to +12V) and centred around 0V. This is then fed in to a voltage step-up transformer which drives the AQ2000 hydrophones which also function as projectors.

The receiving side comprises of a AQ2000 hydrophone pair connected to a pre-amplified sampling device with a 96kHz 24bit ADC. The converted digital stream is fed to a computer via a firewire bus and provides the inputs for the online processing software of the localisation system. The current implementation of the online processing software written in ADA running on a Windows-XP system accesses the audio input stream via the DirectSound API.

At each sending event, the receiving side processes a block of 320 audio samples (approximately 3.3 ms) from the two hydrophone channels. The size of the receiving time window (considering the approximate speed of sound in water as  $1500 \text{ ms}^{-1}$ ) allows the 1.3 ms MLS signal to propagate up to 3m underwater. Varying this time window gives a means for extending or reducing the effective range of the acoustic localisation system when coupled with the voltage step-up of the sending stage. The beginning of the received block is aligned with the send start time.

The synchronisation between the sending and receiving events is done by triggering the sending event on the microcontroller via the serial port of the computer. This hard-wired synchronisation shown in the block diagram in figure

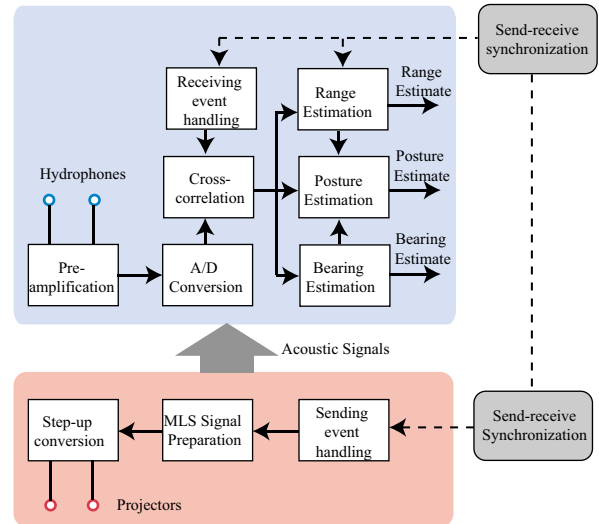


figure 2: Block diagram showing the functional components of the acoustic localization system.

2 would be replaced by the long-wave radio communication scheduling system [3] in the final implementation on the actual Serafina submersibles. In addition to synchronisation, in the case of multiple members in the local neighbourhood, this would also provide the acoustic localisation system with a locally collision-free schedule for sending such that, only one sending event takes place within a local neighbourhood, eliminating cross-talk.

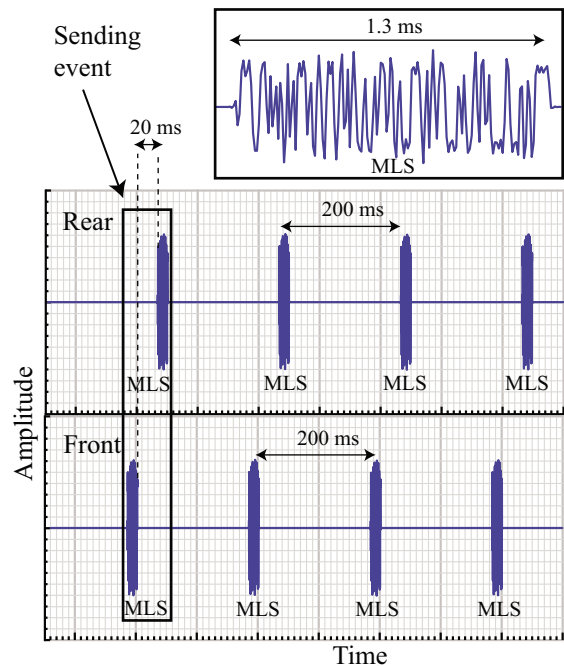


figure 3: Outgoing signals from the two projectors at the front and rear of the submersible depicting four sending events.

### III. ESTIMATION PROCEDURE

As mentioned in the previous section, a receiving event generates four signals (two stereo pairs). The two signals produced by the two hydrophone channels corresponding to the front projector sending would be denoted by  $S_{f1}$  and  $S_{f2}$  while the two signals produced by the two hydrophone channels corresponding to the rear projector sending would be denoted by  $S_{r1}$  and  $S_{r2}$ . The following subsections will describe how these signals are cross-correlated and processed to obtain the estimates for relative bearing, pose and range while figure 4 depicts these quantities geometrically.

#### A. Bearing Estimation

Cross-correlating the two signals  $S_{f1}$ ,  $S_{f2}$  and searching for the position of the peak in the correlation curve provides the relative shift  $\gamma_1$  (in sample points) between the two channels. A cubic spline interpolation with an interpolation step of 0.1 is used to obtain sub-sample resolution when searching for the peak. Similarly the signals  $S_{r1}$ ,  $S_{r2}$  are cross-correlated to obtain the relative shift  $\gamma_2$  (in sample points). These two values are converted to distances  $\delta_1$ ,  $\delta_2$  (in meters) respectively using the following general formula:

$$\delta_n = \frac{\gamma_n v_a}{f_s} \quad (1)$$

where  $f_s$  is the sampling frequency (96kHz in the current experiments) and  $v_a$  is the speed of sound in water (1475.5 ms<sup>-1</sup> as calculated by Mackenzie's [5] nine-term equation with parameters  $T = 18^\circ\text{C}$ ,  $D = 1.0\text{m}$  and  $S = 0.073\text{‰}$ ).

Then  $\delta_1$ ,  $\delta_2$  are used to calculate the bearing estimates  $\theta_1$ ,  $\theta_2$  (figure 4) for the front and rear of the submersible using the following formula:

$$\theta_n = \pm \text{atan}\left(\frac{\sqrt{d^2 - \delta_n^2}}{\delta_n}\right) \quad (2)$$

where  $d$  denotes the distance between receiving hydrophones (0.3m in this case). The  $\pm$  sign in (2) denotes the front/back ambiguity arising when using two omnidirectional receivers. This is avoided by the currently used directional hydrophones.

The main bearing estimate  $\theta$  is then given by:

$$\theta = \frac{\theta_1 + \theta_2}{2} \quad (3)$$

#### B. Range Estimation

As described in section B, the hard-wired synchronisation (which would be provided by the long wave radio communication scheduling system in the actual implementation) provides the actual send time of the acoustic signal. A wavefront detection procedure applied to signals  $S_{f1}$  and  $S_{f2}$  would give the average wavefront arrival delay  $t_{r1}$  for the front projector sending and similar processing of signals  $S_{r1}$  and  $S_{r2}$  gives  $t_{r2}$  for the rear projector sending. Considering the speed of sound in water  $v_a$  the distances to the two ends

of the sending vehicle  $r_1$  and  $r_2$  can be calculated using the following general formula:

$$r_n = t_{rn} v_a \quad (4)$$

The main range estimate  $r$  is given by:

$$r = \frac{r_1 + r_2}{2} \quad (5)$$

#### C. Pose Estimation

Considering figure 4, the pose  $\alpha$  of the sending submersible can be derived geometrically and can be expressed with the currently known quantities as follows:

$$\alpha = \theta_2 + \text{acos}\left(\frac{r_1}{l} \sin(\theta_1 - \theta_2)\right) \quad (6)$$

where  $l$  is the length of the submersible (or the separation between the two projectors  $p_1$ ,  $p_2$ )

#### D. Secondary method for estimating range and pose

An additional method for estimating  $r_1$  and  $\alpha$  can be obtained by geometrically analysing figure 4. For this, the acoustic path difference to the two projectors  $p_1$  and  $p_2$  from the origin, of the coordinate frame attached to the observing submersible, denoted by  $x$  needs to be known.

Figure 5 shows a geometrical decomposition of the problem of finding  $x$ . In this,  $x_1$  and  $x_2$  are the acoustic path differences to the two projectors  $p_1$  and  $p_2$  from the two receiving hydrophones  $h_1$  and  $h_2$  respectively. Cross-correlating the two signals  $S_{f1}$ ,  $S_{r1}$  and searching for the position of the

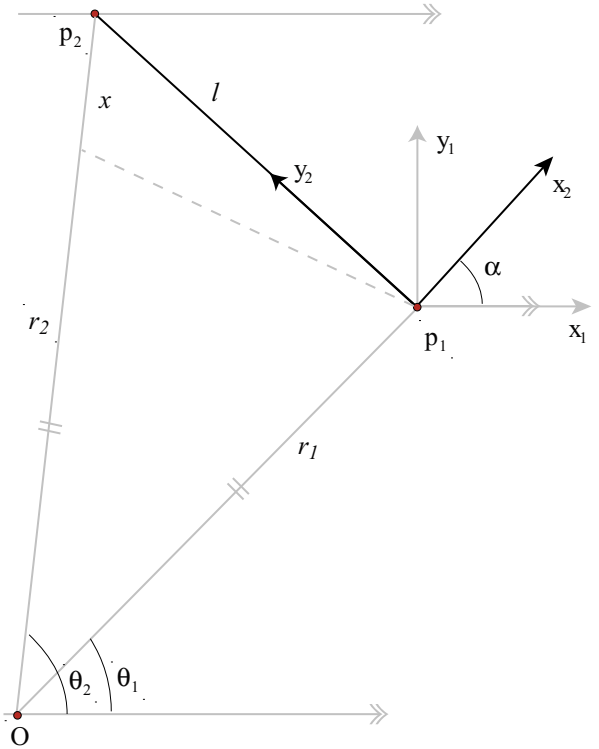


figure 4: Geometric description of the quantities  $\theta_1$ ,  $\theta_2$ ,  $r_1$ ,  $r_2$  and  $\alpha$ .  $l$  is the separation between the two projectors  $p_1$  and  $p_2$ . Also:  $t_2 = r_1 + x$ .

peak in the correlation curve and converting it in to a distance (as in section A) gives  $x_1$  while similar processing of the two signals  $S_{f_2}$ ,  $S_{r_2}$  gives  $x_2$  and  $x$  is given by:

$$x = \frac{x_1 + x_2}{2} \quad (7)$$

Now with  $x$  known the following formulae gives the new range estimates and pose estimate as follows:

$$r_1 = -\frac{l}{\sin(\theta_2 - \theta_1)} \cos\left(\frac{\theta_2 - \theta_1}{2} + \text{asin}\left(\frac{x}{l} \cos\left(\frac{|\theta_2 - \theta_1|}{2}\right)\right)\right) \quad (8)$$

$$r_2 = r_1 + x \quad (9)$$

Using  $r_1$  and  $r_2$ ,  $r$  can be obtained by (5).

$$\alpha = \frac{(\theta_2 + \theta_1)}{2} + \frac{\pi}{2} + \text{sgn}(\theta_2 - \theta_1) \cdot \text{asin}\left(\frac{x}{l} \cos\left(\frac{\theta_2 - \theta_1}{2}\right)\right) \quad (10)$$

#### IV. EXPERIMENTS AND RESULTS

##### A. Experimental Setup

The experimental setup consists of two Serafina mock hulls mounted with Benthos AQ2000 hydrophones. One, mounted with two hydrophones (functioning as projectors) at the front and rear end is used as the sending rig and has all the electronics (microcontroller, step-up converter, step-up transformer) and power supply in an attached waterproof casing. The other mounted with two hydrophones at the sides is used as the receiving rig. The projector spacing of

$l = 0.52\text{m}$  is used for the sending and hydrophone spacing of  $d = 0.3\text{m}$  is used for receiving. These dimensions were chosen according to the actual hull geometry of the Serafina Mark II submersibles.

Both the rigs are connected to 1.2m shafts and mounted on a gantry which is placed on top of the circular outdoor testing pool (diameter: 4.2m, depth: 1.5m, medium: freshwater). When mounted on the gantry, both the sending and receiving rigs are immersed 1.0m in water. As shown in figure 6, the receiving rig is kept stationary while the gantry arm with the sending rig is rotated (varying  $\theta$ ) about an axis going through the origin of the coordinate frame attached to the receiving submersible. Furthermore, the distance ( $r$ ) between the two rigs can be arbitrarily set and the sending rig can be mounted at an arbitrary orientation ( $\alpha_0$ ) with respect to the gantry arm. For a given experimental run  $r$  and  $\alpha_0$  were kept constant while  $\theta$  was varied by moving the gantry arm.

The hydrophones on the receiving rig are connected to the pre-amplified 96kHz sampling device which is connected to notebook computer running the online acoustic localisation software. This software triggers the sending (providing the hard-wired synchronisation) via the serial port which is connected through an RS232 serial link cable running to the waterproof case of the sending rig.

Additionally two compass modules, each with a PNI MicroMag3 3-axis magnetometer [11] are attached to the sending and receiving rigs to provide reference values for the bearing estimates. These too are connected to the notebook computer via the serial ports.

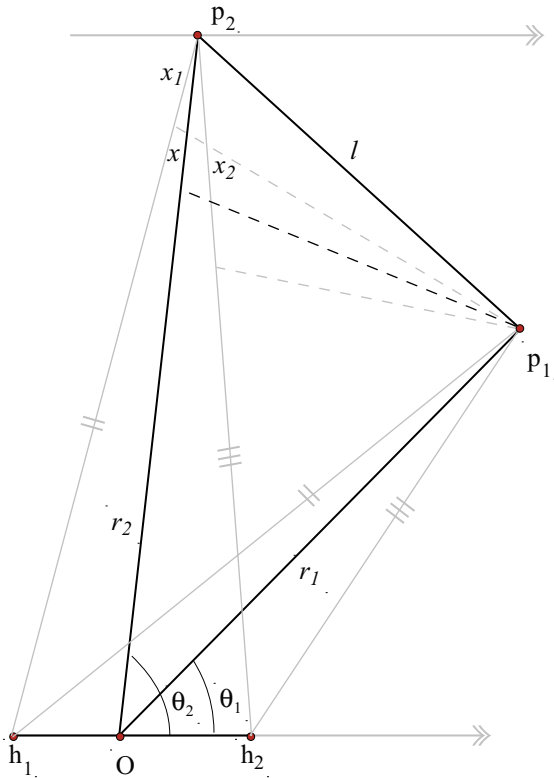


figure 5: Measurement of  $x$

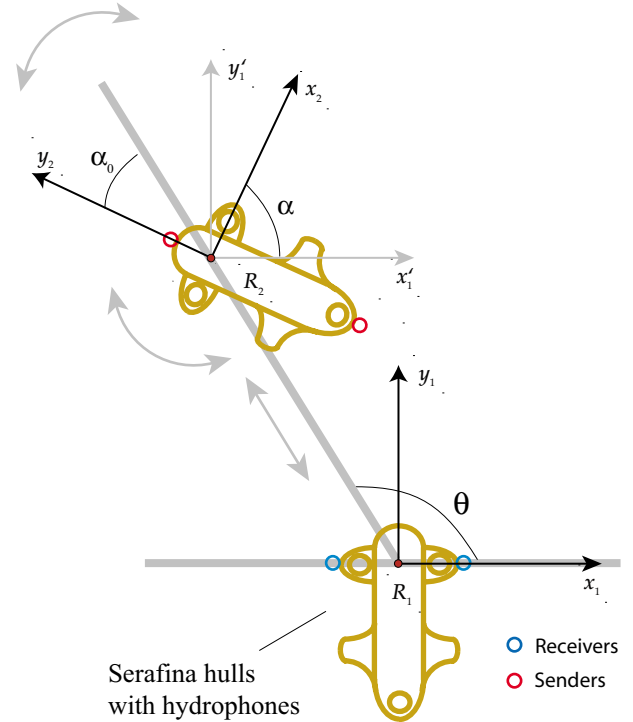


figure 6: Experimental setup

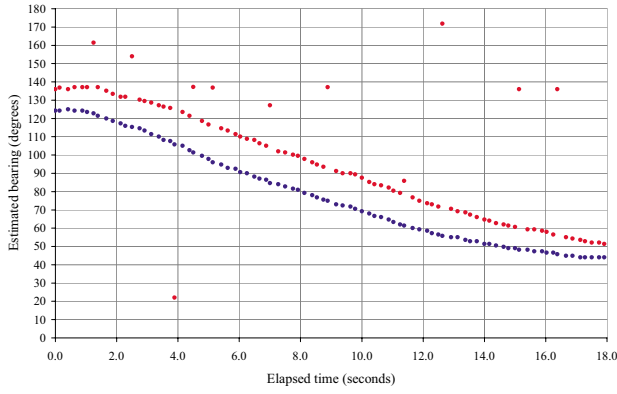


figure 7: Bearing estimates  $\theta_1$  (blue) and  $\theta_2$  (red) for a clockwise rotation of the gantry arm ( $\alpha_0 = 45^\circ$ ,  $r = 1$  m)

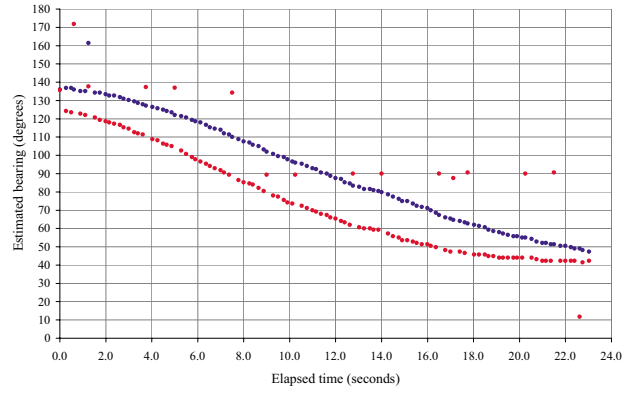


figure 9: Bearing estimates  $\theta_1$  (blue) and  $\theta_2$  (red) for a clockwise rotation of the gantry arm ( $\alpha_0 = -45^\circ$ ,  $r = 1$  m)

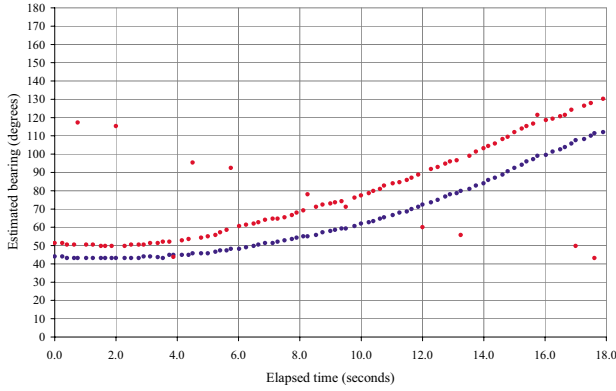


figure 8: Bearing estimates  $\theta_1$  (blue) and  $\theta_2$  (red) for an anti-clockwise rotation of the gantry arm ( $\alpha_0 = 45^\circ$ ,  $r = 1$  m)

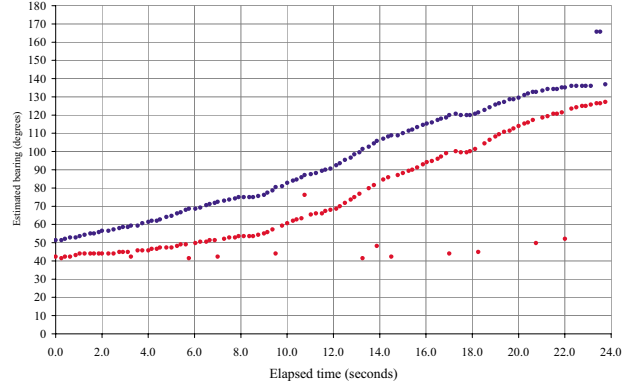


figure 11: Bearing estimates  $\theta_1$  (blue) and  $\theta_2$  (red) for an anti-clockwise rotation of the gantry arm ( $\alpha_0 = -45^\circ$ ,  $r = 1$  m)

### B. Experimental procedure

The experiment is carried out by manually moving the gantry arm, varying the value of  $\theta$  while the online localisation software is running on the notebook computer. Currently sending events are triggered at a rate of 5Hz and hence the update rate of the bearing, pose and range estimates is 5Hz. The estimated values are continuously displayed on the screen of the computer and also written to a disk file for later analysis.

At the start of each experimental run, a calibration phase is used to make sure the timing accuracy and synchronisation between the sending and receiving is achieved. This is achieved within the first 10 sending events (2s) and calculating the bearing estimates continue from there onwards.

Due to the size constraints of the testing pool, the actual motion of the gantry arm restricts the range of  $\theta$  to approximately  $15^\circ \rightarrow 165^\circ$ .

### C. Experimental Results

Figure 7 and 8 shows plots of two experimental runs with  $r = 1.0$  m and  $\alpha_0 = 45^\circ$  for clockwise and anti-clockwise rotation. The estimates for  $\theta_1$  and  $\theta_1$  are plotted against the time elapsed. Each of these experimental runs lasted for approximately 18s resulting in an angular velocity of  $8.3^\circ\text{s}^{-1}$ .

Figure 9 and 11 shows plots of two more experimental runs with  $r = 1.0$  m and  $\alpha_0 = -45^\circ$  for clockwise and anti-clockwise rotation. The estimates for  $\theta_1$  and  $\theta_1$  are plotted against the time elapsed. These runs were slightly slower than earlier lasting for approximately 24s resulting in an angular velocity of  $6.25^\circ\text{s}^{-1}$ .

Since the orientation of the sending rig with respect to the gantry arm ( $\alpha_0$ ) was fixed for each experimental run, the relative pose of the sending rig relative to the receiving rig varies with  $\theta$  as follows:

$$\alpha = \frac{\pi}{2} - (\alpha_0 + \theta) \quad (11)$$

## V. CONCLUSIONS

The implementation discussed in this paper represents an intermediate stage of the relative localisation system that is being developed for deployment in the Serafina MarkII submersibles. This is the first time an online implementation of the relative localisation software was tested. The results presented in the earlier section is from the preliminary experiments conducted with this new online setup.

Given the test environment in which the experiment was conducted is quite prone to acoustic reflections, the performance of the bearing estimation system is satisfactory. The raw results presented in the previous section included a number of outliers but these could be eliminated by introducing a simple tracking/filtering scheme. Considering the velocities at which the submersibles would be moving underwater, an update rate of 5Hz is sufficient. However, attempts would be made to find out the maximum possible update rate for the localisation system with regard to limited processing speeds.

In presented results the range of the bearing estimates is approximately  $40^\circ \rightarrow 140^\circ$ . This can be attributed to the directionality of the used hydrophones. For future experiments, more than one pair of receiving hydrophones would be used to cover a greater angular range. The developed online implementation of the relative localisation system has met the initial performance criteria of estimating the bearing of neighboring submersibles at an acceptable update rate. More experiments would be conducted to test the performance of the system against other criteria such as accuracy and resolution of the estimates in different underwater environments such as lakes and oceans. The next stage of development would also concentrate on miniaturising the receiving side and to port the online localisation system on to an embedded processor so that it can be readily deployed on the Serafina MarkII submersibles.

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