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Acoustical Localization in Schools of Submersibles

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Most forms of swarm coordination require frequently updated relative position and posture information about at least all near neighbours. The Serafina project [1][2] considers comparatively small submersibles (40cm in lengths) but in large numbers. This imposes constraints in terms of size and energy consumption of the components. It also requires high degrees of flexibility as the school configuration changes frequently and fast.

This article suggests a low-cost localization method which involves the communication system [3] and fuses information on the long-wave radio band with wide-band acoustic readings in order to generate range, bearing, and posture estimates of all surrounding submersibles, i.e. all submersibles in sensing range. MLS- (maximum lengths sequence) signals are employed for high interference robustness and deployability even in cluttered environments which usually impose multiple specular reflections and possible resonance effects.

A number of physical experiments are discussed which tests for precision, sensing range, interference robustness, and motion sensitivity. All those experiments refer to inter-school localization. Absolute localization (with respect to external, global landmarks) need only to be solved for one of the submersibles in the school (as all internal, relative locations are known) and is not discussed in this article.

1. Introduction

In robot swarming each individual needs to know the positions and orientations of at least its near neighbours. The Serafina project ([1], [2]) aims to have many small submersibles (about 40cm in length) in large schools. While the small size imposes constraints in terms of size and energy consumption of the components the swarming behavior require high degrees of flexibility as the spatial configuration changes frequently and fast.

The research is motivated by the need for a small, low-cost underwater localization, and posture estimation system for the Serafina submersibles. In swarm context, localization usually refers to relative localization and the proposed system estimates relative bearing and can be extended to estimate relative posture as well.

2. Bearing and Posture Estimation

Bearing Estimation

The proposed method uses wide-band acoustic signals which are transmitted from the small Serafina submersibles and received on up to six miniature hydrophones on each neighbouring submersible enabling estimation of bearing and posture as seen from those neighbouring Serafinas. The relative bearing of the sending submersible can be calculated by measuring the phase shift of the received signal channels. The phase shift δ is obtained by cross-correlating the received signal channels (figure 5) and detecting the peak in the correlation curve. The relative bearing estimate θ_e of the sound source is given by:

$$\theta_e = \pm\operatorname{atan}\left(\frac{\sqrt{(4r^2-\delta^2)(d^2-\delta^2)}}{\delta\sqrt{4r^2+d^2-\delta^2}}\right) \quad (1)$$

where d denotes the distance between receivers, r the radial distance to the source. When $r \gg d$ (for practical purposes $r \geq 2d$ satisfies this condition) the above equation can be approximated by the much simpler form below:

$$\theta_e = \pm\operatorname{atan}\left(\frac{\delta}{\sqrt{d^2-\delta^2}}\right) \quad (2)$$

The ± sign in (1) and (2) denotes the front/back ambiguity arising in a two (omnidirectional) receiver setup. This problem can be overcome using multiple

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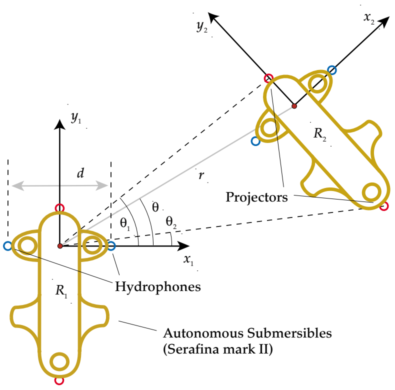

figure 1: Bearing and range definition

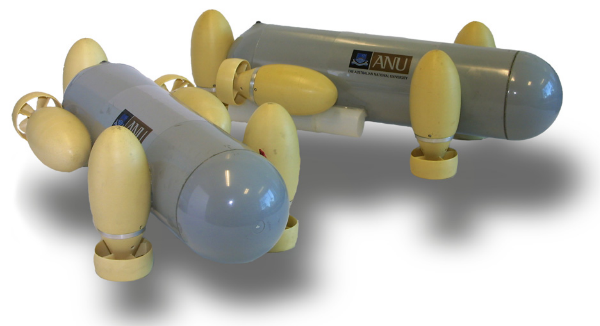

figure 2: Serafina –school of autonomous submersibles

receiver pairs, or (more biologically motivated) by employing directional hydrophones and tracking sound sources.

While cross-correlation of received signals will deliver the relative bearing, there is still no estimation of ranges. In fact, for very near neighbors (when $r < 2d$), according to (1) the range r is required in order to produce the bearing estimate. However, in most cases (2) is sufficient to obtain the bearing estimate.

Range Estimation: Fusing Long-Wave Radio with Acoustic Readings

One way of obtaining range information would be to go back to common methods of reflective measurements which would require significantly higher energies. If on the other hand the actual sending point in time (on a different submersible) could be detected by some other means then the simple difference between sending and receiving time gives a linear measurement of range. Fortunately this is supplied by other modules of the Serafina communication system which includes long-wave radio and optical communication channels. Synchronizing the acoustical with the optical and long-wave radio transducers results not only in a precise range measurement, but also reduces (or eliminates) cross-talk as the communication channels (while having similar broadcast ranges) are controlled by a locally collision free schedule. This is implemented by means of the dynamical distributed omnicast routing method as introduced in [3].

Posture Estimation

By consecutively sending MLS signals from the projectors at the bow and aft ends of the submersible and separately cross-correlating the received signal pairs to obtain the relevant phase differences will provide two bearing estimates for the two ends of the vehicle. Combining the range information with this gives the posture/orientation of the sending submersible. The main bearing measurement can be derived from of the two end bearing measurements using a simple weighted average depending on the actual positioning of the receivers on the submersible.

3. Cross-Correlation of MLS signals

Maximum Length Sequence (MLS) signals are employed to produce the wide band acoustic signals. It has high interference robustness and provides deployability even in cluttered environments which usually impose multiple specular reflections and possible resonance effects.

The theoretical characteristics of maximum length sequences (MLS) are well known and explored since the early 60's [4]. However the resulting characteristics of mixed multiple MLS signals underwater, transmitted with highly non-linear transducers in moving water with many specular reflections from the environment can still not be fully theoretically addressed.

MLS Signals of arbitrary degree can be generated using a computer program developed by us. The degree n of the MLS signal governs the length l of the sequence as $l = 2^{n+1} - 1$.

The length of the sequence and the employed sampling rate of the digital to analog converter determines the duration of the outgoing signal. Even though longer MLS signals give better resolution of the cross-correlation peak resulting in higher precision of the estimated bearing, the longer duration has its drawbacks. They are: undesirable echoes in cluttered or enclosed environments, higher processing overhead, smaller frequency of estimates (f_E).

As a compromise MLS signals of degree 6 (length 127) are employed which gives a choice of 18 different signal forms of which some show a specifically small maximal cross-correlation.

4. Experiments

Experimental Setup

Our current experimental setup employs two Benthos AQ2000 hydrophones as receivers and two Audiowell AU5550 piezoelectric transducers as the projectors.

Two Serafina hulls with acoustic transducers are mounted on a gantry with an arm that can be rotated (figure 3). The whole gantry is placed on top of our circular outdoor pool (diameter: 4.2 m, depth: 1.5 m, medium: freshwater) immersing the Serafina hulls 1 m underwater. This setup restricts the motion to one plane and therefore two receiving hydrophones separated by a distance $d = 0.36\,\mathrm{m}$ are sufficient.

With the hydrophones mounted on the Serafina hull on the centre, the transducers on the Serafina hull mounted on the gantry arm sends out a continuous acoustic pulse train while being rotated around the centre axis a_1. The pulse train consists of length 127 MLS signals and 30 kHz marker signals (figure 4). The signals arriving at the hydrophones are captured and recorded for off-line analysis. The digital-to-analog conversion for the outgoing signals and analog-to-digital conversion for the incoming signals are implemented on a synchronized 24-bit 96 kHz sampling device connected to a notebook computer. This sampling frequency gives a MLS signal duration of approximately 1.3 ms and a gap of about 102 ms between the MLS pulses and the marker signals is employed to ensure that all the reverberations off the pool walls have sufficient time to decay. Two consecutive MLS pulses have a gap of around 208 ms which translates to a maximum estimate sampling rate of $f_E = 4.8\,\mathrm{Hz}$.

A geared DC electric motor attached to the side wall of the pool is used to move the gantry arm with a constant angular velocity such that the transmitting Serafina makes a 160° arc around the stationary receiving Serafina. Using this setup, the radial distance

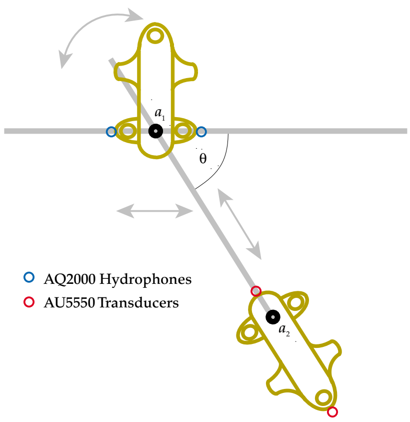

figure 3: Experimental setup

r (within constraints imposed by the size of the pool) between the sender and the receiver as well as the angular velocity ω at which the gantry is rotated can be varied.

As the gantry is rotated ($\theta : 10° \rightarrow 170°$) the induced phase shift δ at the receiving hydrophone pair is given by:

$$\delta = \sqrt{(r\sin\theta)^2 + \left(r\cos\theta + \frac{d}{2}\right)^2} - \sqrt{(r\sin\theta)^2 + \left(r\cos\theta - \frac{d}{2}\right)^2} \quad (3)$$

where d is the distance between the receiving hydrophones and r is the radial distance between the sender and the receiver. Equation (3) is the inverse function of (1).

The received signals were recorded and the 30 kHz marker signal was used to slice the pulse train in to segments containing only the MLS pulse. Each of the two channel MLS pulses were cross-correlated using the algorithm given in [6]. The phase shift between the channels is obtained by searching for the peak in the cross-correlation plot (figure 5). A cubic spline interpolation is used to interpolate peaks which lie in between sample points. By using an interpolation step of 0.1 samples the minimum achievable resolution could be improved close to 0.35° (for static measurements). In general the minimum achievable angular resolution (in the dynamical case – moving submersibles) R_{min} is given by:

$$R_{min} = \frac{\omega}{f_E} \quad (4)$$

The position x (in sample points) of the peak in the correlation plot is related to the actual phase shift δ (in metres) by:

$$\delta = \frac{xv}{f_S} \quad (5)$$

where f_S is the sampling frequency (96 kHz in our experiments) and v is the speed of sound in water ($1475.5\,\mathrm{ms}^{-1}$ as calculated by Mackenzie's [5] nine-term equation with parameters $T = 18°\mathrm{C}$, $D = 1.0\,\mathrm{m}$ and $S = 0.073\,‰$).

Experimental Results

A number of experiments with different r values and different angular velocities were conducted.

For comparison, results obtained in two different experimental runs are included. Figure 7.b shows the phase shift x vs. samples and figure 7.a bearing estimate vs. samples for $r = 1.4\,\mathrm{m}$, $\omega = 3.2°\mathrm{s}^{-1}$ which gives $R_{min} = 0.67°$.

Figure 8 shows the same measurements for $r = 1.0\,\mathrm{m}$, $\omega = 6.0°\mathrm{s}^{-1}$ which gives $R_{min} = 1.25°$.

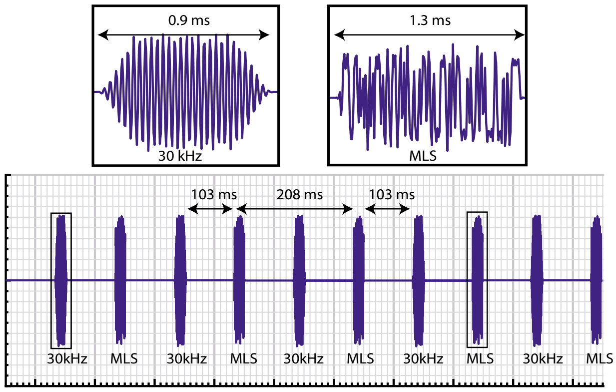

figure 4: Employed outgoing pulse train structure

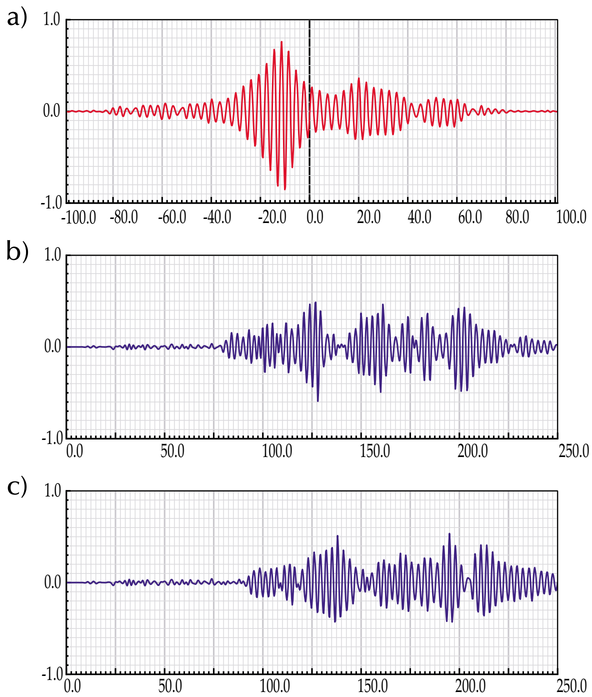

figure 5: b) and c) represent the received MLS signals normalized amplitudes over the samples; a) shows the MLS cross-correlation result over the sample-shift, corresponding to bearing $\theta = 120°$ (actual bearing estimation $\theta_e = 119.6°$ in this measurement; and in general $|\theta - \theta_e| < 8°$).

Analysis of Results

The non-linearity of the sending and receiving transducers seem to have a detrimental effect on original MLS signals introducing a high pass filtering with $f_C \approx 32\,\text{kHz}$ (figure 6). However, still the cross-correlation of the received signals provides the bearing information with lowered precision. The introduced frequency filtering results in an uncertainty of x (δx) of approximately ± 3 samples. By consider the uncertainties for all quantities involved (substituting (3) in (1)); $\delta d = \pm 0.01\,\text{m}$, $\delta r = \pm 0.01\,\text{m}$, $\delta v = \pm 10\,\text{ms}^{-1}$, $\delta f_S = \pm 0.0\,\text{Hz}$ the following error formula for the estimated bearing is obtained:

$$\delta\theta_e = \pm\sqrt{\frac{c_1 + c_2 x^2}{c_3 - c_4 x^2}} \times \frac{0.18°}{\pi} \qquad (6)$$

with

$$c_1 = 6.643982700 \times 10^{13}$$
$$c_2 = 6.035228494 \times 10^{9}$$
$$c_3 = 4.050000000 \times 10^{9}$$
$$c_4 = 7.382203000 \times 10^{6} \qquad (7)$$

This translates to a maximum nominal error bound of $\pm 8°$ for $60° \le \theta_e \le 120°$. In figure 7.b and figure 8.b the solid red curve depicts the ideal variation of x as θ is varied. In figure 7.a and figure 8.a the dashed blue line depicts the ideal variation of θ_e while the two dashed red curves denote the maximum error bound corresponding to $\theta_e \pm \delta\theta_e$. As can be observed from these plots, the resulting bearing estimates lie well within the error bounds for most of the range. The deviations at the two extremes of the range can be explained as follows; The hydrophones used in this experiment are directional with an approximate forward opening angle of $100°$ within the operating range. When the sending projectors reach the sensitivity boundary of the receiving hydrophones, the probability of one or both of them detecting a signal bounced off the pool wall instead of the direct signal increases.

5. Conclusions

From the obtained results we conclude that this approach can be successfully implemented to measure relative bearing and posture of underwater vehicles – even with highly non-linear projectors and hydrophones. While it seems obvious that the achieved resolution and precision can be improved by the employment of more wideband, omni-directional transducers, and higher sampling rates, it is already sufficient for the problem at hand: relative spatial es-

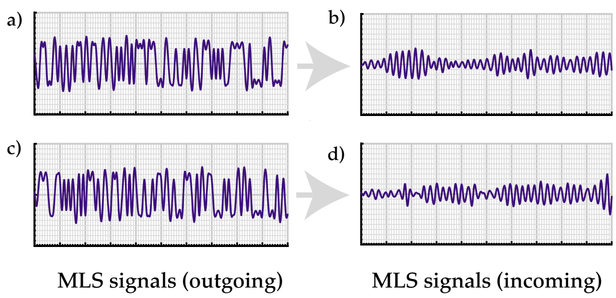

figure 6: Actual MLS signal sent out and the corresponding signals received by the hydrophones

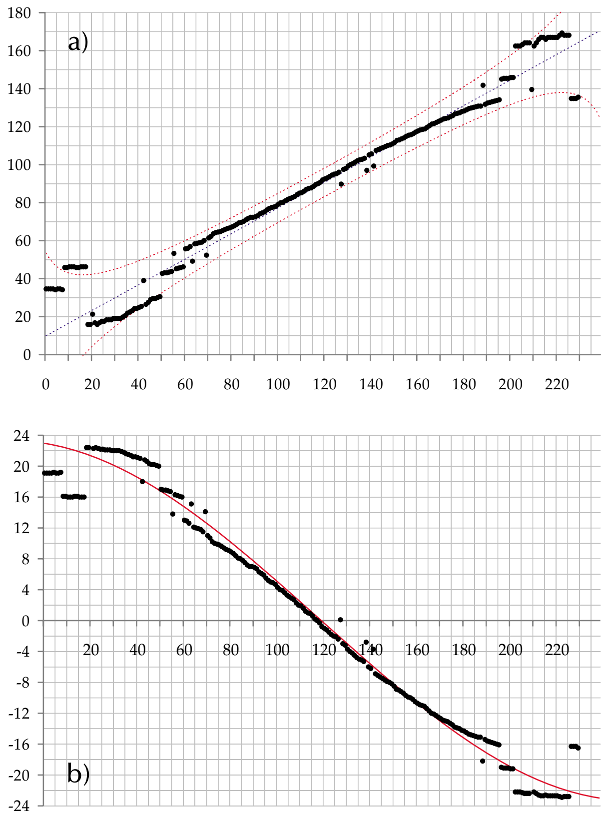

figure 7: $r = 1.4\,\mathrm{m}$; a) estimated bearings with error margin; b) measured phase shift x over samples set

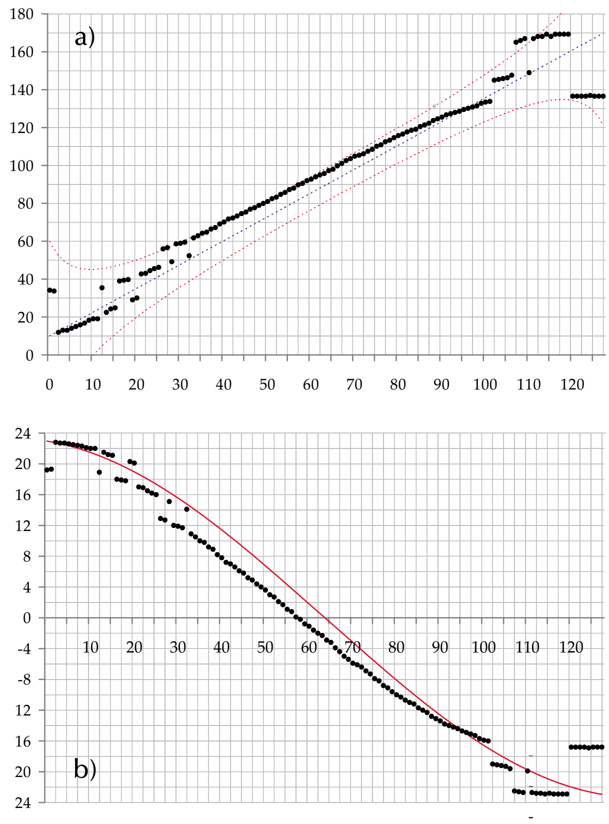

figure 8: $r = 1.0\,\mathrm{m}$; a) estimated bearings with error margin; b) measured phase shift x over samples set

timations in dynamical schools of submersibles. However the extension to three dimensional measurements, i.e. the utilization of more than two microphones still needs to be done.

Other experiments and extensions which will be implemented in close future include: Measurement of the ratio of employed energy to achievable minimum error and maximal range with respect to bearing as well as the control of a bounded range for the acoustical based estimations. A bounded range is in fact essential for scaling up to larger schools of vehicles as otherwise multiple measurements in the same school could not take place without interference.

The Serafina project will incorporate the results presented here and integrate these estimates into the existing and further developed control and communication concepts. Specifically the close integration between communication and position estimation layers into more spatially oriented forms of communication will be essential for future large submersible school applications.

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