A Flexible Navigation Support System for a Team of Underwater Robots

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***Abstract*— The primary and somewhat interrelated challenges affecting deployment of Autonomous Underwater Vehicles (AUVs) are navigation and communication. We have developed miniature, agile, easy to carry and deploy AUVs equipped with a suite of sensors for underwater environmental sensing. In this paper, we propose a support system for multiple AUVs where a group of Autonomous Surface Vehicles (ASVs) coordinate to provide external positioning reference. They transmit an acoustic ranging pulse and then broadcast their position using acoustic communication. Communication errors are detected by using a novel approach where data decoding is coupled with navigation. Our system achieves scalability in the number of AUVs by using one-way travel time for ranging and making the AUVs passive receivers. Further, it allows the ASVs to be repositioned during a mission, so that they can provide positioning aid from a closer range. This is an advantage especially in shallow water environments, where range measurement errors increase significantly with increasing distance. We describe our system in detail and evaluate it with simulations based on real data as well as field experiments.**

I. Introduction

Application of robots to sensing tasks scales better than static sensing nodes in terms of spatial coverage [1]. Additionally, robots can specifically target regions of higher interest for gathering data [2], [3], [1], as well as execute maneuvers for identifying and tracking specific patterns [4]. However, underwater environments pose a number of challenges for robotic sensing applications, which primarily stem from high attenuation of electromagnetic waves in water. Radio communication does not work beyond extremely short distances and satellite-based positioning is unavailable in water. Employing acoustic signals is a common approach for both navigation and communication in underwater environments [5]. An accurate on-board position estimation is necessary to follow a pre-planned trajectory during sensing missions and to provide a geo-reference for the data collected. Communication is essential for coordination as well as for command and control of robots.

We are developing methods for cooperative sensing in lakes with the Vertex Autonomous Underwater Vehicle (AUV) [6] (see Fig. 1). We previously developed an acoustic navigation system where a number of static acoustic beacons deployed on the surface provided regular ranging pulse according to a fixed schedule [7]. Multiple range measurements were then combined to estimate the AUV position. A drawback of our system was that it required the beacons to be static, and its positions to be communicated to the AUV prior to launch.

Fig. 1: The Vertex AUV with its sensor suite in the front, protected by a white cage. The AUV is about 70 cm long, weighs 7 kg, and can be carried and deployed easily by one person.

In this paper, we present a flexible navigation support system consisting of a group of Autonomous Surface Vehicles (ASVs), each equipped with an acoustic beacon. We combine acoustic ranging with acoustic communication so that the beacons can transmit their own position along with a ranging pulse. This relaxes the need for the beacons to be static. Further, the ASV positions can now be reconfigured while the AUV is performing a sensing mission. By following the AUV trajectory but without having to maintain any controlled formation, the ASVs can provide positioning aid from a closer range during long missions. This is an advantage especially in shallow water environments, because reflections and multi-path effects result in frequent outlier range measurements.

A central component of our system is encoding beacon positions in an acoustic signal. However, underwater acoustic communication is a difficult problem due to unique channel characteristics. Local phenomena such as turbulence and temperature gradients cause strong amplitude and phase fluctuations. In addition, the received signal is also contaminated by time-varying interference between several reflected propagation paths [8]. Such effects usually increase with distance and cause interference between consecutive data packets [9]. The use of multiple carrier frequencies provides significant improvement in bandwidth and offers robustness against frequency-selective channel effects. However, this approach is susceptible to Doppler shifts on moving devices, which need to be estimated and compensated, increasing receiver complexity [10]. In our system, we use multiple carriers to enhance bandwidth, but have a conservative spacing between the carrier frequencies to minimize Doppler distortion. In

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This work was funded by the Swiss National Science Foundation under grant CRSII2_160726/1. https://disal.epfl.ch/research/auvdistributedsensing.

effect, we trade off bandwidth for decoder simplicity.

A number of existing techniques for AUV navigation use acoustic signals in various ways for external position reference. They either rely on range computed from time of flight of acoustic signal, or relative orientation estimated from difference in time of arrival at a multi-receiver array [5]. An approach based on round-trip travel time for ranging combined with a Kalman filter for fusion was presented in [11]. This requires the AUVs to transmit a pulse, which is not scalable for multi-AUV operations. Synchronized clocks eliminate the need for two-way signal exchange for ranging [12], [13]. Recently, Munafò et al. in [14] used acoustic communication for exchanging local timing information between static acoustic beacons and AUVs. Their work relaxes the need for synchronized clocks, which are difficult to implement when permanently installing static beacons below the surface. Other AUV navigation techniques that do not rely on acoustic beacon systems do exist. They combine environmental information (for e.g, ocean currents) with a Doppler Velocity Log (DVL) [15] or an Acoustic Doppler Current Profiler (ADCP) [16].

For our work, we use miniature AUVs and operate in various small inland lakes, where installing static beacons is either not feasible or not allowed. Regardless, installing static acoustic beacons limits the operational area of the AUVs, or requires a large number of beacons for higher coverage. Further, the small size of the AUV (0.7 m in length) makes it incompatible with off-the-shelf hardware such as SONAR and DVL for navigation or with commercially available acoustic modems. Therefore, we rely on MEMS-based inertial measurement modules, and we have developed small-sized acoustic transceivers for ranging and communication.

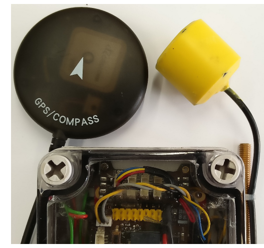
The proposed system does not need any installed infrastructure or precise timing hardware, can be easily deployed in any new environment and is scalable in the number of AUVs. In particular, our contributions are (1) implementing Frequency-Division Multiplexing (FDM) to encode beacon positions as acoustic signals, (2) using current position estimate of the AUV and range measurements to detect communication errors, and (3) combining ranging and communication on acoustic beacons to form a mobile support network for AUV operations. We demonstrate our method with a combination of real field trials as well as simulations that augment data from real experiments.

We begin by introducing the various components of the system in Section II. In Section III, we provide a walk through of the various steps towards development of the acoustic navigation system. Section IV presents the results gathered during experiments. Finally, we discuss the planned enhancements to the system and conclude the paper in Section V.

II. Relevant System Components

In this section, we briefly describe the components of the whole system as well as subsystems on each AUV that are central to this work. For completeness, we also briefly recap relevant components from our previous work in [7].

(a) AUV acoustic transceiver



(b) Surface beacon

Fig. 2: Acoustic transceivers used on surface and on the AUV. Both versions have identical hardware but are packaged differently for ASVs and AUVs.

A. On-board navigation

The navigation is performed in a local-level NED frame (axes aligned along North-East-Down directions) with the origin fixed at the launch point. An Extended Kalman Filter (EKF) framework is employed for navigation, which fuses inertial measurements with a comprehensive model of the dynamics of the AUV. It is complemented by a depth sensor, effectively reducing navigation to a 2D problem. A Global Navigation Satellite System (GNSS) receiver provides a position fix whenever the AUVs are on the surface. Range measurements from the acoustic subsystem are fused into the position estimate within the Kalman filter framework, as illustrated earlier in [7].

B. Acoustic transceivers

Each robot is equipped with an acoustic transceiver, which consists of two piezoelectric transducers, one for transmitting acoustic signals and the other for receiving them. These are respectively connected to the digital-to-analog output and analog-to-digital input of a microcontroller with appropriate amplification stages. The output transducer has a bandwidth of about 10 kHz in the 44 kHz range, which allows encoding of different signals for ranging and data transmission. For acquiring the received signal data, the microcontroller continuously samples the ADC input at a frequency of 160 kHz. It is equipped with a hardware Digital Signal Processing (DSP) unit for signal processing. On detecting a ranging pulse, it stores the raw signal and records a time stamp. In this paper, the acoustic transceivers on the surface vehicles act exclusively as transmitters, and those on the AUVs are configured to be receivers. The surface beacons are also equipped with a GNSS receiver for positioning and a radio module for communicating with the base station.

C. Synchronized clocks and one-way travel time

Our system relies on synchronized clocks for one-way travel time based ranging and for scheduling transmissions from multiple beacons. We use timing information from the GNSS receiver module to synchronize clocks across robots. First, we use the timing Pulse emitted Per Second (PPS) by the Ublox M8N GNSS receiver module, which has an accuracy of the order of 10 ns, to tune the speed of the clock and eliminate the clock drift. Second, we use the absolute time information received from the GNSS module to set the wall-clock time. For AUVs, this synchronization

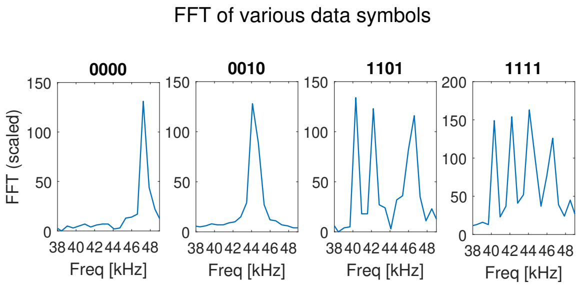


Fig. 3: FFT of various signals that encode different binary numbers. Each bit is represented by presence of a different frequency. When all bits are zero, a fifth frequency is added to the symbol instead of transmitting a silent signal. The symbols here represent the numbers 0 (binary 0000), 2 (binary 0010), 13 (1101) and 15(1111).

is done while they are on the surface, and a temperature compensated crystal oscillator with higher accuracy, and a rated clock drift of 0.3 ppm is used when underwater. This translates to a range measurement error of less than 1 m over 1 hour, which is insignificant compared to accumulated error with navigation based exclusively on dead reckoning. The PPS signal is also connected to an interrupt pin on the transmitters to trigger transmission of the ranging pulse. The receivers then simply need to measure the time between the previous full second and the signal arrival time to obtain time-of-flight and compute range.

D. Data modulator and demodulator

We employ the Orthogonal Frequency-Division Multiplexing (OFDM) approach for modulating data into an acoustic signal. We divide a data packet into individual symbols, where each symbol is an acoustic pulse of a duration of 1.5 ms. Each symbol is a sum of sinusoids of up to four carrier frequencies and encodes four bits, as shown in Fig. 3. A presence of a frequency indicates that the corresponding bit is 1, and an absence denotes 0. Therefore, the signal encoding the bits $[b_0, b_1, b_2, b_3]$ is mathematically represented as

$$s(t) = \sum_{n=0}^{3} b_n A sin(2\pi f_n t), \tag{1}$$

where f_n is the nth carrier frequency, and A is the amplitude of the signal. We use four carrier frequencies in the range 40-46 kHz, spaced by 2 kHz. When all bits are zero, the signal $s(t)$ is replaced by a single frequency sinusoid of 47 kHz, in order to avoid having a 'silent' symbol. With four carrier frequencies, we have sixteen unique symbols (representing numbers from 0-15). These sixteen symbols are precomputed and stored for efficient transmission.

In addition to offering robustness against frequency dependent channel distortions [10], this OFDM approach has the additional advantage of simple demodulator implementation. On the receiver side, demodulation is carried out by computing a Fast Fourier Transform (FFT) of the received signal, which is efficient to do using the hardware DSP unit of the microcontroller. The values of individual bits are then deduced by identifying the frequency components that are present in the FFT.

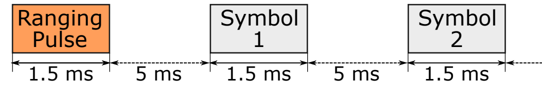


Fig. 4: The chain of individual signals (ranging pulse and data symbols) transmitted by each beacon. Each signal is 1.5 ms in duration and is followed by a pause of 5 ms before the next signal is transmitted. The transmission is triggered by the PPS signal from the GNSS receiver.

III. Methodology

External position reference for AUVs is provided by acoustic signals broadcast by beacons deployed on the surface. The AUVs receive and process these signals to obtain beacon positions and range, which are used to perform a position update.

A. Ranging pulse and beacon position broadcast

To avoid interference, surface beacons take turns and transmit in their designated transmission slots, according to a fixed schedule based on GNSS time information. During their slot, transmission is triggered by the PPS signal from the GNSS receiver. First, a ranging pulse is transmitted which is used for time-of-flight based range computation, followed by the data packet consisting of a series of symbols. In the time domain, the ranging pulse and a single symbol have a duration of 1.5 ms. Individual signals (ranging pulse or a single symbol) are separated by 5 ms. These parameters were chosen to be conservative, and can be lowered if needed. The transmission scheme is illustrated in Fig. 4.

Since all transmitters are deployed at the surface, we only encode two dimensions of the position. Further, working in a local level frame with origin at the launch point allows us to represent position in meters with smaller numbers, and hence encode them with smaller number of bits. We round the coordinates to the nearest integer and encode them as a signed 8-bit integer, Although this appears to limit the positions (and hence, the operational area) from -127 to $+127$ m in each dimension, the number of bits can be scaled up easily by using additional carriers per symbol or additional symbols. A total of 32 data bits are transmitted, which include 16 bits of position information and an additional 16 bits to mitigate bit errors as explained in the next Section (III-B).

The receivers constantly look for a ranging signal, and on detecting it, record the time stamp, deduce time-of-flight and compute the range. Next, the data reception routine is triggered which acquires the individual symbols in the data packet based on the known time intervals shown in Fig. 4. The demodulator then uses the series of individual symbols to produce a bit stream.

B. Mitigating bit errors

Given that the underwater acoustic channel is highly susceptible to communication errors, measures to detect and correct them are necessary. We attempted two separate approaches to do so. First, we implemented Hamming (8,4) error correcting code [17], which encodes 4 bits of data into a packet of 8 bits by adding 4 parity bits. It can detect up to two bit errors or correct a single bit error. Second, we

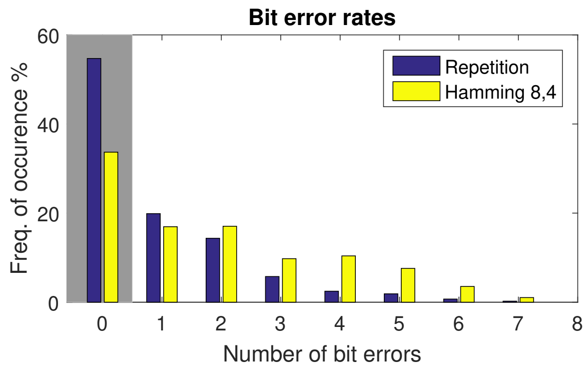


Fig. 5: Bit error rate with two approaches of encoding, Hamming 8,4 error correction code and a one-time repetition. One-time repetition performs significantly better, as shown by the occurrence of zero bit errors (shaded region) in both approaches.

implemented a repetition based-method, where each data bit is transmitted twice. The repetition is done in such a way that two different frequency carriers are used to represent the same data bit. Error detection is done by checking if a decoded bit and its repetition are in agreement. This approach performed better than the Hamming approach because of the characteristics of the channel and the transducer. A comparison of bit error rates is shown in Fig. 5.

The Hamming approach works well with symmetric binary errors, i.e, bits 1 and 0 are equally likely to be misrepresented. This is not true for the OFDM approach used in this paper, where it is unlikely that a bit 0 will be corrupted into bit 1 (which essentially translates to a frequency component being detected when it is not present at all), while the opposite is more likely.

C. Rejecting range outliers and erroneous beacon positions

Echoes and reflected signal arrivals result in outlier range measurements. These errors are exacerbated especially when operating in shallow water bodies or close to the shore, as is the case for the experiments presented in this paper. We perform outlier rejection using the kinematic model of the AUV and the surface beacons, combined with the past range measurements. Specifically, given that the velocities of the AUV and the beacons are bounded, inconsistent range measurements with a large error can easily be identified as outliers and rejected. However, occasional outliers with small errors may be difficult or even impossible to eliminate.

Despite measures for mitigating bit errors in acoustic communication, these errors are unavoidable. These errors corrupt the beacon positions obtained through acoustic communication and result in inconsistent navigation updates. However, since beacon positions are subject to kinematic constraints relative to the AUV, some erroneous positions can be filtered and rejected. We use the corresponding range measurement and the estimated position to the AUV to check the consistency of the received beacon positions. Fig. 6 shows a comparison of true beacon positions, raw decoded positions and the set of accepted positions after filtering routine. About 24 % of the positions are rejected and the impact of communication errors on the navigation solution is reduced.

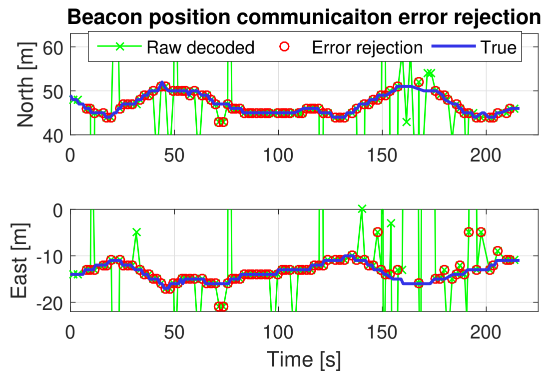


Fig. 6: True beacon positions (obtained via radio communication) are shown along with raw decoded positions obtained via acoustic communication and the result of applying error detection based on kinematic constraints. Rejecting erroneous beacon positions improves overall quality of navigation by minimizing inconsistent range updates.

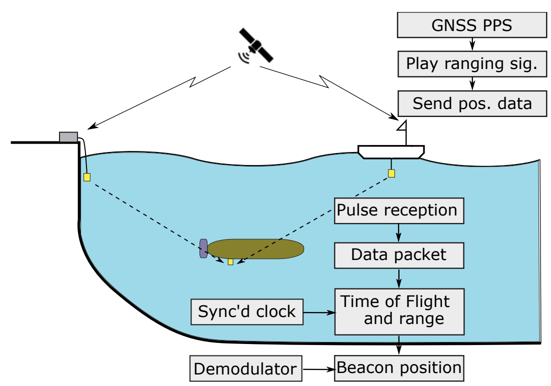


Fig. 7: One beacon is deployed from the shore and another is mounted on an ASV. Both beacons transmit an acoustic signal according to a fixed schedule. The acoustic signal comprises of a ranging pulse followed by a data packet that encodes their position. With synchronized clocks, the AUVs can measure one-way travel time of the ranging pulse and compute range. It then decodes the data packet to obtain the beacon position and perform a position update.

D. Experimental setup

We deployed one beacon mounted on an ASV and another from the shore as shown schematically in Fig. 7. The shore-deployed beacon was used for logistical simplicity, and can also be deployed from an additional ASV. While the shore-deployed beacon was stationary, this information was not used for navigation. It was treated like a moving beacon and its position was obtained via acoustic communication. The sequence of events from ranging pulse transmission to reception are also shown in Fig. 7.

We used a second ASV with an acoustic receiver as a surrogate for the AUV. This ASV is also equipped with similar hardware as the AUV, but has constant GNSS reception and radio availability. Beacon positions received over the radio and GNSS positions are used as ground truth.

In order to analyze the efficacy of our method, we first performed a number of experiments and recorded the navigation output as well as all sensor and communication data. Then, we performed additional simulation experiments by augmenting data from real experiments and recomputing the navigation solution offline for comparison. In particular,

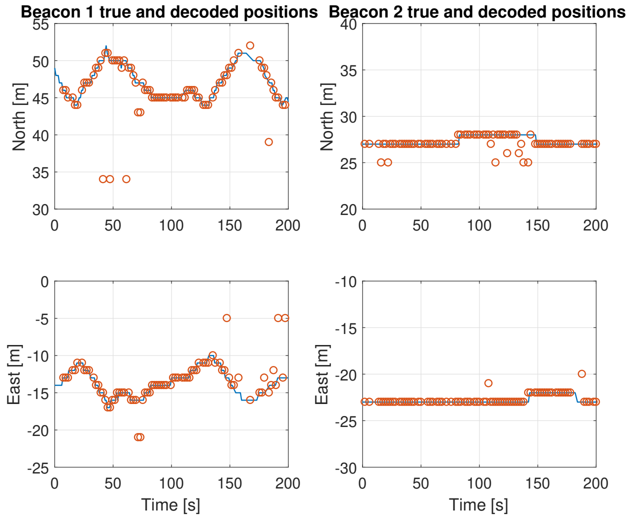


Fig. 8: Beacon positions as decoded by the receiving ASV (red circles) compared with true positions of the beacons (blue lines). While some errors in decoded positions are incorrectly accepted by the filter, the beacon positions are largely accurately tracked.

we replaced the beacon positions obtained via acoustic communication with true beacon positions. This was done to provide the baseline performance for navigation. We present results from simulations as well as experiments gradually increasing in complexity and compare the accuracy of the estimated trajectory.

IV. Experiments and Results

Experiments were performed at a boat pier in a shallow region of Lake Geneva. The water depth in the experimental area was between 1-4 m, and experiments were performed in low to medium wind conditions (< 10 m/s). The shallow water depth exacerbates the challenges of acoustic ranging and communication to a small but significant extent.

A. Tracking beacon positions

We deployed a transmitting beacon mounted on an ASV that was mobile, while keeping the receiving ASV stationary (but not actively holding position). The transmitting ASV obtained its position from the GNSS receiver, transformed it to the local-level NED frame and sent its position via radio as well as acoustic communication. The receiving ASV received the acoustic signal and stored the decoded position information. It also performed rejection and filtering of erroneous positions as explained in Section III-C. Fig. 8 compares the true beacon positions and those obtained by the receiving ASV over acoustic communication. The receiving ASV is able to accurately deduce the position of the beacon.

B. Acoustic navigation

We present results of acoustic navigation from three different experiments with increasing complexity. In all experiments, one beacon was deployed from the shore and was stationary, but it was treated like a moving beacon for the purpose of navigation. The other beacon was mounted on an ASV deployed off-shore. Another ASV with an acoustic

Method / Baseline	Trajectory RMS error [m]
Inertial (Fig. 9a and 9b)	3.55
Floating beacon, radio communication (Fig. 9a)	1.17
Floating beacon, acoustic communication (Fig. 9b)	1.21
Inertial (Fig. 9c)	3.52
One actively moving beacon, acoustic communication (Fig. 9c)	1.66

TABLE I: RMS error over the trajectory for purely inertial trajectory and trajectories estimated with acoustic navigation aid.

receiver (used as a surrogate for an AUV) used the acoustic broadcasts from the two beacons for navigation.

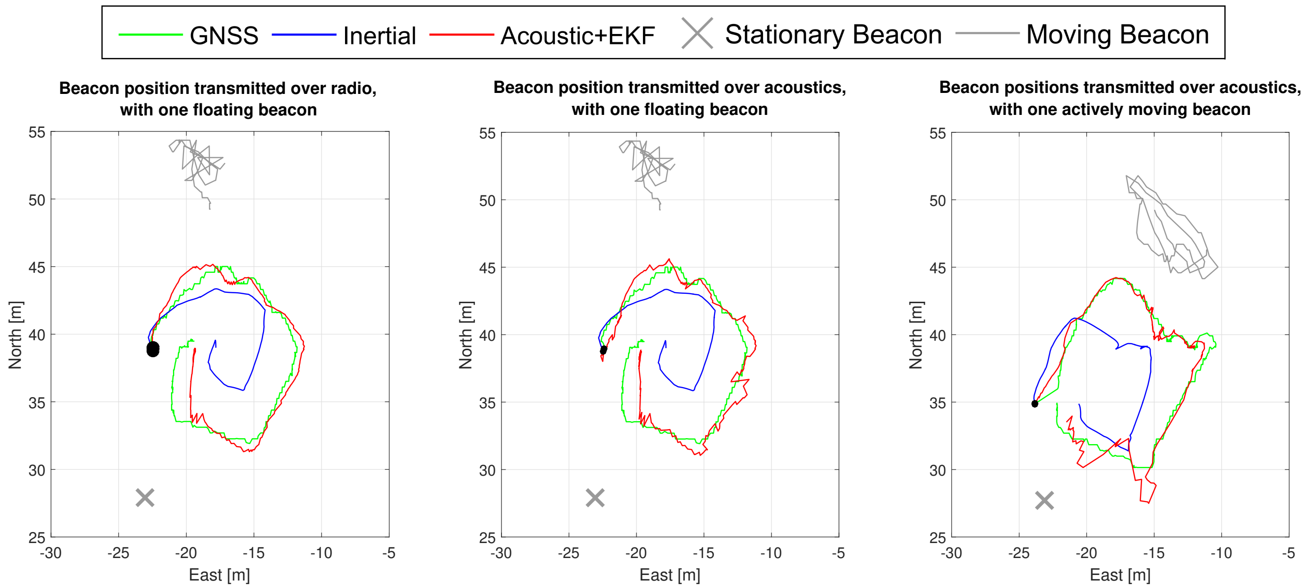
To begin with, the beacon ASV was not programmed to move, but was also not actively holding position either. To demonstrate the effect of error-prone acoustic communication on the navigation solution, we first performed navigation by simulating true beacon positions. The estimated trajectory from this simulation experiment is shown in Fig. 9a. To perform this simulation, we used the data from the real experiment described below (also in Fig. 9b), and augmented with true beacon positions that were recorded during that experiment. The navigation trajectory was then recomputed offline. The estimated trajectory from the corresponding real experiment is shown in Fig. 9b. In this case, the beacon ASV was not programmed to move, and the positions of both beacons were sent over acoustic communication.

Finally, the beacon ASV was programmed to travel back and forth between two waypoints. This was done to study the accuracy of the navigation solution when the beacons move. The estimated trajectory from this experiment is shown in Fig. 9c. As expected, the estimated trajectory in this case has the highest RMS error (see Table I).

V. Conclusion and Outlook

We have presented a multi-ASV system to provide positioning aid for underwater environmental sampling missions with AUVs in lakes and coastal areas. An external position reference is necessary to bound the error in inertial position estimates, which grows over time. Our system consists of acoustic beacons mounted on ASVs which are easy to deploy and facilitate quick measurement missions, even in new environments. We used a novel approach for detecting acoustic communication errors by coupling data decoding and navigation. We demonstrated our system with experiments in a shallow region of Lake Geneva, which is a challenging environment for acoustic ranging and communication.

Our system is scalable in the number of AUVs since the AUVs are passive receivers of information and ranging pulse from the beacons. This implies that there is no periodic communication from the AUV to the surface, since that would break scalability. We envision implementation of a crisis command that would allow a subset of the AUVs to transmit an emergency signal to the surface. Additionally, our usual sensing missions typically involve periodic surfacing of the AUV [4], where the AUV can transmit data and their



(a) (b) (c)

Fig. 9: Trajectories estimated by EKF by fusing inertial estimates with acoustic range measurements and beacon positions. Plot (a) shows a simulation experiment where one beacon is stationary and the other is mounted on a passively floating ASV. Beacon positions were transmitted over radio. Plot (b) shows a real experiment which has the same setup as (a) but beacon positions are transmitted via acoustic communication. Real trajectory data from this mission is used to perform the simulation in (a). Plot (c) shows a real experiment where one of the beacons is stationary as before while the other is actively moving between two waypoints, and beacon positions are transmitted over acoustic communication. Ground truth trajectory obtained from GNSS is shown in all the three plots.

position using radio communication. Using this information and prior knowledge of planned AUV trajectories, ASVs can reposition themselves to be closer to current AUV locations.

A number of enhancements to the proposed system are foreseen in future. Robust error correcting methods that work with asymmetric bit errors will improve quality of communication. We are developing methods for online, incremental smoothing of the AUV trajectory to address the problem of discontinuities and jumps in the AUV trajectory resulting from one-off outliers. While these methods use new data to correct past anomalies, a delayed correction to the trajectory can still be applied.

VI. Acknowledgments

The authors appreciate Darko Lukic's contributions to acoustic communication as a part of a semester project.

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