Relative Acoustic Navigation for Sensing with Low-Cost AUVs

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Autonomous underwater vehicles (AUVs) are increasingly used in a variety of defense, oceanographic, and industry applications. Improvements in computing power and MEMS sensing technology have led to the recent development of very low-cost AUV platforms, such as the Bluefin SandShark [1]. These vehicles have an advantage in that they are both smaller and cost an order of magnitude less than conventional AUVs, so that multiple vehicles can be deployed for spatially distributed sensing. However, there are challenges to the practical use of these vehicles in the ocean. Navigation error accumulates rapidly, on the order of tens of meters per minute due to the absence of a high quality inertial navigation systems and Doppler velocity logs typically available on larger AUVs. Power and space limitations mean that battery capacity is also less than with larger vehicles. This makes it critical to choose sensors, communication technology and autonomous behaviors to extend range and duration.

One particular area of interest is in using virtual arrays of AUVs with acoustic sensing capabilities for a variety of tasks, including mine countermeasures, noise detection/localization, and environmental monitoring. Our recent work has focused on developing payloads, signal processing, and autonomous behaviors to address navigation, sensing and control issues for the practical use of low-cost AUVs for sensing in the ocean. We present here preliminary work on a SandShark AUV acoustic payload, and on autonomous behaviors for vehicle positioning based on range and bearing to a remote acoustic source.

Vehicle and Payload

In partnership with Bluefin Robotics, we have developed a low-power acoustic payload for a prototype SandShark AUV (Fig. 1). The Bluefin SandShark AUV consists of a tailcone housing the propeller motor and fin actuators, a vehicle control computer, an altimeter and pressure/depth sensor, a MEMS accelerometer/gyroscope/magnetometer for orientation estimation, and a GPS/WiFi antenna. Our acoustic and autonomy payload includes a nose-mounted tetrahedral hydrophone array with 0.045 m spacing, a data acquisition system, a Raspberry Pi 3 computer, and a MicroSemi SA.45 chip scale atomic clock (CSAC). The payload computer runs MOOS-IvP for autonomy and performs real-time signal processing of acoustic data. This autonomy system calculates desired speed, heading and depth based on sensed conditions and autonomy algorithms and passes desired values to the tailcone computer, which uses them to execute thruster and fin control. The acoustic payload has a total power draw of less than 5 W.

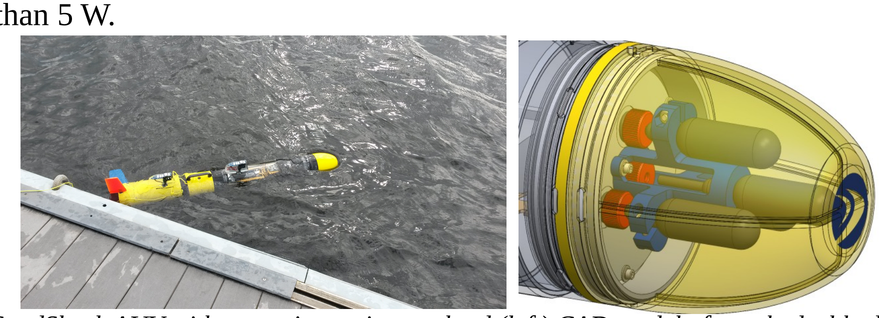

Figure 1: MIT SandShark AUV with acoustic sensing payload (left) CAD model of tetrahedral hydrophone array (right).

Using this system, acoustic data can either be collected continuously or for a selected duration, triggered by a pulse per second (PPS) signal from the GPS-synchronized CSAC, where the rising edge of the PPS signal corresponds to the exact start of the second. While the SandShark acoustic payload is entirely passive and therefore low-power, an acoustic source can be mounted on the dock, a ship, a larger AUV, or an ASV for active acoustic sensing. In an active acoustic context, timing is critical; if CSAC-PPS-synchronized recording on the SandShark begins precisely at the same time that the GPS-

PPS-synchronized source is fired, it possible to establish range from the SandShark to the acoustic source using time-of-flight. A CSAC is required for timing because GPS is unavailable when the vehicle is submerged. 3D acoustic beamforming [2] using data from the tetrahedral phased array provides source bearing/elevation estimates. The combination of range, bearing, and elevation allows us to establish vehicle position relative to a mobile or fixed acoustic source.

Relative position can be extremely useful for correcting vehicle navigation or executing vehicle behaviors for active acoustic sensing. Two contexts are possible: a fixed-source configuration, where the acoustic source is at a known location, and a mobile-source configuration, where the acoustic source is located on a moving vehicle.

Fixed-source

Early testing with the SandShark AUV demonstrated the limitations of its navigational sensor package. To characterize the navigation error and get a baseline vehicle position estimate in real time, a time-sychronized acoustic source was positioned on the MIT Sailing Pavilion dock, and the SandShark deployed in a sequence of autonomous loiter missions. Collected data was processed to compare the acoustic baseline estimate against the internal navigation estimate calculated via IMU and propeller speed. Comparison with the acoustic baseline indicated an error in internal navigation estimated position on the order of tens of meters (Fig. 2), caused by poor calibration of the magnetometer as well as between prop RPM and speed. While this error can be improved with speed table calibration, significant navigation drift is still expected given the low-cost MEMS orientation sensor package on the SandShark.

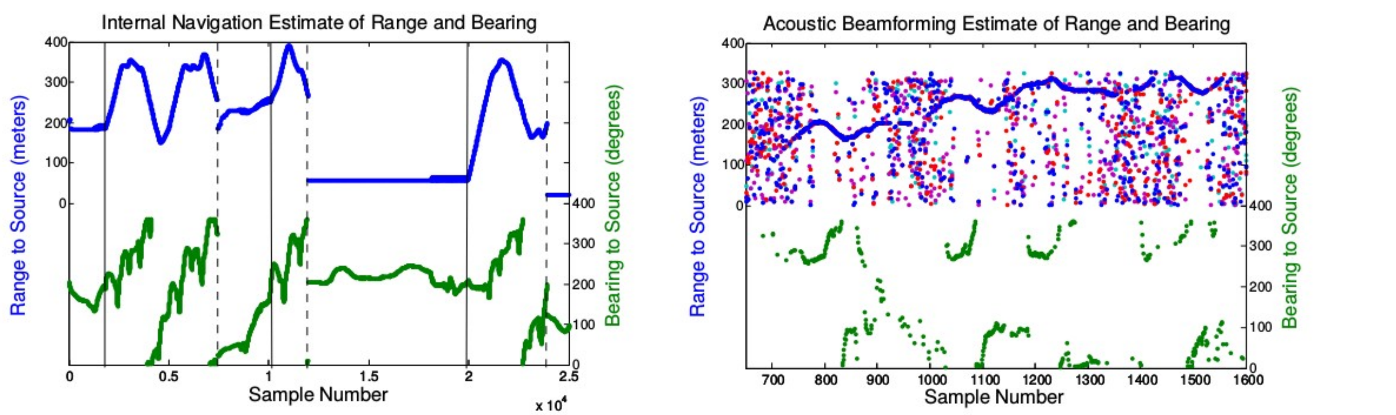

Figure 2: Fixed-source processed data. (a) Internal navigation estimates of range/bearing to acoustic source indicating large jumps in position when vehicle receives GPS fixes at the surface (solid and dashed vertical lines indicate diving and resurfacing events respectively). (b) Acoustic baseline estimates of range/bearing to acoustic source calculated using time-of-flight and beamforming. Beamforming is performed only when variance between time-of-flight calculations of each hydrophone is less than 10 m.

To deal with this level of navigation error, we have two options. The first is to directly use the fixed-source acoustic data for autonomy. Relative range, bearing, and elevation lead to some very useful vehicle behaviors. For example, we can use this data to safety return to the source, to perform constant-range perpendicular sampling, or to execute racetrack patterns towards and away from the source. Such behaviors are independent of compass error, as they calculate desired heading from source bearing relative to vehicle position. The second option is to calculate absolute vehicle position based on the known source location, using what is essentially an inverted USBL scheme: careful filtering and fusion of the acoustic data with internal IMU and speed data would significantly improve navigation estimates. In our initial analysis, however, naive absolute positioning estimation without a proper fusion algorithm produces low quality results due to IMU orientation error.

Mobile-source

The time-sychronized acoustic source can be mounted on an autonomous surface vehicle (ASV) to demonstrate mobile-source behaviors. Operating without communications, the AUV has access to only the acoustic data, so the absolute source position is unknown to the vehicle. Under this paradigm, we wish to investigate what a single AUV or group of AUVs can accomplish using only their relative positions to an ASV, calculated using time-of-flight and beamforming. Initial work will focus on a simple mission in which the SandShark AUV will use relative positioning to track and trail a mobile acoustic source mounted on an ASV, using the behavior illustrated in Fig. 3. Note that because the AUV must maintain a minimum speed in order to remain submerged, and because the body of the vehicle blocks acoustic signals approaching from a 140º arc behind the phased array, the AUV performs trailing by maintaining a 90º bearing to the source with a minimum and maximum range and constant depth, resulting in circling behavior when the ASV is stationary.

The establishment of accurate relative localization would open up a number of interesting multi-vehicle missions. These include the ability to form and maintain geometrical arrays of vehicles for passive acoustic sensing. A group of AUVs would be able to exploit ocean currents for propulsion, if equipped with active buoyancy control or via careful ballasting, enabling the group to perform spatial sampling with increased range and duration. A particularly interesting mission is using a vertical line of AUVs as a virtual acoustic array, enabling accurate acoustic measurement in elevation. The AUVs position themselves so that the source is directly above, and with a desired depth based on their location in the array. The vehicles have to maintain speed to have control, so if a vehicle drifts further than a desired distance or above the desired depth, a behavior is initialized that circles the AUV back into position using range and elevation information.

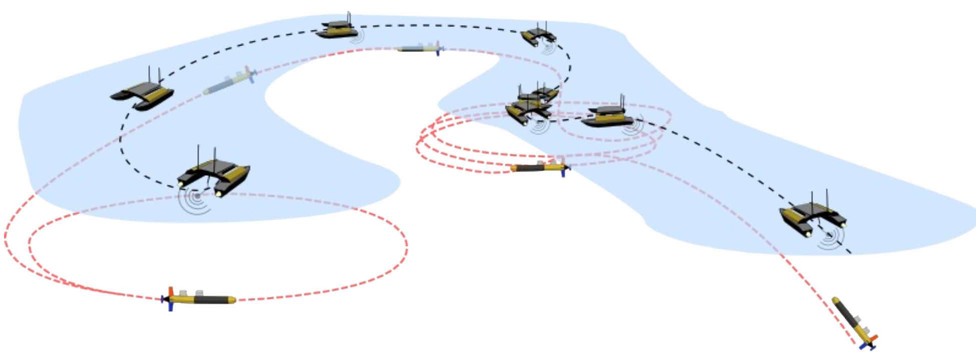

Figure 3: Illustration of track-and-trail of ASV by SandShark AUV using relative positioning.

Conclusion

The ultimate objective of this project is to develop an acoustic system that allows vehicles to localize themselves relative to their neighbors, paving the way to perform relative multi-vehicle behaviors. Here we have presented the initial work towards such a system, and outlined some of the challenges associated with its development, along with interesting behaviors we hope to achieve with our prototype. A particular challenge is in characterizing the accuracy of our relative localization system; to that end, future work will include duplicating our payload on our fleet of Kingfisher ASVs, allowing us to compare localization performance against baseline GPS, as well as integrating a WHOI micromodem into our payload and deploying a commercial LBL system, enabling comparison with LBL estimates. Finally, we hope to implement multi-vehicle behaviors using relative acoustic localization on our Kingfisher ASVs.

References

[1] "Bluefin SandShark", Bluefin Robotics, 2016, accessed 27 April 2016, http://www.bluefinrobotics.com/vehicles-batteries-and-services/bluefin-sandshark/.

[2] Van Trees, Harry L. "Arrays and Spatial Filters", In *Optimum Array Processing*, 77-89. John Wiley & Sons, 2002.