Towards seafloor mapping using an affordable micro-UUV

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***Abstract*—Seafloor mapping and monitoring are essential for creating a sustainable economy and widen our understanding of the ocean environments. However, the cost of conducting underwater operations has always been high. This paper presents our progress on developing an affordable Autonomous Underwater Vehicle (AUV), equipped with an interferometric sonar for seabed mapping at low altitudes or in coastal water. The designed AUV has an interferometric sonar for measuring the seafloor topography and a compact DVL to aid its navigation. This paper also presents an algorithmic pipeline for filtering the noisy swath data points from the interferometric sonar. Field tests have been conducted in a freshwater pond with results presented in this paper.**

***Index Terms*—Autonomous Underwater Vehicle, Seabed Mapping, Bathymetric Mapping, Interferometric Sonar, Sonar Processing**

I. INTRODUCTION

Imaging and monitoring the seafloor has always been a desire for the ocean research community and the offshore industry. Monitoring oceans for marine life [1], oil spills [2], water column [3], and many more scientific data helps us better understand the oceans, and act accordingly for a sustainable Blue Economy. Rapidly changing ecosystems bring forth unforeseeable challenges, to cope with them rapid solutions are required.

Bathymetric mapping is one of the fundamental methods to monitor and image the seafloor. It has a wide range of applications which include but are not limited to navigation charts, mine detection, pipeline inspection, and many more.

Bathymetric mapping surveys are typically done using hull-mounted multi-beam echo sounders (MBES) or single beam sonars [4]. Apart from ship-based systems, remotely operated vehicles (ROVs) with mapping capabilities have been developed to survey relatively small regions of interest. e.g. around a hydrothermal vent [5], cold seep [6], or an underwater archaeological site [7]. They have proven to be powerful platforms for a focused survey. AUVs, on the other hand, comes in various sizes and endurance, offering a more flexible operational paradigm, e.g., multi-robot collaboration [8] and continuous monitoring [9]. But they suffer from constrained communication [10] and uncertain localization [11].

In contrast to the systems that are discussed above, there are other sensing options. e.g. RGB cameras, side-scan sonars, and interferometric sonars. Multi-Beam Sonar Systems (MBES) are generally expensive and come at a larger size. Due to their size, MBES systems were used in relatively large AUVs (e.g., the one in [12]) that require ship supports. In comparison, sidescan sonars are relatively small in size and are convenient to use, but it is difficult to generate 3D maps from their data. Despite the challenge, there are some notable works that made it possible. In the work [13], convolutional neural networks are used to generate range information from side-scan measurements. Interferometric sonar, on the other hand, is capable of generating depth information with proper noise filtering. A swath from interferometric side-scan sonar can be processed and denoised with various methods [14] [15].

In this paper, we present our ongoing progress of developing a seabed mapping Micro-UUV [16]. This paper has an emphasis on interferometric sonar integration and sonar data processing.

The remaining paper is organized as follows. In Section II we cover our design approach. In Section III, sonar point cloud processing methods are described. We present our results in Section IV. Finally, we conclude the paper and discuss future works in Section V.

II. DESIGN

In our application, we decided to use a torpedo-like AUV and design a payload equipped with interferometric side-scan sonar, a Doppler Velocity Logger (DVL), and an embedded computer. The navigation data is enhanced using DVL in the payload section and another Attitude-Heading Reference System (AHRS).

Fig. 1. Micro-UUV with wet payload section. Payload section is in black.

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Figure 1 shows the standard micro-UUV [16] that is been modified for seabed mapping. Our modified AUV has a 24 inch long flooded section (the black portion) for wet-sensor integration. The AUV is 72 inches long with a hull diameter of 4.875 inches. The overall weight is about 20kg.

In the nose section, the vehicle has a single-board computer and sensors, as shown in Fig. 2. Through out the paper, this single board computer will be referred to as the nose computer. The nose computer runs MOOS-IvP Helm [17], which handles low-level control, navigation, and fundamental vehicle guidance. RS232 communication is available from the nose computer to the backseat computer for sophisticated high-level path planning systems. As shown in Fig. 2, our backseat computer (a Jetson TX-2 single-board computer) and a MicroStrain AHRS are linked to the nose computer through RS232 ports.

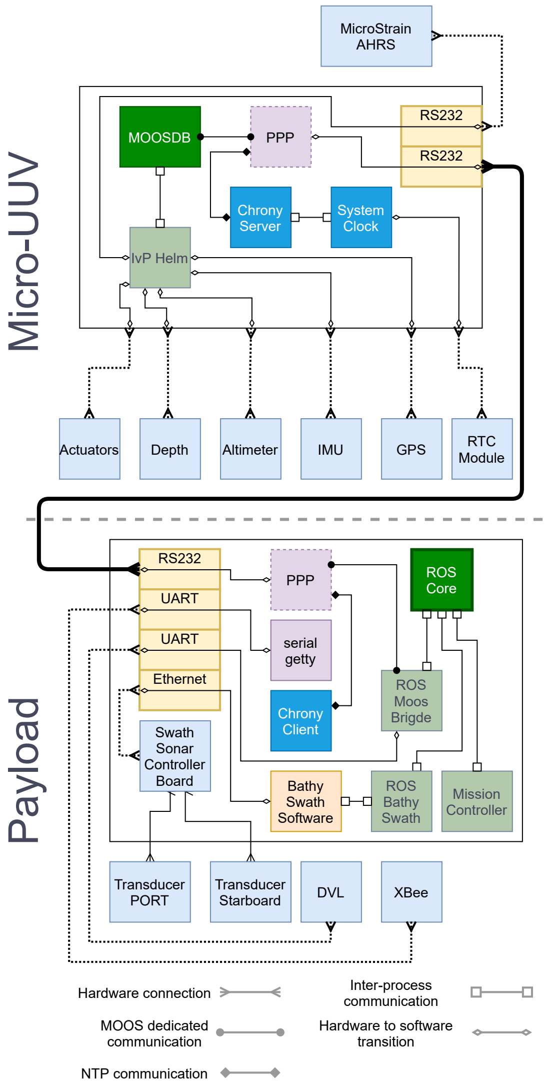
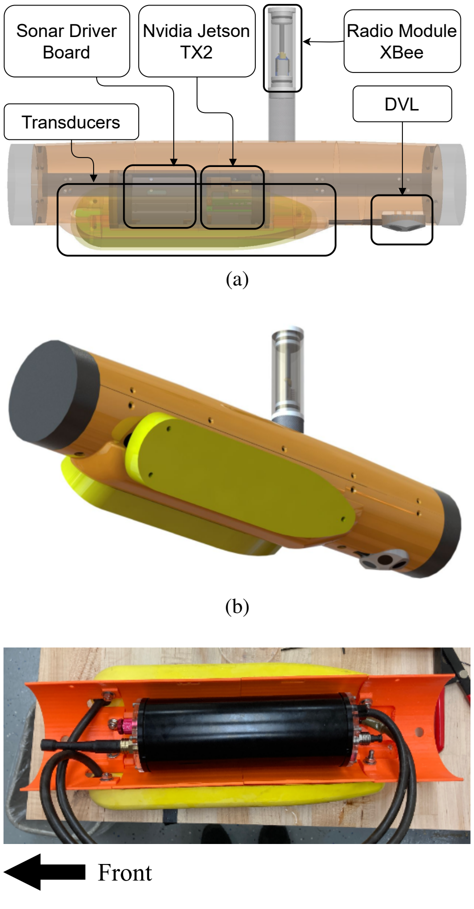


Fig. 2. System integration diagram of the AUV.

Figure 3 depicts the mechanical design of the wet section payload. The payload sensors, such as the interferometric sonar and a compact DVL (from Water Linked AS) are highlighted. The sonar processing board and a backseat computer (NVIDIA Jetson TX2) are enclosed in a pressure housing with 3 inch inner diameter. The backseat computer communicates with the nose computer through a serial link that is translated into the point-to-point protocol (PPP). After establishing an Internet Protocol Version 4 (IPv4) link through PPP communication over the hardware serial, clock, autonomy commands, and sensory information can be exchanged.



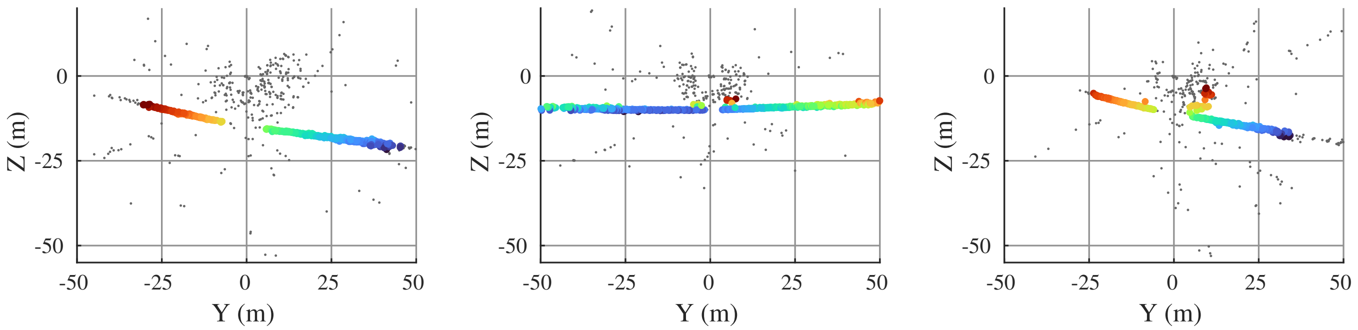
(a)

(b)

(c)

Fig. 3. Designed payload. 3a Side view, CAD model. 3b Bottom view. CAD model. 3c Top view, on the bench without the DVL section.

In the nose computer, all the sensory information is stored in the MOOSDB middle-ware. A program called pNav fetches all the information and generates positioning data. Another program called IvP-Helm produces control commands with the positioning data produced from pNav. The given configuration allows us to introduce new sensors by changing its configuration. It is also possible to obtain sensory information through MOOSDB from another computer within the network. Another advantage of communicating with MOOSDB is that it lets users update the mission parameters during the missions. This allows the backseat computer to make online decision-making when the vehicle is submerged. Our backseat computer runs Robot Operating System (ROS) to interface with sensors and communicates with the nose computer through the MOOSDB-



(a) (b) (c)

Fig. 4. Three graphs shows the DBSCAN application on three different interferometric side-scan sonar readings. Black dots shows the raw data and the colored dots shows the filtering result. Color indicates the depth of the filtered data. Colormap is defined within the boundaries of depth in each data. 4a DBSCAN application example with no noise. 4b DBSCAN application example with some noise left to the center. 4c DBSCAN application example with considerable considerable noise is not filtered out.

ROS bridge. We developed a MOOSDB & ROS bridge to exchange sensory information back and forth between backseat computer and nose computer. By using the bridge, each sensor from the nose computer appears as a ROS topic.

Each MOOS message is sent with a timestamp, just as in the Robot Operating System (ROS). One notable difference with ROS messages, MOOS messages are not structures that hold more than one data point, they are rather key-value pairs with timestamps. However, it is possible to track the related data streams and compiling them into one struct that has multiple data points based on their timestamps.

When sensory data is produced by two different computers, time synchronization is crucial to produce any meaningful data. Adjusting the time with proper steps is also important for any system to operate. In the Micro-UUV, the system clock is synchronized by GPS and backed by a battery-powered real-time clock. Such setup ensures that the AUV will always have the best estimate of the correct time, whereas the backseat computer has no hardware to keep track of its time. To tackle this problem, we integrate Chrony time synchronization daemon that is widely used and available in most Linux distributions. Configuration is done such that whenever both systems detect an active connection to global (Network Time Protocol) NTP servers they synchronize their clocks by the information provided from NTP servers. This is very useful during the development on the bench where internet access is needed but GPS signals are not available.

Console access is trivial while working with Unix-based operating systems. Any serial device can be used to create a console in which the end-user can interact with the operating system. Simple commanding and monitoring are also trivial and do not require lossless communication. We used Getty daemon to create a serial console over an Xbee 900MHz Radio Frequency (RF) serial modem, which allows us to use basic terminal tools to interact with the vehicle up to several kilometers, beyond the WiFi coverage.

III. METHOD

We designed a two-step processing framework to filter the noise both in the raw sonar swaths and the submaps. In the work [18], Density-Based Spatial Clustering of Applications with Noise (DBSCAN) [19] is used to cluster high amplitude points from a single-beam scanning sonar image. Inspired by their work, we apply DBSCAN clustering for each swath point cloud. After the clustering process, we take all the data points that can be clustered. Fig. 4 shows three examples of DBSCAN results on raw sonar swath data.

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Algorithm 1: Statistical Outlier Removal
Input: $C, k, \alpha$ where $C$ is Cloud input, $k$ is the
       number of neighbors, and $\alpha$ is the ratio for
       standard deviation
$n \leftarrow size(C)$
for $i \leftarrow 0$ to $n$ do
    $P_i \leftarrow i^{th}$ point in $C$
    $N_i \leftarrow k$ Closest Neighbors Of $P_i$ in $C$
    for $j \leftarrow 0$ to $k$ do
        $d_i^j \leftarrow$ distance between $N_i^j$ and $P_i$
    end
    $\mu_i, \sigma_i \leftarrow mean(d_i), std(d_i)$
end
for $i \leftarrow 0$ to $n$ do
    $T \leftarrow \mu_i + \alpha \cdot \sigma_i$
    if $d_i > T$ then
        Remove $i^{th}$ Point from Cloud $C$
    end
end
```

We pair the filtered sonar data with the odometry produced by the AUV together and recorded it in the backseat computer's buffer to create submaps. After a predefined number of sonar swaths are collected, a submap is created. The created submap is downsampled to the voxels that are the size of 0.5m to ease the computation and discard repeating data. Next, we further applied statistical outlier removal [20] on a submap to clear the outliers left from the DBSCAN. In Alg. 1, we present the pseudo-code of the statistical outlier removal algorithm used in our framework.

In this framework, the number of swaths to create a submap, DBSCAN's epsilon and minimum points, Statistical Outlier Removal's standard deviation ratio and the number of neighbors are configured as parameters that can be adjusted based on the system performance. In our tests, we set the number of swaths to create a submap to 200, DBSCAN's epsilon value and minimum points to 4.8 and 40, statistical outlier removal's standard deviation ratio and the number of neighbors to 1.4 to 30.

IV. RESULTS

In September 2020, we performed a ship-based survey to validate the sonar performance and collect data for developing algorithms for sonar processing, underwater navigation, and mapping (e.g. SLAM). We equipped the ship with a Nortek DVL-1000, Bathyswath interferometric sonar, and an RTK-GPS unit. Throughout the survey, we collected the precise location of the ship, DVL, AHRS, and sonar readings. We applied the framework discussed in Section III to generate the map with the data collected from the ship survey. Figure 5 shows the resulting seabed map of the survey. Due to an error in mounting configuration, different range readings were acquired for the same point in the seafloor. That resulted in visible strip-like patterns in the map from the ship based surveys.

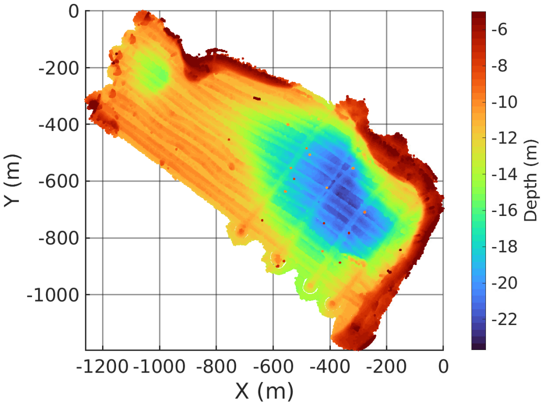
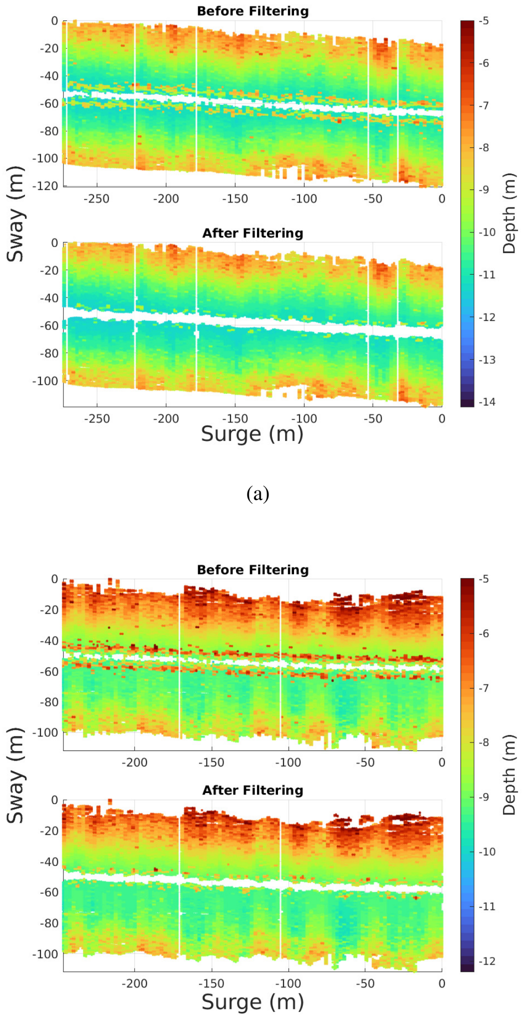


Fig. 5. The resulting bathymetric map of the ship-based survey in the Beach Pond. The ship-based survey was performed with the Nortek DVL-1000, RTK-GPS and the Bathyswath interferometric sonar system.

After validating the sensors, we integrated the sensors onto the AUV. Except, the Nortek DVL-1000 is replaced with a compact WaterLinked DVL which has a similar precision. In June 2020, we conducted an AUV-based survey to validate vehicle performance and test integration stability. Figure 6 shows the Micro-UUV with customized payload on the testing day. However, due to a problem caused by the transportation, two computers lost their communication, and data were recorded separately. As shown in Fig. 2, the IMU is attached to the nose computer, therefore, the motion data wasn't synchronized with the sonar data recorded on the backseat computer.

Fig. 6. Riptide Micro-UUV with modified payload



(a)

(b)

Fig. 7. The result of applying statistical outlier removal algorithm on different submaps. 7a The algorithm has successfully removed most of the noise left by the DBSCAN. 7b Noise still left by the algorithm near the nadir gap.

DBSCAN application on swath data successfully removed most of the noise, as presented in Fig. 4. However, further testing is required to validate the method's performance in locations with steep seabed slopes. Adjusting the DBSCAN's parameter was important, ill-configuration could lead to a greater nadir gap or the inclusion of noise data points into the cluster (see Fig. 4c). Based on the altitude measured by a DVL or an altimeter, the adaptive configuration might help to overcome the mentioned problems.

Statistical outlier removal algorithm was successful in removing most of the noise that is left by the DBSCAN (see Fig. 7a). However, the statistical outlier removal algorithm still left sparse outliers near the center-line in some submaps, e.g. Fig. 7b. One reason for noise to be condensed and clustered together may be caused by the slow surging speed of the AUV, such that more data points were collected in a relatively short distance. To tackle this problem, sonar data can be buffered based on the distance traveled, not the number of swath data collected.

V. Conclusion and Future work

In this paper, we presented our progress on developing seabed mapping AUV. We described our approach to design the software and hardware architecture of the proposed AUV. We also introduced the clustering-based interferometric sonar swath filtering method and statistical method for filtering submaps generated with denoised sonar swaths.

In the future, we plan to work on seamless merging of the submaps, and improving the localization stack integration. The sensor-driven coverage path planner proposed in [21] will be later implemented.

Currently, we are working on the final integration process of the sonar onto the Micro-UUV. Field experiments are planned in the coming months to validate the system integration.

VI. Acknowledgements

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