Infrastructure for 3D Model Reconstruction of Marine Structures

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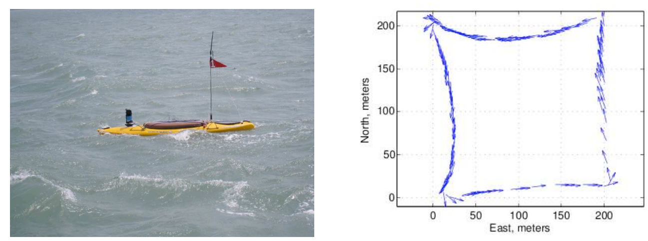
ABSTRACT

3D model reconstruction of marine structures, such as dams, oil-rigs, and sea caves, is both important and challenging. An important application includes structural inspection. Manual inspection of marine structures is tedious and even a small oversight can have severe consequences for the structure and the people around it. A robotic system that can construct 3D models of marine structures would hopefully reduce the chances of oversight, and hence improve the safety of marine environment. Due to the water currents and wakes, developing a robotic system to construct 3D models of marine structures is a challenge, as it is difficult for a robot to reach the desired scan configurations and take a scan of the environment while remaining stationary. This paper presents our preliminary work in developing a robotic and software system for construction of 3D models of marine structures. We have successfully tested our system in a sea water environment in the Singapore Straits.

KEY WORDS: Marine robotics, Inspection of marine structures, 3D mapping.

INTRODUCTION

We are interested in 3D model reconstruction of marine structures, i.e., structures where some part is submerged under water, such as dams, oil-rigs, ships, and sea caves. Model reconstruction of marine structures is both important and challenging. An important application includes structural inspection. For safety reasons, man-made structures need to be inspected regularly for cracks and other deformations. For repair purposes, technicians need to inspect ship-hulls to ensure no damage is left unattended. Manual inspection is tedious and even a small oversight can have severe consequences for the structure and the people inside or around it. This process is vulnerable to mistakes because inspectors must work in uncomfortable positions aboard boats or with SCUBA (Self-Contained Underwater Breathing Apparatus). A robotic system that can construct 3D models of marine structures would enable inspectors to inspect the structures from a more comfortable position in their offices, and hopefully reduce the chances of oversight, which would then improve the safety of marine environment.



(a) (b)

Fig. 1. (a) An Autonomous Surface Craft (ASC) operating in Selat Pauh, located at the west of the Singapore Strait. (b) The black rectangle is the path that the ASC should follow, while the blue arrows show the actual movement of the ASC, as captured by the ASC's GPS and compass. Each arrow shows the heading of the ASC when the ASC is at the position marked by the starting position of the arrow. Due to water currents and wakes, the ASC could not follow the intended path, it drifted more than 50m of its intended positions. Courtesy of Lynn Sarcione [Sarcione, 2010].

Developing a robotic system to construct 3D models of marine structures is challenging due to the nature of water environment. Water currents and wakes make it difficult for a robot to reach the desired scan configurations and take a scan of the environment while remaining stationary (Fig 1 illustrates this difficulty). This difficulty is worsened by the lack of commercial positioning sensors that are accurate enough for the purpose of model reconstruction. For example, a commonly used commercial GPS today would have a standard error of around 5m. This is insufficient for model reconstruction considering the size of the structures we want to inspect, e.g., the diameters of the pillars of a pier, may be around 1m. Although DGPS can have less than one meter accuracy, this high level of accuracy can be achieved only when the DGPS is near to the ground base station, which is not always feasible when the robot operates in the sea environment. As a result, due to the robot's motion uncertainty and lack of accurate commercial positioning sensor, the scanned data may have been taken from a position far from the intended scanning position and even significantly far from the position logged by the positioning sensor. This position uncertainty causes difficulties in merging the scanned data into a single 3D model.

This paper presents our preliminary work in developing a robotic and software system for 3D model reconstruction of marine structures. In particular, this paper focuses on constructing 3D models of parts of the marine structures located above the water surface. We use off-the-shelf hardware components to develop an ASC for scanning marine structures. And develop a simple algorithm to construct 3D models from the scanned data, without GPS information. We have successfully tested our system in sea environment at the Singapore Straits.

In the next section, we present related work and background information on 3D model reconstruction from scanned data. The robotic platform and scanning sensor are discussed in Section ROBOTIC PLATFOR and Section SCANNING SENSOR, respectively. Section PROCESSING THE SCANNED DATA presents a simple algorithm for constructing 3D models from the scanned data. Section EXPERIMENTAL SETUP AND RESULTS and Section SUMMARY AND FUTURE WORK present our experimental results and summarize the paper, respectively.

RELATED WORK

3D Model Reconstruction

For more than two decades, robotic systems for 3D model reconstruction have attracted much attention [Thrun, et.al., 2005]. However, most work have focused on constructing 3D models of structures on land. Some recent papers on this topic include [Carlberg, et.al., 2008], [Jiang, et.al., 2007], [Newman, et.al, 2006], [Nuchter, et.al, 2007]. Due to the difficulty in operating a robot in water environment, few work have tried to construct 3D models using marine robots. Among these few work, most, if not all, tried to construct 3D models of underwater structure using Autonomous Underwater Vehicles (AUV) [Fairfield, et.al., 2007]. Recently, [Leedekerken, et.al., 2010] constructs 3D model of marine structure. However, they rely on accurate positioning from GPS most of the time. This is difficult to attain when we operate in harbor environment, where most of the time, we only receive signal from a small number of GPS satellite, causing large GPS error. In this work, we construct the 3D model without information from any positioning sensor.

In this paper, we present our preliminary work in developing a robotic and software system for 3D model reconstruction of marine structures, where some parts of the structures lie above the water surface and the other parts lie under the water surface.

Iterative Closest Point

A main component in constructing 3D model from scanned data is a registration algorithm. Given two point clouds in different coordinate systems, a registration algorithm finds a coordinate transformation that minimizes the pose difference between the two point clouds. A scanning sensor generates point clouds represented in the coordinate system defined with respect to the sensor's pose when the scan was taken. To construct a 3D model from multiple scans of the environment, we need to transform all of the scanned data into a common coordinate system.

One most popular registration algorithm is Iterative Closest Point (ICP) [Besl and McKay, 1992]. Given two point clouds, called A and B, in different coordinate systems and an initial transformation that transforms A to the coordinate system of B, ICP uses an iterative method to find a better transformation according to an error metric based on distance. In this paper, we use the mean-squared error metric and Euclidean distance. ICP starts by transforming A to the coordinate system of B based on the initial transformation matrix, uses the nearest neighbor criteria to find correspondence between points in A and in B, and computes a new transformation matrix that minimizes the error metric assuming the computed correspondence is correct. This process is repeated, transforming A using the newly computed transformation matrix to compute a new correspondence relation and a new transformation matrix, until the correspondence error is less than the user-defined threshold.

ROBOTIC PLATFORM

To scan the marine structures of interest well, the robotic platform should have high maneuverability for accessing confined places that may be critical to scan the entire structure. For this purpose, we use a SCOUT Autonomous Surface Craft (ASC) [Curcio, et.al., 2005] (Fig 1(a)), a kayak with length and weight of about 3m and 90kg. The ASC has a minimum turning radius of less than 3m. This is much smaller than the turning radius of even a small working boat which in general has around 20m minimum turning radius. As a result, the ASC can access places that are difficult by bigger more stabile marine vehicles. Furthermore, due to its size and light weight, part of the ASC that lies below the water surface is only around 40cm. Hence, the ASC can access shallow water which in general is inaccessible by usual working boats.

The ASC is equipped with a 245N thruster produced by Minn Kota and a steering servo by Vantec for its propulsion and steering. For positioning, a Garmin GPS-18 and an Ocean Server OS5000 compass are installed in the ASC. The ASC can be controlled remotely using a remote control or autonomously from a software.

To facilitate data capturing and autonomous control capability, a Main Vehicle Computer (MVC) is placed inside the main compartment of the ASC. The MVC consists of a pair of single board computers connected through an Ethernet cable. Each single board computer is equipped with 1GB RAM. In addition, one of the single-board computers is equipped with a 120GB hard drive to facilitate large data capturing capability.

SCANNING SENSOR

Due to the water currents and wakes that may move the ASC adversely, we would like to use a scanning sensor that can finish each scanning cycle quickly and has a relatively wide field of view. The high scanning frequency allows each scanning cycle to be completed before the ASC drifts significantly far from the position where the scanning cycle was started. This would reduce the need to adjust different points within a single scan according to the ASC movement, and hence simplify 3D model reconstruction. The wide field of view makes significant overlaps between subsequent scans of the environment possible, despite the unintended movement of the ASC due to water currents and wakes. Significant overlaps between subsequent scans allows us to merge subsequent scans into one coordinate system without knowing the scanner pose when the scans were taken, which is an important capability for 3D model reconstruction when the accuracy of the robot's positioning sensors is low (see Section V for more details on the merging process).

To satisfy the above requirements, we use Velodyne HDL-64E S2 (Fig 2(a)), a 3D LiDAR (Light Detection and Ranging) that finishes each scanning cycle in 0.1 seconds. In each scanning cycle, the LiDAR captures the entire 360^0 horizontal and 26.8^0 vertical field of view with $0.09^0 \times 0.4^0$ resolution. In calm water, the ASC moves around 1-2m/s. In rough water where we operate, the water current is in general around 1m/s-2m/s, making the ASC to generally move with at most 4m/s speed. A scanning cycle of 0.1s means that the ASC would have moved

(a) (b) (c)

Fig. 2. (a) The Velodyne HDL-64E S2 LiDAR in its standard configuration. (b) The Velodyne LiDAR and the mounting platform for placing the LiDAR in an inverted configuration on the ASC. (c) The ASC with Velodyne LiDAR mounted on top of it. An additional pontoon is attached to the ASC to improve stability.

by 10cm-40cm during one scanning cycle. Considering the smallest size of the structure we are interested is often around 1m, moving 10cm-40cm within one scanning cycle means that subsequent scanned data would have sufficient overlapping, a key requirement for ICP to work.

Unfortunately the Velodyne LiDAR cannot be mounted in its standard configuration on the ASC. When the LiDAR is mounted in its standard configuration, it sits low on the water relative to the structures we would like to scan. Since the LiDAR's vertical field of view spans from -24.8^0 to $+2^0$ and its range limit is 50m, in its standard configuration, the LiDAR can only scan parts of the marine structures from the water surface up to around 2 meters above the water surface. This is highly insufficient for our purpose. To overcome this difficulty, we mount the LiDAR in its inverted configuration, thereby generating a vertical field of view that spans from -2^0 to $+24.8^0$ and enabling the LiDAR to scan parts of the marine structures from the water surface up to around 20 meters above the water surface.

However, mounting the LiDAR in an inverted configuration makes the ASC less stable. Since the LiDAR is quite heavy (around 13 kilograms) and its center of gravity lies near the bottom of the LiDAR, which would sit high up in inverted configuration, mounting the LiDAR in an inverted configuration significantly raises the center of gravity of the entire system. As a result, the ASC becomes less stable, especially in roll, and vulnerable to capsizing when operating in rough water environments.

To mount the LiDAR in an inverted configuration and maintain stability, we designed a mounting platform to mount the LiDAR in an inverted configuration on the ASC with two primary considerations, i.e., craft stability and obviously sensor visibility. Fig 2(b) shows the mounting platform. To balance weight and bending strength, the entire mounting structure is made with lightweight aluminum extrusions. The four posts bearing the weight of the sensor are tied together with triangulating pieces in the hull of the kayak to create a rigid platform to mount the LiDAR that is robust to motion in all directions. Further, the four posts are narrow so that they have a minimal effect on the data collected by the LiDAR. Experiments with the LiDAR in this mount show that these posts cast insignificant shadows on the LiDAR returns.

In order to ensure the stability of the ASC, we keep the centroid of the craft low by mounting the LiDAR as low as possible in the kayak without encroaching on the sensor's field of view. Additionally, to protect the ASC from rolling, its most vulnerable direction, we attach port and starboard stabilizers. These stabilizers consist of buoyant pontoons mounted on an aluminum square extrusion assembly that is fixed directly to the LiDAR's mount. The pontoons are streamlined to minimize the added drag to the ASC.

PROCESSING THE SCANNED DATA

To scan marine structures, we move the ASC around the structures with the LiDAR mounted on top of the ASC and continuously scanning the environment as the ASC moves. The scanned data is logged in the ASC's main computer and the 3D model is constructed during post-processing.

To construct a 3D model from the scanned data, we first break the scanned data into a sequence of 3D point clouds. Each point cloud is generated by a scan cycle of the LiDAR, and hence corresponds to a 360^0 horizontal and a 26.8^0 vertical scan of the environment. We assume that the ASC is stationary within one scan cycle of the LiDAR. Due to the LiDAR's high scanning frequency, this assumption generates reasonable results, as we will see in Section VI. Using this assumption, the coordinate system of each 3D point cloud in the sequence is the coordinate system attached to the LiDAR at the beginning of the scanning cycle.

Next, we merge the sequence of 3D point clouds, each in their respective coordinate systems, into a single coordinate system. We merge the point clouds sequentially. The first point cloud in the sequence is transformed into the coordinate system of the second point cloud. The union of the first two point clouds in the coordinate system of the second point cloud is then transformed to the coordinate system of the third point cloud, and so on. This process continues until we transform all the point clouds to the coordinate system of the last point cloud in the sequence. Once the point clouds have been merged in to a single coordinate system, we can use the merged point cloud directly as our 3D model, as in [Linsen, 2001], or we can use methods such as Alpha Shapes [Edelsbrunner and Mucke, 1994], Power Crust [Amenta, et.al. 2001], etc., to construct a triangular mesh from the merged point cloud.

Finding the right transformation between two coordinate systems is key to the success of the above process. Due to the lack of accurate positioning sensor, we use Iterative Closest Point (ICP) algorithm to

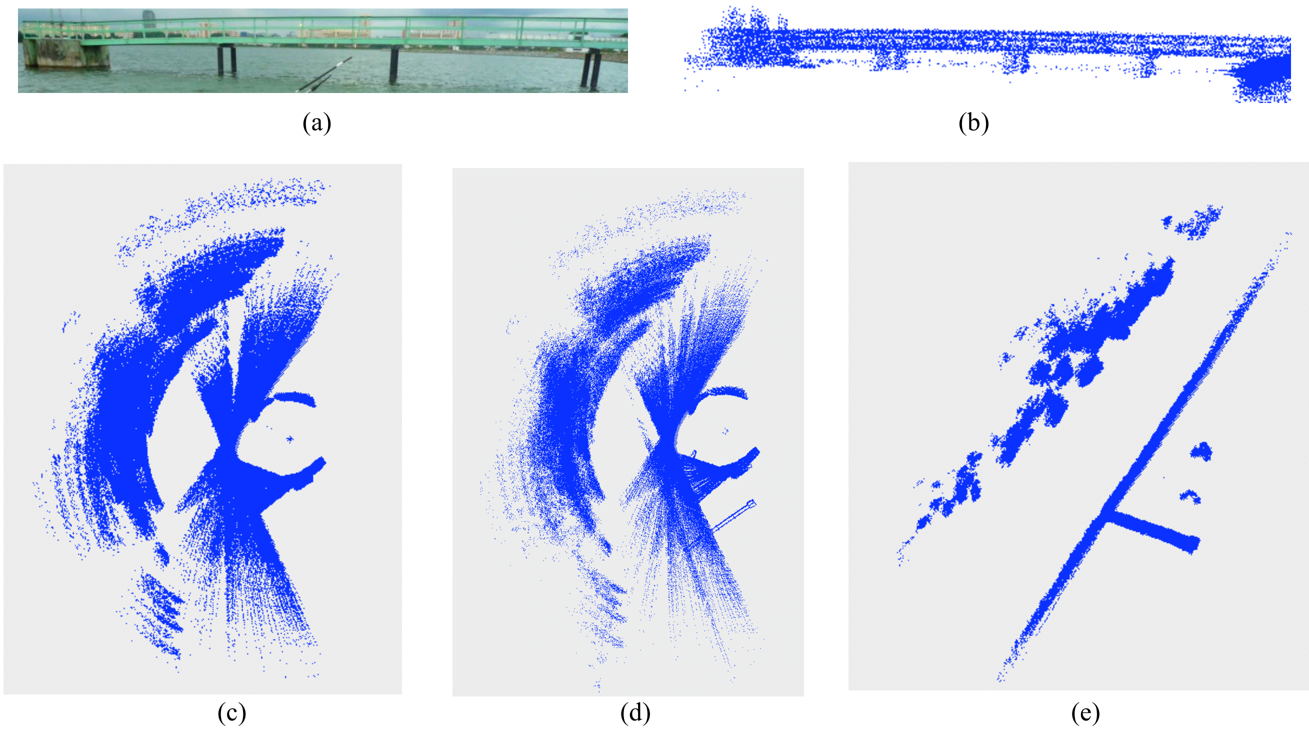


Fig. 3. Reconstruction of a jetty in Pandan Reservoir, Singapore. (a) The target jetty. (b) Side view of the jetty model constructed by our algorithm. (c) Top view of multiple frames of the 3D LiDAR data before processing. (d) Top view of the constructed 3D model based on GPS and compass information. (e) Top view of the constructed 3D model generated by our algorithm.

compute each required transformation. It is widely known that the performance of ICP highly depends on the initial transformation, which is given as input to the algorithm. To determine the initial transformation, notice that we always transform two subsequent coordinate systems. Since the ASC's movement between two subsequent scanning cycles is small (around 10cm-40cm), the identity transformation is in general a suitable initial guess for each ICP process, as we will see in Section EXPERIMENTAL SETUP AND RESULTS.

Whenever coarser data resolution is sufficient to generate a good 3D model for the particular application of model reconstruction, we perform temporal and spatial sub-sampling of the data in order to reduce processing time. The Velodyne LiDAR generates around 8 MB of data per second, which consists of around 250,000 points per scanning cycle and 10 scanning cycles per second. When the water environment is calm such that the error in the ASC's movement is less, many nearby scanning cycles generate redundant data. In this case, we perform temporal sub-sampling. Temporal sub-sampling is performed by clustering point clouds that have been generated within a user-specified time resolution together, and represents each cluster with only a single point cloud. When less spatial resolution is sufficient, we also perform spatial sub-sampling to each point cloud. Spatial sub-sampling is performed by discretizing the bounding box of the point clouds into a regular grid with a user-specified resolution; the points inside the same grid cell are considered the same and are represented by only one point. Algorithm 1 presents the overall algorithm.

Algorithm 1 Construct a 3D model from a sequence of point clouds P. The input s and t a re the user-specified spatial and temporal resolution, respectively.

Construct3DModel (P, s, t)

MergedData = P[1].

For i = 2 to |P| step t do,

    MergedData = SpatialSubSampling(*MergedData*, s).

    P' = SpatialSubSampling(P[i], s).

    Let T0 be the identity transformation matrix.

    T = ICP(*MergedData*, P', T0).

    MergedData = Transform(*MergedData*, T).

    MergedData = *MergedData* U P'

Return *MergedData*.

EXPERIMENTAL SETUP AND RESULTS

We have conducted experiments in both calm water and rough sea water environments to test the effectiveness of our system in constructing 3D models of marine structures. In particular, the goal of the experiment is two folds. First is to test the capability of our robotic system, i.e., the ASC with a LiDAR mounted in an inverted configuration on top of the ASC, in scanning the environment. Second is to understand the performance of our simple reconstruction method in constructing 3D model of marine structures from the scanned data.

During the two experiments, we control the ASC with the LiDAR mounted on top of it using a remote control. The ASC is controlled to move around the marine structure of interest with the LiDAR continuously scanning the perimeter of the structure as the ASC moves. The data was logged in the ASC's main computer, while the 3D model reconstruction from the scanned data was performed off-line in a 64bit Intel Xeon E5405 PC with 4GB RAM. The reconstruction algorithm is implemented in C++ and the ICP implementation is adapted from [Bergstorm]. For comparison, we show the results of merging the scanned data based on the GPS and compass information alone.

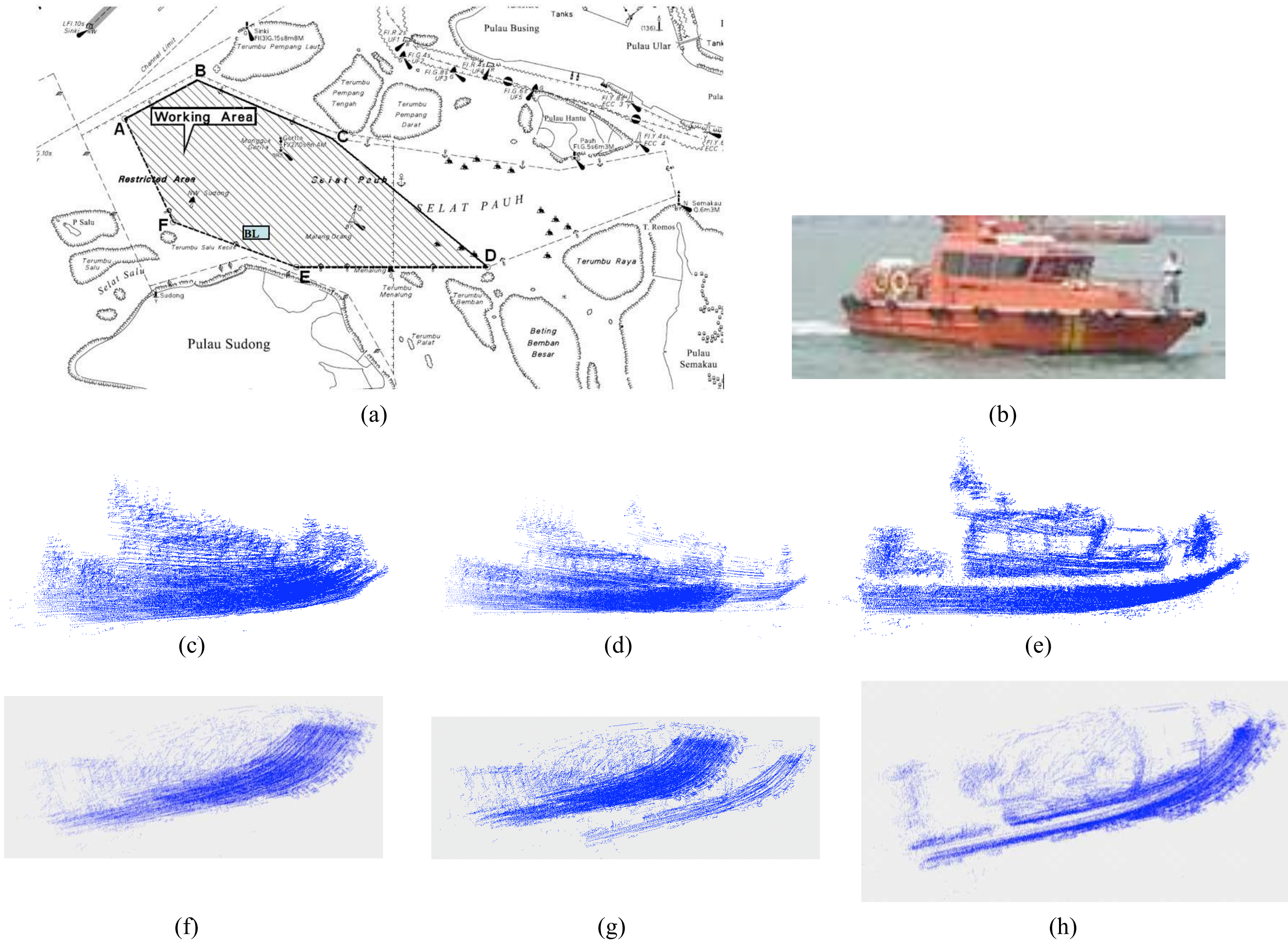


Fig. 4. Reconstruction of a slowly moving boat in rough sea water environment, in Selat Pauh, Singapore. (a) Our operating area. (b) The target boat. (c) Side view of multiple frames of the 3D LiDAR data before processing. (d) Side view of the constructed 3D model based on GPS and compass information. (e) Side view of the constructed 3D model generated by our method. (f) Top view of multiple frames of the 3D LiDAR data before processing. (g) Top view of the constructed 3D model based on GPS and compass information. (h) Top view of the constructed 3D model generated by our method.

The first experiment was performed in calm water environment, in Pandan Reservoir, Singapore. In this experiment, the marine structure of interest is a jetty, illustrated in Fig 3(a). To give an illustration of the difficulty in merging the scanned data, Fig 3(c) shows the resulting 3D point clouds scanned by the LiDAR over 10 seconds period, plotted in one coordinate system. Fig 3(d) shows the 3D model generated by transforming the point clouds to the coordinate system of the first point cloud based on GPS and compass information alone. Fig 3(b) and Fig 3(e) show the results of our 3D model reconstruction algorithm on the above data set.

The second experiment was performed in rough sea water environment in Selat Pauh at the Singapore Straits (Fig 4(a)). The water currents in Selat Pauh is around 1m/s to 2m/s [Ooi, et.al, 2009]. In addition, Selat Pauh is a busy strait with a significant amount of ship traffic, causing high frequency water wakes that significantly disturb the motion of small marine vehicles. In this experiment, the marine structure of interest is a slow moving boat, illustrated in Fig 4(b). Although the boat is moving slowly, the water currents and wakes cause the boat and the ASC to drift and move up and down significantly. As an illustration of the effect of water currents and wakes on the scanned data, Fig 4(c) and Fig 4(f) show the 3D point clouds scanned by the LiDAR over only 2 seconds period, plotted in one coordinate system. Fig 4(d) and Fig 4(g) show the 3D model generated by transforming the point clouds to the coordinate system of the first point cloud based on GPS and compass information alone. Fig 4(e) and Fig 4(h) show the results of applying our 3D model reconstruction algorithm to the above data set.

The results show that our robotic system for 3D model construction of marine structures is reliable to operate in rough sea water environment. The resulting scanned data indicates that the LiDAR's mounting platform does not pose significant degradation in the quality of the scanned data. Furthermore, due to the high scanning frequency of the Velodyne LiDAR, the simple merging algorithm we propose is sufficient to construct a rough 3D model of marine structures when there are large overlaps between point clouds generated by different scanning cycles.

Despite the above promising results, there is still plenty of room for improvement, both in terms of hardware and software. In terms of hardware, the availability of highly accurate positioning sensor for the

ASC would improve the 3D model reconstruction. The key in improving the reconstruction algorithm is in finding robust registration criteria in the presence of noise and lack of features. In this paper, we assume that the ASC does not move within a single scanning cycle. However, when the ASC operates in very rough water, this assumption would be largely violated even though the scanning cycle of the LiDAR can be performed within 0.1 seconds. Hence the ASC movement within a scanning cycle needs to be taken into account when constructing the 3D model. Furthermore, many marine structures are featureless, such as dams, or consist of non-distinguishable features, such as bridges with its regular pillars. The lack of distinguishable features in marine structures increases the difficulty in identifying correspondence between points in different coordinate systems, in particular when the amount of overlap between point clouds at different coordinate systems is small. A more robust algorithm for finding correspondence would improve the quality of the generated 3D model.

SUMMARY AND FUTURE WORK

We have presented our preliminary work in developing a robotic and software system for 3D model reconstruction of marine structures. In this paper, we focus on model reconstructions of parts of the marine structures that lie above the water surface. We show how off-the-shelf robotic platform and sensors can be assembled together to construct a robust system for 3D model reconstruction. We have presented a simple algorithm for constructing a 3D model from the scanned data. The system has been tested in both a calm water environment and a rough sea water environment.

A number of avenues are possible for future work. One avenue of interest is to extend the capability of our system to construct 3D models of an entire marine structure, including parts of the structure that lie above and below the water surface. The main question here would be what kind of sensor should we use to scan parts of the structure that lie below the water surface? How should we mount these sensors on the ASC? How should we construct a 3D model of the entire structure when parts of the structure that lie above the water surface and under the water surface are captured using different sensors? Another avenue is in improving the level of accuracy of the 3D model we can reconstruct.

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