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LiDAR based Autonomous Navigation for USV Pipeline Inspection

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Abstract: In general, the use of transportation is one of the techniques that allows anything to move faster without consuming a lot of energy. These also applies to the pipeline-based transfer of liquids, gases, and other substances. Therefore, these pipelines need to inspected to keep them free of corrosion and in good shape. However, this pipeline is occasionally located in a location that is challenging for humans to access, such as located above the water surface, then Heron Unmanned Surface Vehicle (USV) is proposed to overcome the aforementioned problems. This study discusses the development of the Heron unmanned surface vehicle's (USV) autonomous SLAM navigation, path planning, and collision avoidance system. Additional sensors, such as a Velodyne 3D VLP16 lidar sensor and an Axis pan-tilt-zoom (PTZ) camera, will be mounted to the Heron USV to enhance the autonomous navigation capabilities of the Heron USV. The Robot Operating System (ROS) navigation stack is use to provide the framework for the hardware and software of the robot to develop the Simultaneous Localization and Mapping (SLAM) based autonomous navigation and path planning algorithm. The lidar sensor data has been analyzed, showing that the lidar sensor can identify the surrounding environment and objects around the USV. The results show that the suggested USV can navigate autonomously in a water environment, including path planning, and can avoid obstacles. Due to the data collected from the lidar sensor, the USV can also generate a map for the unknown area while navigating around the simulated environment, which aids in visualizing the current state in the environment and can be used in pipeline inspection.

Keywords: Autonomous Navigation, Unmanned Surface Vehicle (USV), Robot Operating System (ROS) Navigation Stack, Simultaneous Localization and Mapping (SLAM)

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1. Introduction

Figure 1 shows the scenario of pipeline environment. Pipelines are widely used in industry and engineering as a way of transporting resources such as gas, water, and any other item that may be delivered via pipes. This pipeline might occasionally cross water areas, such as rivers or the ocean, by being installed beneath bridges or using pipeline racks. However, these pipes are frequently subjected to circumstances that might cause damage, such as corrosion on the pipeline's outer surface. So, inspection work is required to verify that this pipeline is free of damage and faults like this. However, the current inspection method demands a significant amount of energy for the workers to move along the pipeline, it is time-consuming, and there are situations when the pipeline's structure and work area are difficult to access by humans, including when the pipelines are narrow and above the water level, which can risk employees' safety and health [1]. As a result, the goal of this study is to solve these challenges by developing an autonomous navigation unmanned surface vehicle (USV) to fulfill the pipeline inspection method of approaching and moving along a pipeline without requiring workers to expend energy.

Figure 1: Scenario of Pipeline Environment

This autonomous vessel can navigate in dangerous to workers place and unknown environment with minimal human intervention. Moreover, since it is an autonomous navigation vessel, it comes with different approaches such as path planning, localization and mapping by integrated with SLAM algorithm [2]. Simultaneous Localization and Mapping (SLAM) algorithm provides path planning, obstacle detection and mapping, guidance and control. To perceive and recognize external environment conditions, exteroceptive sensors including Velodyne 3D VL16 lidar and Axis pan-tilt-zoom (PTZ) camera are installed onboard. Raw sensor data from the lidar is used to generate map in GMapping and to plan the path by detecting the obstacles around the USV's vessel. This can generate the map while navigate the USV vessel to the goal without collide with any object.

Robot Operating System (ROS) is a system that allows a robot to perform autonomous navigation, such as the unmanned surface vehicle employed in this study. In recent years, the robotics community has created algorithms that allow robots to operate with increasing levels of autonomy, ranging from quadrotor helicopters to humanoids to land-based mobile robots. However, robots continue to offer some difficult difficulties for software programmers. So, in order to address some of these challenges, a software platform known as Robot Operating System, or ROS, is established. It is an open-source robot meta-operating system. It has all of the characteristics expected of an operating system, such as hardware abstraction, low-level device control, common functionality implementation, message passing between processes, and package management. It also provides information and libraries for locating, generating, writing, and running code on a variety of platforms [3].

2. Methodology

This section describes the methodology which is carried out through this paper which consists of an overview system of proposed USV, software development, and experimental program to test the accuracy and efficiency of the developed algorithm.

2.1 System Overview of Proposed USV

Figure 2 shows the Heron M300 USV developed by Clearpath Robotics. The USV is stable, agile, and fast, and it can maneuver into narrow locations such as bridge-supporting columns [4]. This catamaran design vessel has anti-fouling thrusters with a very shallow profile as well as a built-in GPS for simple access to navigation data.

Exteroceptive sensors such as a Velodyne 3D VLP16 lidar and an Axis pan-tilt-zoom (PTZ) camera are mounted onboard to detect and identify surrounding environmental conditions. Raw lidar sensor data may be retrieved and delivered directly to the processing unit. The processing unit is a 2.2GHz Intel ATOM processor embedded computer.

Figure 2: Heron M300 USV [5]

Figure 3 shows the Clearpath Heron M300 Overview System block diagram. Onboard embedded PC Heron is powered by Ubuntu Linux 18.04 with ROS Melodic, and the development computer or laptop should operate the same operating system as the Heron computer. Raw sensor data from the Velodyne 3D VLP16 lidar and Axis pan-tilt-zoom (PTZ) camera could be accessed and delivered directly to the processing unit.

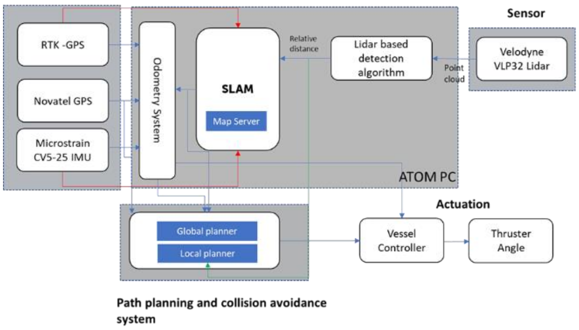


Figure 3: Clearpath Heron M300 Overview System block diagram

The processing unit integrates navigation data, detects/tracks numerous objects, and avoids collisions autonomously. The data from the Velodyne Lidar Sensor will be sent to a lidar-based detection algorithm as the collision avoidance system for the Heron USV. These data will be relayed to the vessel controller, who will use them to regulate the thruster angle and operate the Heron M300 independently. The overall specifications of Clearpath Heron M300 are shown in Table 1.

Table 1: Heron USV system specification

	Specifications	
Dimensions	1300 x 940 x 340 mm	51.2 x 37 x 13.4 inch
Draught	120 mm	
Weight	28 kg	64 lbs
Max Payload	10 kg	22 lbs
Rated speed (forward)	1.7 m/s	5.6 ft/s

Moving Distance (max)		
(1 way)	9.5 miles	15.2 km
(2 ways)	4.7 miles	7.4 km
Battery Pack	14.4 V 29 Ah NiMH	
Operating Time	2.5 h @ 1.0 m/s	
	10 h standby	

2.2 Software Development

A. Autonomous Navigation Algorithm Development

Figure 4 shows the Flow chart for autonomous navigation. Autonomous robots have the potential to improve inspection operations by offering the ability to navigate in risky locations to increase productivity, decrease cost and improve the accuracy of work. Various problems in autonomous navigation like mapping, localization, and path planning can be solved using multiple approaches. First of all, the Heron M300 will read the sequence of data from the lidar sensor then get the initial position of the Heron vehicle and get the goal point [29][29]. The path of the Heron will be calculated to get the desired path before it sends to the PID controller. The collected data will be sent to the PID controller then determine the Heron USV to follow the path smoothly. The robot controller will receive the data and will drive the vehicle to the desired path. The Lidar sensor will detect if there are obstacles around the Heron vehicle then it will reset the position of the Heron USV until there are no obstacles along the Heron path.

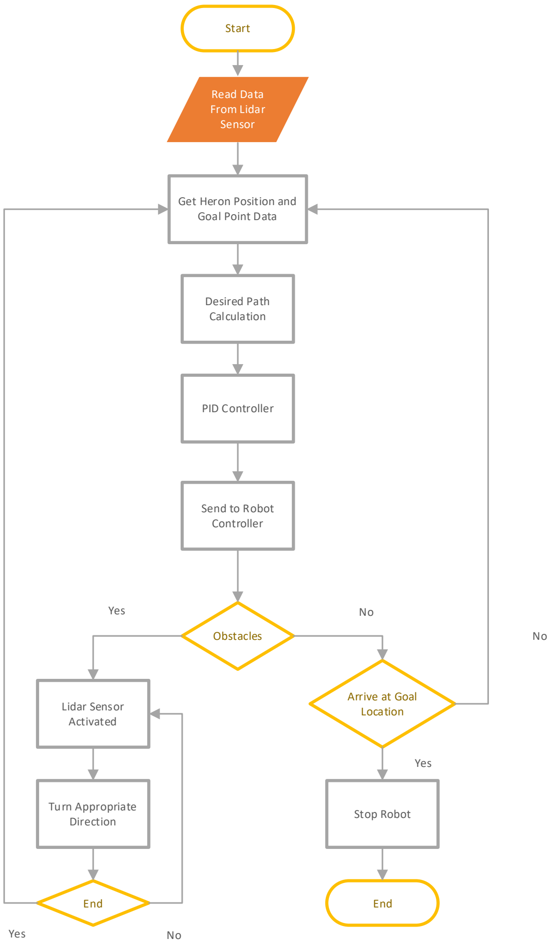


Figure 4: Flow chart for autonomous navigation

Since the Heron hardware is mounted with the lidar sensor, it will transmit the 30 signal to collect the data of the Heron USV surrounding first and the Heron USV will read the data from the lidar sensor. This data is to get the initial Heron position and to get the Heron's goal point. Also, this data will be used for localized the Heron position and to create the map by using the SLAM algorithm. After getting the Heron position and goal point, the desired path will be calculated by using the global cost map and global path planning. It will create a path for Heron to navigate safely. The function of the PID controller is to track the maneuver of a self-driving vehicle and to regulate a system to effectively follow a desired path. The robot controller will receive the data and will drive the vehicle to the desired path. Another function of the lidar sensor is to detect if there are obstacles around the Heron vehicle then it will reset the position of the Heron USV until there are no obstacles along the Heron path..

B. Autonomous SLAM algorithm

The Simultaneous Localization and Mapping (SLAM) method is used to determine vessel position while simultaneously developing and updating a map of an unknown environment. The robot employs measuring devices and sensors to establish its location by utilizing landmarks. Many types of SLAM algorithms exist but in this paper, the SLAM algorithm used is the GMapping algorithm. GMapping is an extremely capable Rao-Blackwellized particle filter that generates grid maps from laser data. As a ROS node named slam GMapping, the GMapping package enables laser-based SLAM [5]. It can construct a 2-D occupancy grid map using laser and posture data collected by a mobile robot using slam GMapping. The laser data is generated from the Velodyne VLP16 lidar sensor data.

C. Path Planning, Obstacle Avoidance and Actuation

Path planning algorithms consist of two (2) navigation planning which is global path planning and local path planning. The global path planner can generate a path in an entirely known environment. The occupancy grid map, which is SLAM-based, shows whether the grid area is occupied or not to plan the path [6]. While the local path planner is a method that uses sensor data to determine whether there is any object or obstacle along the route and will avoid the object by constructing a new route that is safer and shorter.

Figure 5 shows the Heron USV ROS computational graph. Furthermore, the recovery behaviors are included in the algorithm to provide safety precautions if the vessel detects itself to be stuck or collides. The USV contains many nodes including the vessel model, sensors, SLAM, Odometry, path planning and obstacle avoidance, and vessel controller. Each of these nodes has its topic that is connected to perform the autonomous navigation for USV. For example, the scan topic was connected to the SLAM topic to send the data from the laser to perform the SLAM algorithm.

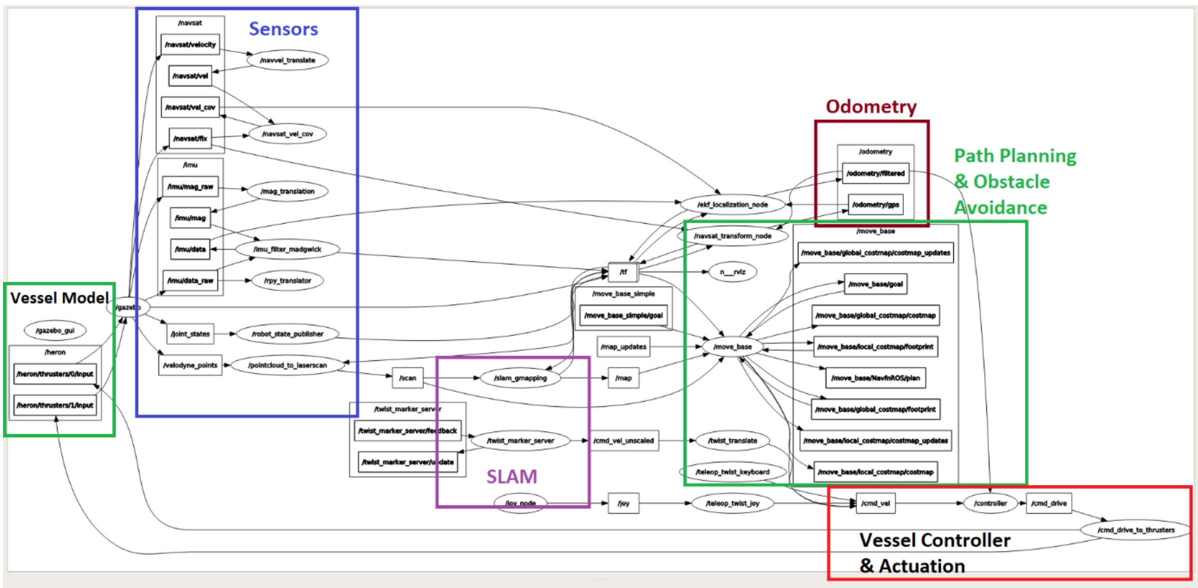


Figure 5: Heron USV ROS Computational Graph

3. Results and Discussion

This chapter describes the outcomes of an experimental program for the Clearpath Heron M300's simulation-based autonomous vessel navigation system. This involves displaying a real-world illustration of the hardware vessel, which is the Clearpath Heron USV. This experimental program uses the developed autonomous SLAM algorithm to detect objects using the point cloud data from a 3D lidar sensor. The algorithm will then simultaneously create a map of the surrounding area and update it as the vehicle conducts autonomous exploration in the uncharted territory [7]. Moreover, it has been demonstrated that the path-planning algorithm can maneuver and navigate to the target point while avoiding static obstacles. Lastly, the last test is for the Heron vessel to perform autonomous obstacle avoidance of any obstacles, whether static or dynamic while doing exploration.

3.1 Autonomous SLAM Algorithm

Before the development of the autonomous SLAM algorithm, the Clearpath Heron vessel was mounted with a Velodyne VLP-16 3D lidar sensor, as shown in Figure 6, to detect objects in the proximity of the vessel, as well as a PTZ axis camera to capture a visual on top of the heron.

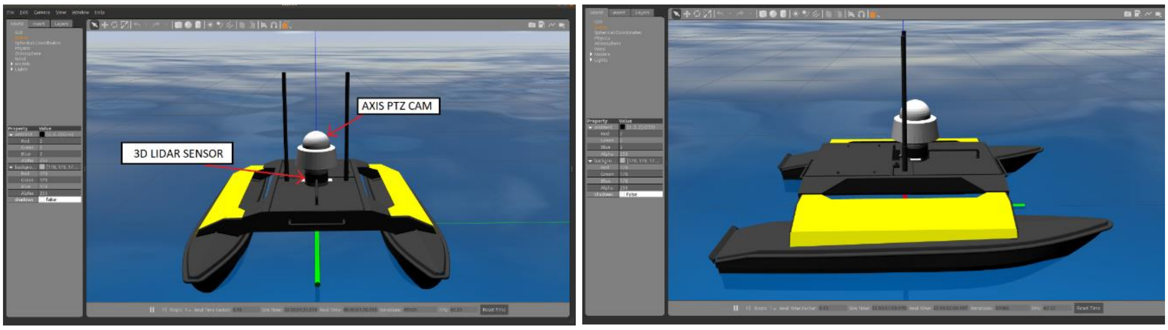


Figure 6: Heron Vessel Mounted with 3D Lidar Sensor and Axis PTZ Camera

Once installing the 3D lidar sensor, it ought to be tested to determine the sensor's object detection capabilities and accuracy so that it can be used in the autonomous SLAM algorithm. This test is performed in two conditions which are without objects around the vessel and with objects around the vessel. The results showed that this test analyzed several outcomes, such as the range of the laser scan, obstacle range, and ray trace range.

Figure 7 shows the result of the laser scan. A laser scan is a laser light emitted by a 3D lidar sensor at a distance of 0.45 meters to 7 meters and a height of -0.1 meters to 0.7 meters. Because the vessel will travel beneath the pipeline, the height of the laser must be measured. Because the heron's maximum height is 0.32 meters, it is convenient to set the laser's maximum height to 0.7 meters. As a result, when an object is within this range, the laser ray (yellow dot line) is visible in the RVIZ.

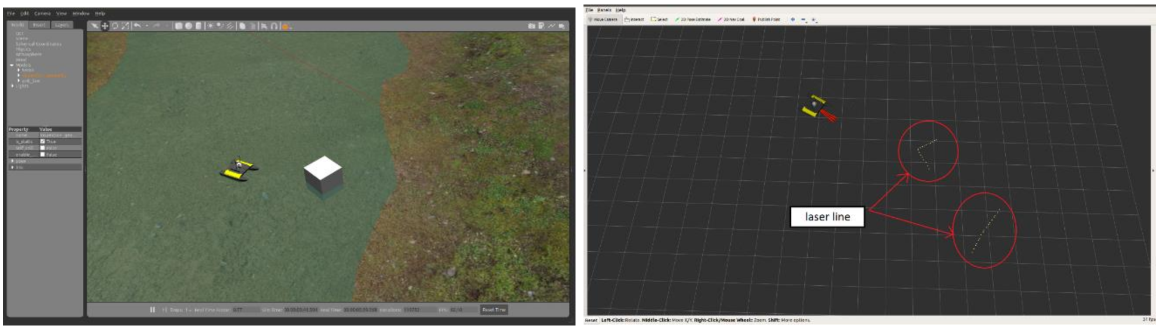


Figure 7: The Result of The Laser Scan

Figure 8 shows the range of ray traces and obstacles. Here, the ray trace range parameter specifies the range of free space that will be raytraced given a sensor reading. Setting it to 7.0 meters means that the robot will try to clear space in front of it up to 7.0 meters away based on sensor readings.

In the RVIZ, the dark area is the area that the sensor has explored, whereas the bright area is the area that the sensor has not observed. As a result, when the heron passes through an unknown location, the bright area darkens. Besides, the obstacle range configuration observed by the lidar sensor is set at 6.5 meters, which indicates that the robot will only update its map with data about obstacles that are within 6.5 meters of the lidar sensor base. If there are any objects or obstacles within this range, the sensor will detect the object and will be displaying the blue light around the object in RVIZ as shown in Figure 8.

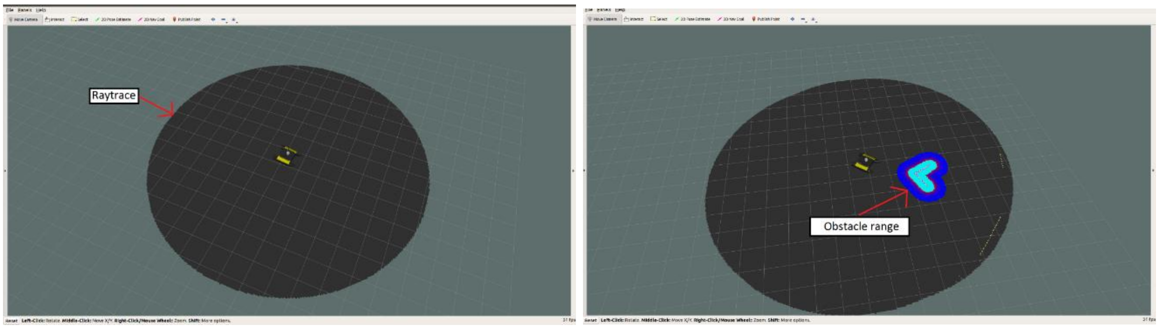
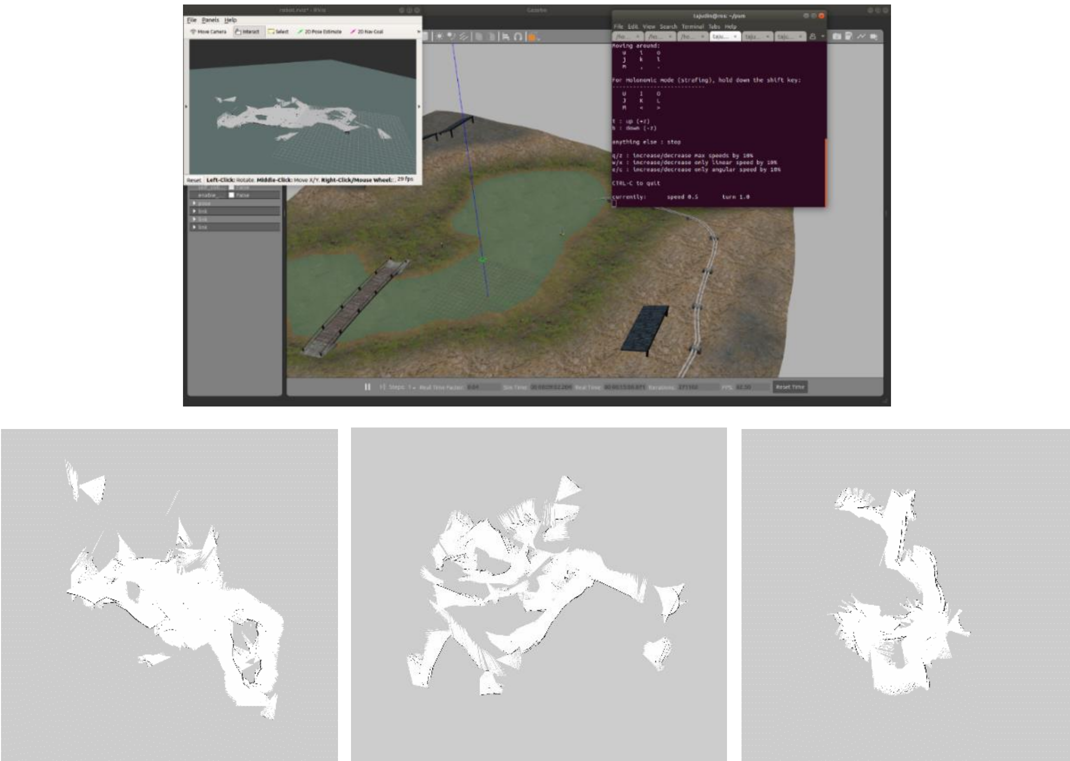


Figure 8: The Range of Ray trace and Obstacle

Figure 9 shows the map created by the SLAM algorithm. According to the results of the tests, the heron can construct a map by using data from the lidar sensor while exploring, and it performed multiple experiments to determine the accuracy. While controlling the Heron vessel by keyboard, it will explore the area and will generate the map. It is called GMapping. This test was repeated several times, and the findings revealed that all the tests were capable of producing a map, however, the map produced was not particularly accurate. This data is needed when navigating to perform pipeline inspections in environments with numerous hazards such as pipeline racks, rocks, or any other thing that could cause an accident to the USV. The USV will avoid obstacles along the path to perform the inspection by using the data obtained. Also, this data can generate a map by scanning the environment while navigating for performing the inspection in an unknown environment.



Map 1 Map 2 Map 3

Figure 9: Map created by the SLAM algorithm

Based on the Figure 9, it was found that the map generated by Heron USV was not particularly accurate with the simulation world. This error occurs when the heron starts moving from its start position, and the global cost map from SLAM is randomly moved. So, the position of any obstacle or lake bank detected by the heron will always change, causing the generated map to be inaccurate. But, the map still can be generated.

3.2 USV Path Planning, Obstacle Avoidance and Actuation

Path planning algorithm is a trajectory planning method that allows a robot to navigate from a starting configuration to a goal configuration by constructing a path to complete a task. It is made up of two parts: 1) global path planner and 2) local path planner. The global path planner can generate a path in an entirely known environment. The occupancy grid map, which is SLAM-based, shows whether the grid area is occupied or not to plan the path. While the local path planner is a method that uses sensor data to determine whether there is any object or obstacle along the route and will avoid the object by constructing a new route that is safer and shorter.

Figure 10 shows a test for Heron USV to navigate on the lake environment map that has been generated by SLAM GMapping. The result of this study indicates that even with an inaccurate map, Heron vessels still can plan the path to avoid the obstacles and can navigate in the environment while avoiding the obstacles. By setting up the location of the Heron and setting up the goal, Heron will find the shortest path while avoiding the obstacles.

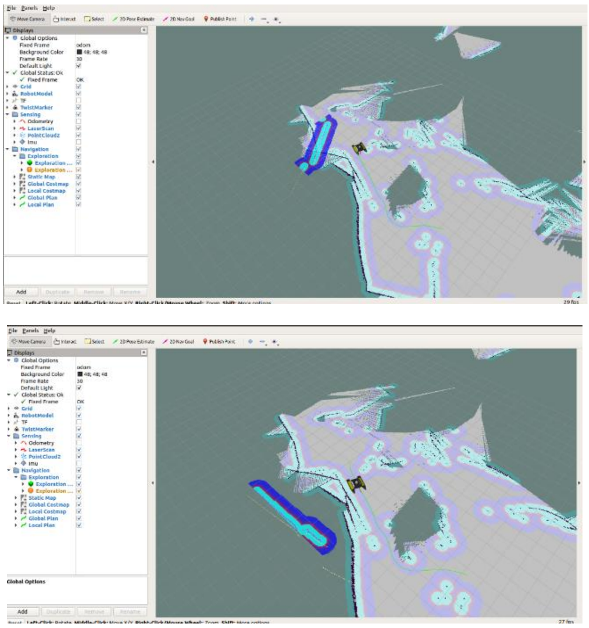
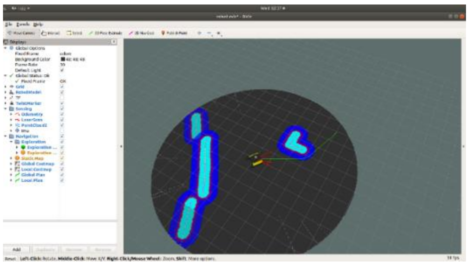
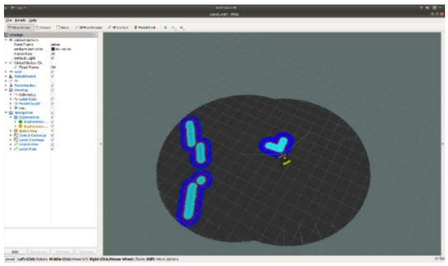


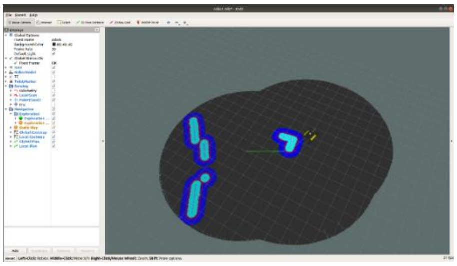
Figure 10: Path planning and Obstacle avoidance in generated map

Figure 11 shows a test without a generated map. For the result in Figure 10, it is hard to see the Heron navigating to the goal while avoiding the obstacles because the map is a bit fuzzy and not accurate. Also, when the goal point is set too far, the Heron is not able to reach the goal however it will randomly move anywhere. So, the Heron has been tested without using the generated map to navigate to the goal while avoiding the obstacle as shown in Figure 11.





a) Start point b) Obstacle avoidance



c) Goal point

Figure 11: Path Planning Test Without Generated Map

Referring to the result above, it was known that the Heron USV was navigated along the path from the starting point to the goal point while avoiding the obstacle near the vessel. The green line is the path planner that has been produced for heron followed. All of the results in this experiment were obtained through simulation as a reference to the real-world pipeline environment. This USV's movement represents how it will operate when performing pipeline inspection in terms of navigating through the pipeline till it reaches its goal while avoiding hitting any objects along the way. As a result, the effectiveness of path planning and obstacle avoidance can be used to replace pipeline inspection by workers.

4. Conclusion

ROS based autonomous navigation on heron is currently still in working progress as there are several errors and failure for each experiment. 90% of the overall progress made so far has been successful. The project 's objectives, which included developing an algorithm for autonomous navigation and visual pipeline inspection as well as integrating hardware and software for Heron USV to accomplish these tasks, were met, but the navigation system still has some issues. In conclusion, this project still has many things that can be improved to make this project perfect and can be used in the future. By doing the experimental programmed, it can give an impression of the effectiveness and able to evaluate the performance of the proposed algorithm in this project produces.

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