Barrett, Vandor & Kohler: Past Iteration of RoboFish

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Applying Structured Light Laser Imaging to Underwater Obstacle Avoidance and Navigation

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***Abstract*—Identifying and safely navigating submerged obstacles in shallow waters is a difficult task as common navigation technologies based on acoustic sensing systems are not efficient in littoral zones[5]. Developing a vehicle-mounted active 3D reconstruction (structured light) imaging system that can be used for real-time obstacle detection and avoidance is now a viable approach to solving littoral navigation due to its affordability. Structured light has been researched and demonstrated as an object reconstruction technique, with particular focus on three-dimensional mapping and scanning[6]. Although it has been successfully applied to object reconstruction, utilizing the structured light data as an input to the on-board navigation stack has not yet been extensively tested. As a proven solution for highly accurate object reconstruction, the application of structured light to obstacle avoidance provides promise for improved vehicle navigation in littoral waters.**

The proposed sensing system is comprised of a single USB webcam and a blue-green line laser that can be easily integrated into existing computing hardware. By filtering the wavelengths of light viewable by the camera such that the only detected light is that produced by the laser, software on-board the vehicle can detect the laser line accurately under the majority of conditions. The object recognition and range estimation algorithms output estimates of an obstacles position based on the position of the laser line detected in the filtered camera frame.

The obstacle avoidance algorithm calculates the best route based on the structured light input by iterating through an array of distance values and optimizing for the largest section of clear water. The on-board vehicle controller then dynamically sets motor values and directions to maneuver around obstacles.

Keywords - Structured Light, Underwater Vehicles, Obstacle Avoidance

I. Introduction

Autonomous Underwater Vehicles (AUVs) have a wide range of applications in marine sciences, and are prevalent in the scientific, military, commercial, and policy sectors. The ability of AUVs to operate independently and take high-resolution sensing systems into extreme environments has revolutionized our understanding of oceanic ecosystems. Many of the systems that exist today are highly functional for these extreme oceanic environments, but are ill-suited for the challenges unique to shallow water navigation[4]. Developing AUVs capable of shallow water navigation requires new sensing systems specifically designed for shallow water environments. To that end, the Olin College Robotics Laboratory has developed a proof of concept sensing and software system that uses structured light to develop range estimates and integrate those estimations directly into the on-board vehicle navigation suite.

II. Littoral Water Vehicle Navigation

Many of the existing underwater vehicle solutions are designed for long endurance and/or open water exploration and sensing missions. As a result, these systems take advantage of sonar, Acoustic Doppler current profilers, and other well-developed aquatic navigation solutions pioneered decades ago and moderately improved upon in modern vehicles[7]. While these types of sensing systems are adept at navigating open water, they are poorly designed for shallow water environments that have more variation in bottom profile, noise due to increased traffic near shore, and other factors mitigating the effectiveness of common underwater vehicle navigation techniques[1]. As the undersea robotics industry progresses, vehicles will need to be more adept and capable of operating under a wide range of conditions and environments without relying on a single sensor or sensor type (i.e. motion, magnetism, proximity, etc.) for navigation[8]. To that end, more research is being conducted into optical and other sensing systems not as well-researched in undersea environments.

Structured light laser imaging systems are currently in use within the ocean sciences community largely for highly accurate imaging and mapping of the seafloor. These systems work by projecting a known pattern of light onto a scene using a laser and utilizing the deformation of that pattern on objects within the scene to calculate the depth and surface information of those objects[6].

The main benefit of optical systems over other methods of range sensing underwater are the higher accuracy and resolution provided by 3D reconstruction underwater. There are two types of optical techniques for 3D reconstruction underwater: active techniques and passive techniques. Active techniques are largely based on structured light imaging to determine the distance between the vehicle and the object while passive techniques fuse multiple views of the same scene to acquire an accurate picture of the object underwater[2].

While both methods of active optical 3D reconstruction are affected by scattering and absorption underwater, structured light sources allow imaging at longer distances and provide higher contrast[2]. As a result, the research conducted focused on developing a proof of concept structured light imaging system.

III. System Development

The structured light laser imaging system consists primarily of software with representative hardware used for development and prototyping. The software system has three major components: the laser input into the camera, the range estimation, and the obstacle avoidance algorithms integrated directly into the vehicle controller. Figure 1 below shows the laser, filter, and camera as mounted on a proof-of-concept system used for testing and validation.

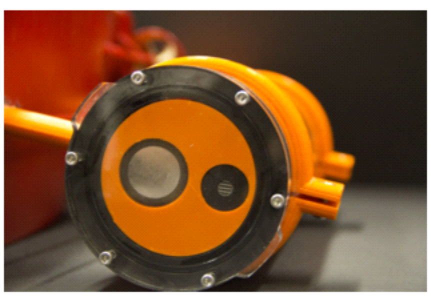

Fig. 1. The camera, laser, and filter system installed on the prototype test bed vehicle.

The system works by projecting a blue-green laser line onto the environment within the field of view of the on-board camera. Range estimation is calculated by adjusting the slope of the projected line based on the relative angle of the laser and fitting an equation based on that slope to a known equation. These range values are then passed into an obstacle avoidance algorithm that iterates through range values and optimizes for the largest clear section of water. The obstacle avoidance algorithm is tied directly into the on-board vehicle controller, allowing motor speed and directions to adjust dynamically based on the output of the structured light sensing system. Figure 2 describes the flow of information through the system.

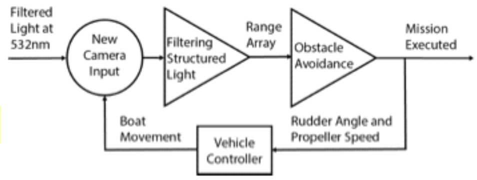

Fig. 2. The flow of information through the system, from the camera input to the obstacle avoidance output to the vehicle controller.

A. *Sensing System*

Given the need for real-time control of the vehicle, the sensing system data-flow was designed to be as efficient as possible. The sensing system consists of a common USB webcam and a 532nm blue-green line laser chosen for its ability to pass through water. A traditional coated band-pass filter is placed over the camera such that the only wavelengths visible are those centered around the 532nm line laser. The camera runs at a maximum of thirty frames per second, but data is processed asynchronously. Data from the camera and the laser is then passed via serial to an on-board Odroid XU4 computer that runs all of the processing and range estimation software. Using low-cost, off the shelf sensor components and 3D-printed mounting hardware allowed the structured light system to remain affordable at a sub $500 price point. Table III-A below shows the full bill of materials for the proposed structured light sensing system as developed for the proof of concept. Future implementations that incorporate the structured light system internal to a vehicle circumvent the need for external waterproofing and will thus be even cheaper.

Bill of Materials	
Primary Components	Cost
Blue Robotics Pressure Hull	$143.00
Blue Robotics 6mm Cable Penetrator	$4.00
Blue Robotics Acylic End Cap	$10.00
532nm Green Laser Line Module	$54.16
Edmund Optics 25nm Diameter Filter	$105.00
Microsoft Lifecam Cinema	$43.55
ODROID-XU4	$113.70
Total:$473.41	

B. *Software System*

The software system is comprised of four main steps: calibration, computer vision filtering, laser ranging, and distance estimation. Initially, calibration is conducted to set accurate values based on current lighting and water conditions. A hue, saturation, value (HSV) mask, brightness, and other camera calibration variables are set utilizing OpenCV in order to isolate the intensity of the laser line within the image. Previous distance value arrays are also passed into the system and used as the basis to calculate distance from the camera to an array of the center of mass of the pixels that make up the laser reflection. These values are then optimized and iterated upon for a set of known distances to better tune the calibration. This accurate calibration file is then saved separately and utilized during live operation of the system.

During live operation, the on-board Odroid XU4 computer takes raw input from the USB camera and the blue-green line laser and immediately applies common OpenCV filtering techniques and brightness, auto-focus, and masking adjustments to further enhance the camera image. An OpenCV line is then projected onto the image optimizing for the highest light intensities within the camera's field of view. This allows the line projected on the camera image to closely approximate the actual laser line. The height of the projected line is then corrected based on the angle of the laser to create a more accurate pixel height value. A range estimate is created using the equation $a * b * log(x - c)$ where a, b, and c are distance coefficients (in pixels) from the calibration process, and x is the height of the projected laser line in pixels. Lastly, this pixel range value is converted into meters to generate a realistic range value to a detected object[3]. The estimated ranges to obstacles in the field of view are stored as an array of range values. Figure 3 shows an example output from the range estimation system.

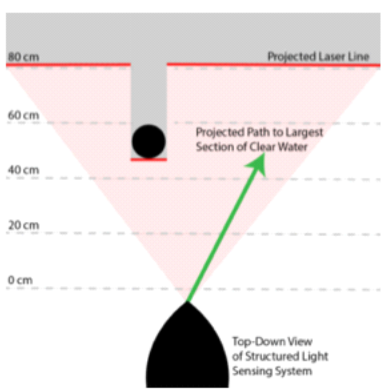

Fig. 3. A top-down view of the output of the range estimator on the filtered and processed camera image.

These real-time range estimates are then passed to the obstacle avoidance algorithm to calculate the best path through the water using Robot Operating System (ROS). ROS allows for the efficient passage of data through the system as a consequence of its publish-subscribe architecture. Each component of the software system is treated as its own ROS topic such that it can subscribe to topics for use as inputs and publish messages on its own topic. The diagram below describes the flow of ROS messages through the system.

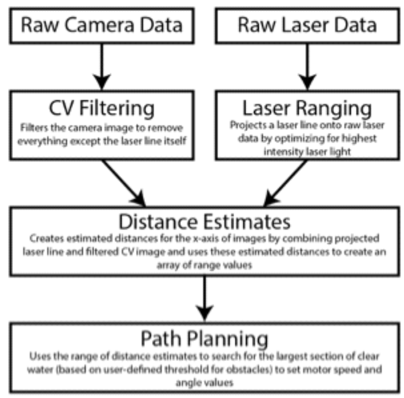

Fig. 4. A diagram describing the flow of information through the software system.

The obstacle avoidance algorithm subscribes to the published range estimation values and calculates the best path for the vehicle by iterating through range estimation values to find the largest consecutive set of numbers above a user-defined threshold, representing the largest section of clear water. The user-defined threshold allows for precise tuning of the path planning system. This enables users to define a close threshold and faster but potentially less accurate obstacle avoidance or slower and more accurate obstacle avoidance from the system. Once a gap between obstacles is found, the vehicle then converts the location of the gap in pixels to motor angles and determines an appropriate speed value based on the distance to the detected obstacle. Motor angles and corresponding speed values are then published and passed via serial communication to the on-board Arduino vehicle controller. The on-board vehicle controller constantly reads the serial input from the obstacle avoidance system and adjusts motor speed values and angles dynamically.

C. Vehicle Prototyping and Development

A test bed vehicle platform was developed to validate the proof of concept structured light system when integrated into a vehicle. For the purposes of field testing, a 21" long model-scale tugboat was used with the structured light sensor system in its own waterproof pressure hull. Figure 5 shows the current test bed.

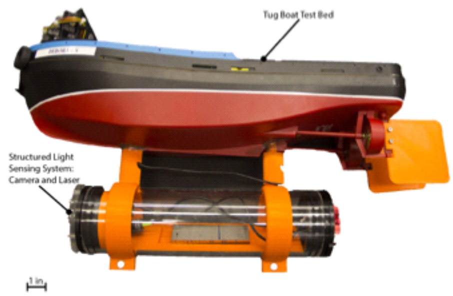

Fig. 5. The test bed vehicle platform for proving the feasibility of the structured light sensing system at detecting and avoiding obstacles underwater.

The benefit of testing the structured light sensing system in this manner is the ability to quickly troubleshoot issues directly and to test the system on a vehicle with predictable behaviors. While this platform clearly demonstrates the utility of the structured light sensing system for surface vessels, it can just as readily be integrated directly into an autonomous underwater vehicle. The next iteration is intended for integration into an underwater vehicle to more robustly test the structured light sensing system.

IV. Testing

A. Experimental Methods

Before the structured light sensing system could be fully deployed, testing was done in multiple phases to prove out each component of the system. Initial testing was done with a laser and camera to test the ability of the camera to recognize laser deformations on obstacles within the field of view. Further testing was done with with the laser and camera and a simulated boat to refine the ranging and obstacle avoidance algorithms. Once the structured light sensing and vehicle systems were refined, a full system test was done on the test bed vehicle platform with two submerged columns in the Olin College Robotics Lab research pool.

B. Process

The process for testing the sensing system was split into phases of functionality. The first tests were performed to show the sensor could recognize objects at specific distances, then at specific distances with varied positions in the field of view. After this standard was met, the navigation algorithm was tested above water in a static, controlled test environment. These tests include a fixed laser setup attached to a fully simulated vehicle as well as the actual prototype vehicle test bed.

After these two points of functionality were met, the system was calibrated and tested in a series of situations underwater. In-water testing consisted initially of a single obstacle placed directly in front of the vehicle and grew progressively more complex. Figure 6 shows an example testing configuration in which the boat was stationary in the water and the structured light sensing system accurately planned a path for the largest section of clear water between the two obstacles.

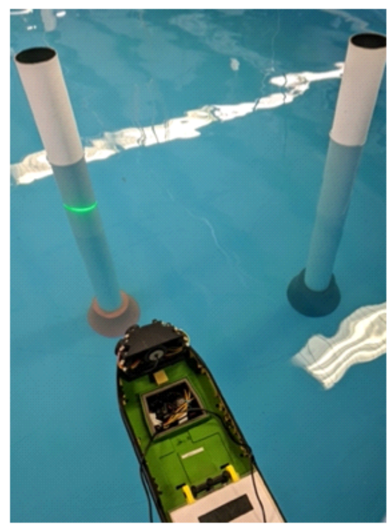

Fig. 6. An example in-water testing configuration in which the structured light sensing system must accurately detect the obstacles and the on-board vehicle controller determines the largest section of clear water between the obstacles.

C. Results

Results from the full system test of the structured light sensing system integrated directly into the on-board vehicle navigation conclusively show that such a system can be used for obstacle avoidance in near real-time conditions. Sensor output was accurate over a range of 70cm, with accuracy consistently within three centimeters as described in figure 7.

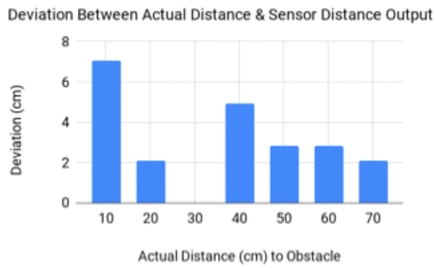

Fig. 7. This graph shows the deviation of the sensor from the actual or measured distance at each 10 centimeter interval. The deviation reduces in the 50-70 centimeter range, suggesting further testing could show greater accuracy in that range.

Furthermore, the system performed remarkably well under increasingly more difficult conditions. Figure 8 shows the results of a fully simulated test in which the large arrow represents the intended direction of the boat.

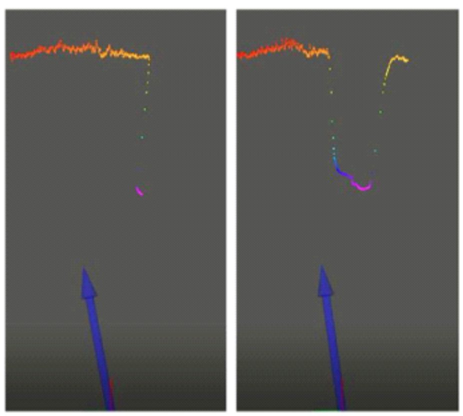

Fig. 8. This figure shows the simulation results where a moving obstacle is detected in two different frames and the plan planning algorithm updates the direction of motion.

The structured light sensing system was also tested while the vehicle was moving. Initial testing proved that the system was capable of accurately avoiding a single obstacle in the field of view. Further testing proved that the vehicle is capable of navigating around columns at varying distances, around columns placed next to one another, and between columns on either edge of the field of view. See the Pathfinder testing playlist for videos from vehicle testing. Figure 9 shows the comparison between sensor system output and actual measured distance during vehicle testing.

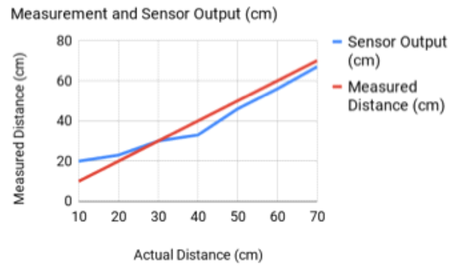

Fig. 9. The graph illustrates the accuracy of the sensor when detecting obstacles at varied distances. The blue line is the output of the sensor and the red line is the measured or actual distance of the obstacle from the sensor.

V. Conclusion

Based on the developed system and results from preliminary testing, utilizing structured light sensing is an accurate and feasible method for obstacle avoidance underwater. Incorporating this structured light sensing system into shallow water vehicles will remove the reliance on single-sensor based systems.

The structured light sensing system integrated into littoral water vehicles should also enable more robust navigation in shallow waters. Improved shallow water navigation will allow scientists, military operators, businesses, and private citizens to develop a better understanding of the coastal environments around them. With easy external and internal implementation into new and existing vehicle platforms, the proposed structured light sensing system has the potential to be a cost-efficient method for conducting coastal ecosystem research and understanding more about the day-to-day state of these waters. By making littoral zones more easily navigable, the proposed structured light sensing system should be able to open up coastal research and data collection to a much broader community, thereby increasing the interest of the scientific community and encouraging further innovation in the space.

A. Considerations for future work

Given the success of the proof of concept phase of the project, further iterations will focus on refining and improving the existing system. Preliminary field testing, while useful in validating the success of the system, demonstrated the limited range of the current structured light sensing system. As a result, much of the future work will focus on improving the blue-green line laser and camera to extend the range of the system as far as possible. The range sensing and obstacle avoidance algorithms will also be iterated upon to account for the improved sensor setup. The improved system will also undergo turbidity testing to determine the success of the sensing system under adverse environmental conditions. Extending the range of the system and meeting the challenges associated with turbid water and increased attenuation under real-world conditions should exponentially improve the next iteration of the structured light sensing and software system.

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