Low-Cost Autonomous Surface Vehicle for Water Monitoring

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Abstract

Water bodies are central to communities, and provide countless societal and ecological benefits. Human harm in the form of pollution and climate change has done nearly permanent damage to these habitats, and a lack of effective monitoring of these water sources has made it challenging to assess the damage done. While methods such as manual water sampling exist, problems arise when considering the ability of these approaches in allowing real-time monitoring and free movement. In this study, through a rigorous build and testing process, we introduce a novel, low-cost Autonomous Surface Vehicle (ASV) with offline waypoint movement and a comprehensive object avoidance system. Utilizing a cost-effective USB camera-based system for perception, the introduced ASV reduces costs by over 80%, while effectively maneuvering around obstructions and moving on command. The ASV has the potential to be used in under-resourced communities to understand the health of water bodies, as well as to allow individuals to adapt to changes caused by ecological destruction. The system may aid in enabling widespread environmental monitoring and effective conservation efforts, improving community and ecosystem wellbeing.

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Key Words

water monitoring, autonomous surface vehicle, data collection, environmental conservation, cost-effectiveness

Abbreviations & Acronyms

autonomous surface vehicle (ASV), artificial intelligence (AI), red-green-blue (RGB), laser imaging/detection/ranging (LIDAR), central or graphics processing unit (CPU, GPU), global positioning system (GPS)

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Biography

Mihir Garimella is a student at Nashua High School South in Nashua, NH. Mihir is passionate about research on various issues that involve AI, robotics, and the sciences, specifically the application of models in healthcare and environmental studies. He loves working on solutions to problems to help his community through various organizations and programs, such as HSxAI, an outreach program Mihir started to introduce high schoolers to AI through casual, conversational discussions with leading researchers. At school, Mihir is a senior member of the FIRST Robotics Team, as well as a member of student government, and president of the AI and Science Research clubs. Outside of academics, Mihir is on the varsity swim and tennis teams, and enjoys listening to music, boxing, and programming. Mihir plans to study computer science and economics in the future

Introduction

Coastal areas and inland water bodies play an important role in the overall health of an ecosystem. Being beneficial ecologically, aesthetically, culturally and economically, the long-term sustenance of such habitats is crucial to surrounding communities and biodiversity (Caissie et al. 2012). While efforts are made to improve the global supply of freshwater, a mix of harmful factors introduced within the last 50 years has made ensuring the wellbeing of water bodies increasingly difficult. Challenges such as climate change, pollution, and environmental disturbance caused by humans in pursuit of various natural resources, all contribute to declining optimism in the future survival of vital water features (Chaudhry & Malik 2017).

To best allow nearby communities to learn from, adapt to, and push back against, the countless negative changes taking place in water resources central to their own lives, water monitoring and other similar techniques have been used. Monitoring the quality of water in coastal areas and water bodies is crucial for identifying sources of pollutants, understanding climate trends, and assessing adherence to water usage policies.

In the realm of water monitoring, scientists have employed methods including manual sampling, high-frequency monitoring buoys, and remote sensing (Zainurin et al. 2022). These techniques, while effective situationally, fail to account for aspects such as real-time monitoring, and advanced studying of spatiotemporal variations (microtrends) in smaller, task-relevant sections of water bodies. To solve these issues, the rapid introduction of more capable technological tools since the start of the 21st century has enabled the advent of autonomous surface vehicles (ASV) (Jeong et al. 2020).

In the specific case of water monitoring, ASVs have been seen as large, boat-like robots that float on the surface of a water body, carrying an array of devices including various monitoring devices related to specific features of water bodies, and a central hub facilitating communication between data collected on-board and a receiver on shore. The unique characteristics of ASVs effectively overcome conventional problems of on-demand monitoring and information abundance to observe region-specific changes by providing a constant stream of data from random points in the water body, as well as from the same region at different time periods.

Improvements from the ASV, however, come with additional drawbacks, namely expensive utilization costs and restricted movement flexibility in the face of obstacles (Kimball et al. 2014). In this study, we introduce a novel low-cost ASV, programmed with a waypoint navigation system and AI-based object avoidance mechanisms to ensure full vehicle safety and real-time, location-specific, data delivery. Constructed with a focus on a modular and cost-effective design for monitoring, and the integration of an automated waypoint navigation and an object perception, avoidance strategy, the designed ASV provides a cheap and safe method of monitoring bodies of water, allowing under-resourced communities an effective method of understanding ecosystems fundamental to survival.

Materials and Methods

Physical Design

The ASV introduced (Catabot-6) was designed with goals of stability, maneuverability, modularity, and cost-effectiveness. Structurally similar to a catamaran, Catabot-6 is built atop of two buoyant pontoons connected by a metal frame (See Figure 1). The decision to use such a structure in favor of an alternative design, such as a monohull vehicle, stems from the relatively low draft caused by catamaran boats, making them safer in shallower waters (Wei-Yuan Dzan et al. 2013). Located on the undersides of each of the pontoons, BlueRobotics T200 motors are used to propel Catabot-6 in the water based on movement information provided by the central electrical box used for full connection of the system. With a simple wiring setup, the motors provide a powerful acceleration system for the vehicle while reducing potential room for error.

Figure 1. Image of Catabot-6, with pontoons, main frame, and electrical box.

To accomplish a modular design, Catabot-6 consists of a primary base of an electrical box, metal frame, pontoons and motors. This approach allows for the addition of sensors and components for specific tasks in an unobtrusive manner, not affecting the performance of the vehicle. This includes water monitoring devices, such as the 3 sensors built into the system, detecting levels of pH, temperature, and distilled oxygen.

In accordance with the cost-effective objectives, cost-efficient parts were used whenever viable. Most noticeably, Catabot-6 utilizes a single RGB camera to assist navigation in contrast to the typical LIDAR systems found on ASVs. While this approach introduces severe challenges in terms of visibility and resolution which complicate the navigation design, the choice to use a standard camera reduced imaging costs by over 99% ($100 vs. $10,000).

The Jetson Nano is utilized as the primary onboard computer, running all navigation and object avoidance programs independently on the vehicle. In addition to its standard CPU, the Nano has a built-in GPU, a necessity when dealing with high rates of image data as expected from the RGB camera. The on-board GPU allows Catabot-6 to handle data, process images, and make calculations at a much faster rate than if there was only a CPU, ensuring safety of the vehicle through more efficient decision making and processing.

To connect the physical system to the control station on land, a BlueRobotics Navigator Flight Controller and Raspberry Pi 4b are used in conjunction. The flight controller serves as a main hub for all devices, including the GPS and radio. An image of the electrical box and full relevant schematic is provided in Figure 2. However, as the specifications make it incompatible with the Jetson Nano on-board, the Flight Controller is routed through a Raspberry Pi. Used as a second computer, the Raspberry Pi allows for compatibility, connection, and streamlined data communication between the Flight Controller and the Jetson Nano.

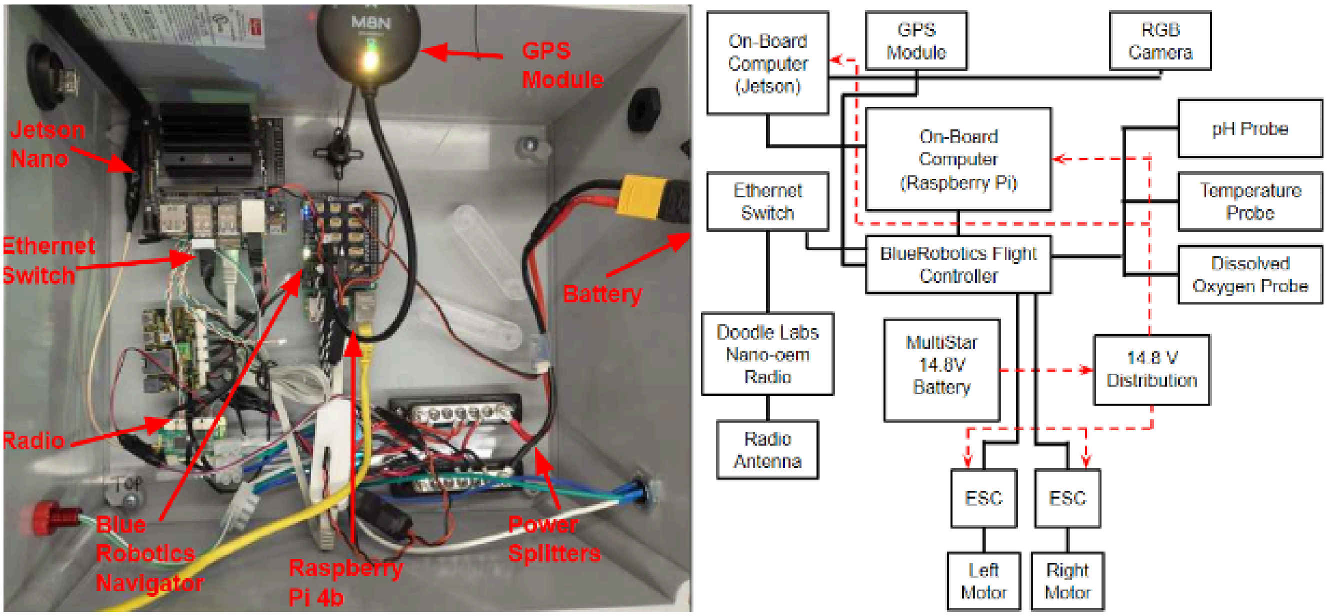

Figure 2. Annotated electrical box, and full schematic of components on Catabot-6

System Logic

Many surface vehicles are designed to be used as vehicles to collect data for water based studies in different fields. Consequently, autonomy is a valuable feature, reducing researcher involvement and collecting data passively. Many strategies to ensure the safe movement of ASVs have been tested, many of which rely on various unsupervised learning techniques. Methods range from Deep Reinforcement Learning to Neural Networks (Cai et al. 2021). Others have attempted to create more explainable and understandable strategies centered around mathematical algorithms, such as Kalman Filtering (Herlambang et al. 2020).

Catabot-6 is programmed with different levels of autonomy to allow for varying levels of control by the user. In manual mode, a remote controller is used to navigate the bot via movement of joysticks, allowing Catabot-6 to move in all 4 cardinal directions. In Guided mode, full control of the bot is given to a set of programs for complete autonomous movement. With the development of a low cost vehicle, the capability of navigation focused hardware onboard differs significantly from other ASVs. To account for this, the autonomy of Catabot-6 is split into two distinct processes: Waypoint Navigation and Object Detection/Avoidance.

Waypoint Navigation is initialized with set target coordinates provided by a navigator at start. At every step in Catabot-6s navigation, the shortest straight line path from the position of the bot to target coordinates is calculated. The bot then rotates to align with the determined path via motor updates sent through Robot Operating System (ROS) middleware, and then moves straight forward at a constant speed.

It is not enough, however, to assume that we can travel to our waypoint unobstructed. Compared to the design of other ASV, we are restricted by the amount of equipment we can utilize to understand the area around our robot, with a RGB USB camera being used in favor of a more expensive LIDAR system. Catabot-6 is programmed to overcome these limitations through an explainable and effective avoidance system. Pixel data from the cameras is first processed from our onboard camera using Python as our primary backend language. We utilize the state-of-the-art open-source YOLOv8 algorithm to identify and report objects in the surroundings of Catabot-6. The smaller YOLOv8s architecture was implemented for lightweight implementation and efficient decision-making. The model consists of a series of 3 primary networks which together identify features in RGB images and use Feature Pyramid Networks to summarize these low-level characteristics to general representations (Yang et al. 2023). Catabot-6 camera data is segmented with YOLOv8s to identify prominent objects in the surrounding area and determine if the immediate forward path of Catabot-6 is blocked, accounting for a safety margin and the size of the bot. When an obstructive object is detected, we implement a simple and efficient avoidance algorithm to move around the object, displayed by Figure 3.

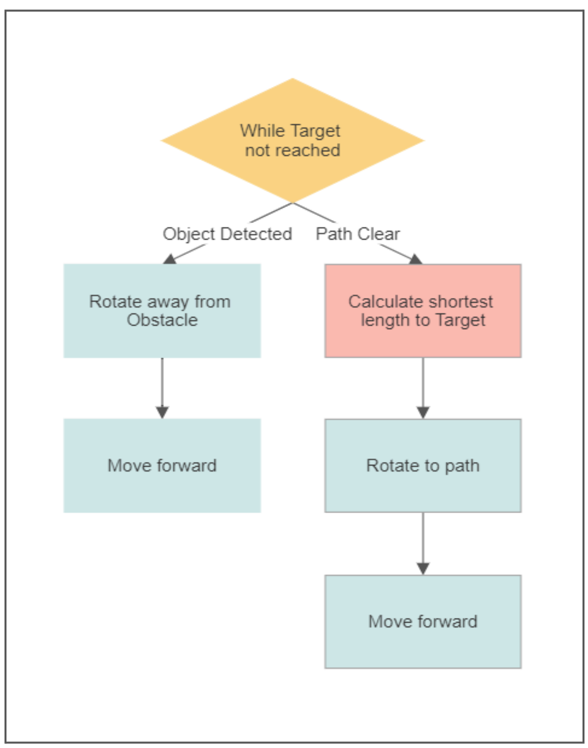

Figure 3. Flowchart diagram of object avoidance and waypoint navigation system

When used together, the Waypoint Navigation and Object Avoidance strategies work to move Catabot-6 to discrete points. This can be applied to a variety of tasks, including data collection at individual locations in a body of water, or mapping out complete strips or sections of these habitats. Figure 4 displays an example scenario in which Catabot-6 is forced to make a decision to navigate around an obstacle and reach a target.

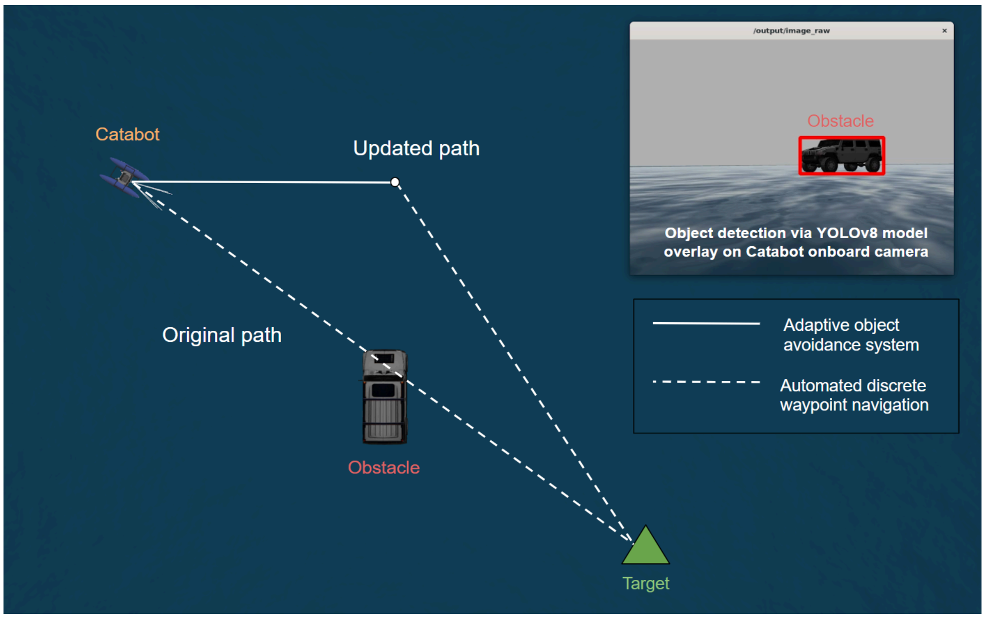

Figure 4. Catabot-6 Decision Making Process in Obstructed Path Example

Results

Catabot-6 effectively accomplishes the objectives set, of a modular and cost-effective design with fully functional navigation and object avoidance capabilities. The total cost of Catabot-6, including the on-board monitoring devices was approximately $1,300, representing an 84% drop in ASV costs, while retaining and improving on features contained in high end alternatives (Kimball et al. 2014). Figure 5 illustrates the final stage of Catabot-6.

Figure 5. Catabot-6, floating in water. The system was produced for slightly under $1,300 USD.

Similarly, the performance of Catabot-6 demonstrates the effectiveness of the AI navigation pipeline approach used in overcoming the limitations caused by using an RGB USB camera rather than a more expensive LIDAR camera. Figure 6 shows the path followed by Catabot-6 in a physical test trial performed at Wilson's Landing, Hanover, New Hampshire.

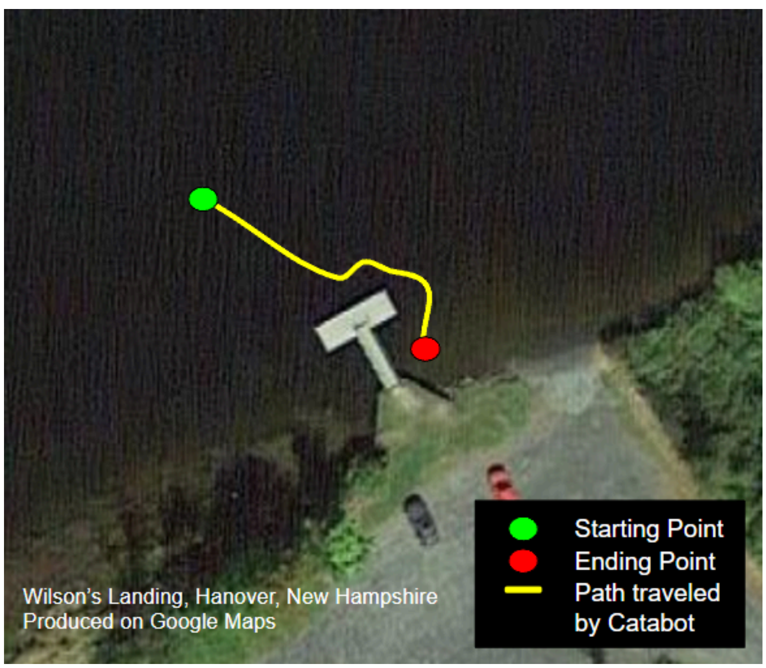

Figure 6. Flight log of Catabot-6 in test trail around dock.

As shown in the image, Catabot-6 not only reaches the set final destination behind the dock and in front of the shore, but the vehicle also takes a smooth and efficient path to avoid the dock. The stages of navigation and the functionality of Catabot-6 is also demonstrated, with the initial, unobstructed waypoint navigation calculating the shortest path to the end point, followed by a step of repositioning away from the dock, a step of moving away from the dock, and the final waypoint navigation step, taking Catabot-6 from its newly adjusted position to the end point.

Discussion

In this study, we introduce Catabot-6, a novel low-cost ASV with a fully functional navigation and object avoidance system. The significance of the introduced approach extends beyond its movement capabilities. The modular design of Catabot-6 makes it suitable to carry various forms of water quality monitoring devices with simple implementation, and the cheap and autonomous nature of the ASV make it an effective tool in understanding the health and biodiversity in water bodies. While the strength of Catabot-6 is evident, it is not without limitations. The use of a 2d object detection system and multi-computer setup suggest areas for improvement. Future work could involve experimentation with alternative statistical object detection (edge detection, clustering), the addition of a depth perception stage to better understand how far an obstacle is, and development of dedicated firmware to route data from the flight controller to the primary computer directly. Such efforts would increase the robustness and reliability of the introduced system, reduce costs further, and expand current understanding of water monitoring techniques. The novel low-cost ASV introduced in this study signifies an important advancement in water monitoring techniques. As a cost-effective and standalone system, Catabot-6 has the potential to be utilized as a tool in all communities to better understand the status and wellbeing of ecologically diverse and crucial ecosystems in bodies of water, as well as help quantify, and allow groups to adapt to, changes in water quality caused by pollution, climate change, and general human ecological destruction. As more research is done exploring the intersection of robotics and water body health, approaches such as the proposed highlight the broad value of easily accessible and autonomous systems, paving the way for widespread environmental monitoring and helping deliver optimally timed conservation efforts.

Conclusions

- In this study, we develop a surface water data-collection vehicle to solve the environmental issues of incomplete or inaccessible information regarding the health of water bodies.
- The introduced vehicle is not only significantly less expensive than current models, but contains a sophisticated navigation system, consisting of both driver-controlled and fully autonomous modes, for simple and safe implementation by inexperienced users.
- The modular design of Catabot-6 allows for a comprehensive system, effectively allowing all sensor-based measurements in water bodies to be efficiently integrated and tracked through the vehicle.
- Catabot-6 is an economically accessible, autonomous, water-monitoring vehicle enabling researchers and conservationists in all settings, from small rural towns to large established cities, to learn from, engage with, and adapt to changes in local water systems with accurate, real-time information about the quality of water bodies.

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