DEVELOPING A MINIATURE SMART BOAT FOR MARINE RESEARCH

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ABSTRACT

Developing a Miniature Smart Boat for Marine Research

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This project examines the development of a smart boat which could serve as a possible marine research apparatus. The smart boat consists of a miniature vessel containing a low-cost microcontroller to live stream a camera feed, GPS telemetry, and compass data through its own WiFi access point. The smart boat also has the potential for autonomous navigation. My project captivated the interest of several members of California Polytechnic State University, San Luis Obispo’s (Cal Poly SLO) Marine Science Department faculty, who proposed a variety of fascinating and valuable smart boat applications.
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- Bridget Benson, Ph.D., for communicating this project to potential clients and stakeholders within the marine science community

- Jeff Chamberlain, for giving me a model Radon boat hull for this project
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Chapter 1

FORMAL PROJECT DEFINITION

The goal of this project is to develop an advanced, low-cost, smart boat to facilitate marine science research. Realizing this goal is no easy task. Many challenges and limitations will arise. The vessel’s miniature size will limit the amount of physical space available for components. As with any boat, it will operate in an uncontrolled environment. Safely navigating the near-shore conditions (waves, wind, currents, etc.) will be difficult. These complex external variables create the need for precise motion control. A well-designed boat and the waterproofing of that vessel are critical to ensure reliable operations. Battery life and operating range are limited. In light of these factors, utilization of GPS and compass data will be essential to facilitate autonomous or assisted navigation.

The development of a smart boat consists of important requirements. The miniature boat must safely house various electronic elements. The vessel should be designed to ride ocean waves comfortably and self-right when capsized. As well, the operator should have the option to control the vessel directly or autonomously.

There are numerous advantages to miniature marine vessels. They can navigate into hard-to-reach locations with ease, operate for lengthy periods of time in tight spaces, and explore areas previously inaccessible to marine scientists.

In developing my smart boat, I discovered there is a lack of low-cost, open-source tools and hardware available for marine robotics. Furthermore, the community of marine robotics developers is far less robust than that supporting aerial drones or remote-controlled cars.
Members of Cal Poly’s Marine Science Department faculty expressed “overwhelming interest” in my platform. Numerous suggestions arose concerning ways in which my smart boat might be used for purposes beyond amusement. For example, the boat could be upgraded and modified to collect stray fish for fisheries, monitor black abalone, observe and study clams, collect mussels, retrieve buoy data, measure wave heights for climate change research, track erosion on pier pilings, or conduct water quality tests at predetermined GPS coordinates. Furthermore, the platform could explore conservation of power by riding waves, water currents, or wind gusts. As a long-term goal, communication could occur between multiple smart boats or devices to enhance operation.
The following section will describe my construction of a generic smart boat. This is intended to display the basic mechanical design of the optimal version of a smart boat.

2.1 Jet Drive Overview

I discovered that implementing a jet drive is the best system to operate the boat. Concealing the spinning blades inside the hull reduces drag, increases nozzle thrust, and protects fingers, kelp, and other objects from the impeller. Jet drives are powerful and common for advanced marine vehicles. For example, the U.S. Coast Guard utilizes jet drive technology in their Response Boat - Medium (RBM) [1]. The jet drive sucks in water from the bottom of the boat and accelerates it through a chamber and out through the exhaust hole. The jet drive system seems to be the best choice for precise motion control because of its advanced technique to direct and enhance water flow.

I learned key elements that are necessary to create a successful jet drive [2]. Creating a jet drive requires more than simply putting an impeller in a pipe. I found the exhaust hole should be higher in elevation than the intake hole. The exhaust hole should sit at or above the water line. Proper pressure difference must be induced to accelerate the water. Therefore, placing a nozzle at the exhaust is critical. The nozzle should have a smaller diameter than the intake hole. This is necessary for the impeller to create enough pressure difference to suck up the water.
2.2 The Bucket Steering System

In jet boats, the turning mechanism is referred to as a “bucket.” The bucket can change orientation to direct the water flow from the nozzle to steer the boat. In advanced jet boats the bucket can even orient to direct the flow of water backwards, to reverse the motion of the boat. It is important to place the bucket outside the exhaust of the jet drive to direct the flow correctly. Placing the bucket inside the jet drive chamber will add turbulence to the jet drive exhaust — thus, only attempt to direct the flow of water once it has exited the exhaust hole.

2.3 Improving Durability and Appearance

The hull should be made from a sturdy, waterproof material, such as plastic or fiberglass. I added foam pipe insulation to surround the boat’s borders to serve as an O-ring. This outer O-ring acts as a physical bumper for collisions and a means to seal the top watertight.

To accomplish this, mount metal brackets inside the boat. Then manually screw down a wooden or acrylic top into the brackets with wingnuts, until the top clamps to the brackets securely with the O-ring in between. This should create a watertight
barrier with a removable top. Lastly, I added an LED light strip to enhance the look of the boat.

Figure 2.2: Pipe Insulation O-ring and Bumper
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<th>Component</th>
<th>Description</th>
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<td>DC Motor</td>
<td>This motor will spin the impeller. Brushed or brushless motors will both work, but some brushless motors can be waterproof.</td>
</tr>
<tr>
<td>2</td>
<td>Universal-Joint Drive Shaft</td>
<td>This drive shaft will extend into the pump’s chamber. The universal-joint allows for more tolerance in the motor’s position.</td>
</tr>
<tr>
<td>3</td>
<td>Impeller</td>
<td>The impeller should spin freely inside the jet drive chamber.</td>
</tr>
<tr>
<td>4</td>
<td>High-Torque Hobby Servo</td>
<td>This servo will control the steering of the bucket via a push-rod.</td>
</tr>
<tr>
<td>5</td>
<td>Steering Bucket</td>
<td>The steering bucket should act as a rotating nozzle to direct water flow.</td>
</tr>
<tr>
<td>6</td>
<td>Bent Pipe</td>
<td>The jet drive chamber is made from a bent pipe that connects the intake and exhaust holes.</td>
</tr>
<tr>
<td>7</td>
<td>Electronic Speed Controller (ESC)</td>
<td>The ESC will control the motor’s speed based on a pulse-width-modulation (PWM) input signal.</td>
</tr>
<tr>
<td>8</td>
<td>A 2S LiPo Battery</td>
<td>The battery should be rated for high discharge and should be sized according to the boat’s specifications.</td>
</tr>
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Table 1: Components for a Generic Jet Drive

2.4 Constructing the Jet Drive

Construct the jet drive chamber by assembling PVC pipe, bending metal pipe in an L-formation, or using a plumbing P-Trap. I discovered that a plumbing P-Trap is already in the desired shape and size to serve as this chamber. However, if you have experience with a pipe bending machine, metal pipe may be the best option to achieve the best fluid dynamics of the chamber. The impeller shaft runs from the cabin of the boat into this pipe. This allows the motor to stay dry in the cabin while spinning the impeller inside the wet pipe. Finally, steering will be controlled by the servo, which will turn the bucket via a handle and push-rod that extends from the pipe. Within the pipe I added sink strainers to filter out foreign object debris, like seaweed. I hoped to mimic a successful system that I found in a YouTube video [3]. However, my initial attempts with PVC pipe failed to create
enough suction to propel water up the pipe. I then turned to the P-Trap option, which was a mild improvement.

The next step in constructing the jet drive is to drill a hole in the center of the curved portion of the chamber, to house the shaft component of the drive shaft. The impeller should be mounted inside the tube onto a bearing, or mounted in a hole, so its vibrations can be muted. If the propeller collides with the jet drive tube’s sidewalls, friction will slow or stop the motor. It may be necessary to cut more pieces of pipe to stabilize the drive shaft and impeller.

The drive shaft of my smart boat is a universal joint drive shaft intended for model boats. The universal joint allows the motor to be placed in any orientation. The drive shaft extends from where the motor is mounted in the dry chamber into the wet jet drive tube. The drive shaft may need lubricant or a viscous marine sealant to ensure water does not enter the dry chamber from the jet drive tube.

Next, install the nozzle and rotating bucket to extend from the exhaust hole. Include a piece of wood to serve as a handle to help actuate the rotations. Use a brass rod to create a push rod from the servo to the bucket handle. Test the jet drive system in water prior to installation in the hull. When the jet drive is ready, bore two holes for the intake and exhaust of the jet drive. You may need to drill an additional hole to allow access for the bucket push-rod. Glue the jet drive into the hull with a strong waterproof adhesive.
Figure 2.3: Jet Drive Implementation Using a Plumping P-Trap
While researching which computer architecture to use, I discovered the ArduPilot community [4]. I noted that many online autonomous boat projects used the ArduPilot system for navigation [5]. Due to high cost, however, I opted not to use the recommended ArduPilot hardware devices like the Pixhawk. I also realized that a smaller microcontroller would be capable of accomplishing my goals.

3.1 Choosing the Best Computing Hardware for my Smart Boat

I developed the computational side of my smart boat platform from my interest in an online project. It discussed how to create a robot car controlled through its own WiFi access point using an ESP32-CAM microcontroller [6].

I found the computer architecture from this robot car project to be highly relevant to the development of my smart boat. I adapted and expanded the computer program and architecture successfully.

I decided to use an ESP32-CAM microcontroller at a cost of only 10 dollars. This microcontroller live streams its 2 MP camera feed, GPS, and compass data. Consequently, it should be capable of autonomous navigation.

Since the ESP32-CAM is so small, some issues arose related to its size. The ESP32-CAM board has no built-in cable connection to allow communication with my computer. To address this, I bought the ESP32-CAM-MB model. This model includes a specialty ESP32-CAM hat that has a micro-USB to serial adaption. The
hat includes hardware buttons for IO0 and RST which make it easy to toggle between programming mode and execution mode. I found and downloaded the correct driver, and was able to configure my ESP32-CAM to run through my Arduino IDE. I verified that the board worked by uploading a web camera server example that accessed my home WiFi.

3.2 Serial Communication

I aimed to connect the ESP32-CAM’s GPIO pins to the boat’s peripherals. The specialty hat blocked access to the pins, and the leads on the back were too short to use unless soldered. I anticipated this issue and purchased a separate USB to TTL adapter that would also allow for serial communication with my computer. The driver and configuration for this device was challenging to set up. For example, when I was wiring on a breadboard, communication failed. I learned the serial pins were very sensitive, so I directly connected the wires. The adapter is connected to the main UART TX/RX terminals of the board at GPIOs 1 and 3. The driver for the adapter was hard to find but, once again, I could communicate with my computer’s Arduino IDE. Now, I had physical access to the unused pins, but I had to manually ground IO0 and click the on-board RST button to toggle between programming mode and execution mode.

3.3 Interfacing the GPS and Compass

My next task was to configure the BN-880 GPS and magnetometer. I configured the GPS first. It also uses UART serial communication. As discussed above, the board’s main UART TX/RX ports were occupied by my computer’s serial communication. I learned that I could move the serial communication I needed to an available GPIO
pin. I did this and was able to read my GPS latitude, longitude, and altitude through the serial monitor of my computer.

The magnetometer serves as the boat’s compass. It uses an I2C serial connection. The GPIO pin that was listed in the ESP32 documentation was not available (or accessible) for my small ESP32-CAM board. Once again, I had to learn to programmatically map a serial connection to an available GPIO pin (but this time an I2C serial connection). After some more work, I got both the GPS and magnetometer to work together, displaying their data simultaneously through my computer’s serial monitor.

Figure 3.1: Displaying the GPS and Compass Through the Serial Monitor

3.4 Creating a Custom HTML Hub for Control and Data Collection

I found sample code for a ESP32-CAM robot car on the internet. Uploading this code to the board allowed me to test whether the boat could be controlled through its own WiFi access point. The program worked. By selecting the ESP32-CAM’s WiFi on a separate device, I could see the boat’s camera feed and control hub when I visited its IP address in my web browser. I connected the boat’s motor and servo to the buttons in the HTML and C++ code to allow wireless control. Since the
control hub is HTML, I could access it on any internet-capable device. I confirmed
this by streaming the boat’s camera and control hub on my iPhone.

![HTML Control Hub](image)

**Figure 3.2: HTML Control Hub**

I built a Python script to harvest the GPS data by fetching from the HTML
endpoint on an interval. Specifically, this Python program sends a GET request to
the HTML endpoint to fetch and record the boat’s coordinates every two seconds.
The python script saves the coordinates into a list and then uses the “gmplot”
library [7] to create a web page that plots the GPS coordinates and path into a
Google Map. This feature will allow the user to record the boat’s path as it travels
within range, and offer a visual way of presenting this data.

To control the motor’s speed, there is an electronic speed controller (ESC). The
ESC regulates the 2S LiPo battery’s 7.4V down to 5V for pulse-width-modulation
(PWM) communication. This 5V rail powers the microcontroller and the other
peripheral devices. The wired serial communication with my computer won’t be
available on the water, so I changed the HTML hub to fit my project better by
Figure 3.3: Map Trace Generated from the Python Script Recording the Boat’s Coordinates

displaying the GPS and compass data. I added code in javascript to update the HTML portal on an interval, which allows for real-time data presentation.
Figure 3.4: Wiring Diagram

Figure 3.5: 3D-Printed Smart Boat Displaying the Computer Hardware
The construction of my smart boat was an iterative design process. I developed many implementations as I refined the concept and subsystems.

4.1 First Smart Boat

I created my first smart boat by sanding down a foam surfboard blank to my desired aerodynamic shape. I attempted to make a cavity on the bottom of the board to house the electronics box, hoping to reduce drag. I glued in the electronics box’s lid. This allowed me to snap on and off the electronics box to allow for accessibility (repairs and battery charging). The propeller and rudder extended from the waterproof box to contact the water.

Several issues arose. I did not make the cavity to house the electronics box deep enough, so the box created significant drag when operating. Further, the turbulence created by the drag of the box inhibited the rudder’s ability to control the direction of motion. In addition, the propeller’s angle of attack was inefficient, because it was faced slightly downward to create clearance between the spinning propeller and the body of the boat.

4.2 3D-Printed Micro Smart Boat

I decided to use a 3D printer to produce the second version of my smart boat. I found many online projects on 3D-printed jet boats. I selected my favorite one, and
Figure 4.1: Design of my First Smart Boat

Figure 4.2: Initial Smart Boat Testing
printed the .STL files and advice it provided [8]. I 3D-printed the hull and steering nozzle. To achieve maximum strength, I printed the hull as one part. However, this limited its size to roughly eight inches, the size of the printer bed.

This 3D-printed jet boat was a major improvement from my first iteration. The jet drive system and design greatly improved the operation of the boat.

Figure 4.3: 3D-Printed Smart Boat Test with an RC Configuration

4.3 Air Boat

I developed an air boat as the third version of my smart boat. During discussions with faculty, we noted that the small size of my smart boat limited its capability to serve as a research apparatus. Therefore, I started constructing a larger smart boat that will have much more space to house electronic devices.

I could create a new 3D-printed model, but it was apparent that a well-crafted boat of fiberglass would work much better. Recently, I contacted an individual who runs an Instagram account that features photos of boats and discussions of various hull
designs. I met with him in person, and he graciously gave me a scale model of the hull of a 26-foot Radon boat. This type of boat happens to be the same as Cal Poly’s full-size marine science vessel.

I considered the best way to use this fiberglass model. I could repurpose it as an airboat, based on its current form and from what I learned building my previous smart boats.

During airboat testing, I noted the importance of the rudder’s placement. When the rudder was placed before the propellor, airflow was not directed well. Instead, the rudder acted as a sail that easily blew the boat around when there was wind. However, when the rudder was placed behind the propellor, turning improved dramatically. The stream of thrust could be directed, and the wind against the rudder became less of a factor. Ultimately, I found that the airboat lacked enough power to serve as a rugged smart boat in the environment in which it would operate.

Figure 4.4: Implementing the Gifted Model Boat as an Air Boat
4.4 Fiberglass Boat

I was determined to implement the jet drive system I had envisioned on a scale large enough to house scientific components. My final design was a fiberglass smart boat created by replicating the model Radon boat hull. In the next chapter, I'll explain the process of making a fiberglass mold, which could replicate many model Radon boat hulls.
I continued pondering uses for the Radon model hull that I obtained from the Los Osos boatman. This boat was a rare and useful find for my project. I did not want to cut holes in the boat, because I was afraid I would ruin it. Instead, I embarked on making a replica of it. The boat would act as the "plug" for a mold, allowing me to make as many copies as I would like. I thereby started a lengthy process of learning how to make fiberglass molds. I found a very helpful YouTube video describing the mold-making process [9].

Figure 5.1: Radon Model Boat
5.1 Making the mold

To begin making the mold, I prepped a base to lay down the chemicals over the boat. Next, I sealed the edges and cracks of the base and boat with bathroom caulking. Afterwards, using an airbrush, I sprayed a layer of polyvinyl alcohol (PVA) over the whole area. The PVA acts as a mold-release agent. Next, with a paint brush, I applied a layer of unwaxed gel coat. Gel coat is essentially a super-thick paint. The gel coat adheres to the shape of the plug and then dries. Once the gel coat turned tacky, I applied a layer of fiberglass matting with polyester laminating resin. Once it was fully dry, I was able to release the newly-created mold from the plug. Unfortunately, I think I did not wait long enough for the gel coat to dry, and my mold cracked near the nose of the boat. The nose of the boat also had a poorer final sanding than the rest of the boat, which may have negatively impacted the mold release. Nevertheless, I had finished making the mold.

5.2 Creating a copy from the mold

My next step was to attempt a basic fiberglass "lay-up" from the mold. To do this, I put a layer of masking tape over the mold to cover the cracks and to help facilitate the release of the mold. I then added a layer of PVA to also aid with the release. Afterwards, I laminated a six-ounce fiberglass cloth (not matting) into the mold. I pulled the fiberglass out of the mold once it had hardened. I only applied one-layer of six-ounce fiberglass cloth, which I knew may have been too brittle, but I felt it served as a good test for the mold. The result was as expected, a thin and flimsy replica. In general, boats are made from many layers of thick fiberglass cloth or matting [10]. However, my one-layer test seemed to create the boat structure surprisingly well. I added a "hot coat" of sanding resin to the outside and inside of
Figure 5.2: Applying the Gel Coat
Figure 5.3: Applying the Fiberglass Matting
Figure 5.4: Cracked Fiberglass Mold
the vessel. This extra layer of resin added some weight and strength to the boat. In later replicas, I would add more layers of fiberglass and a finishing gel coat for boat-like strength and durability. Finally, using a metal hole drill-bit, I cut two 1.5-inch holes in the boat for the jet drive system.

Figure 5.5: Fiberglass Smart Boat with Intake and Exhaust Holes Drilled

I believe that by creating a bigger hull, I have begun the process of building an improved smart boat. The larger size will allow enough room to accommodate
Figure 5.6: First Copy from the Mold: One Layer of 6-Ounce Fiberglass Cloth

Figure 5.7: Hot-Coating the Fiberglass Copy with Sanding Resin
scientific research equipment. It would become the advanced research platform I had envisioned.
Chapter 6

FUTURE WORK

For the 3D-printed smart boat, I aim to reduce unwanted water inflow into the boat cavity. I have found no clear solution to this yet, due to the model’s design. Also, the footprint of the computer wiring needs to be decreased to fit inside the boat cavity. Therefore, I plan to solder some connections onto a solder board.

For the fiberglass smart boat, a nozzle and bucket system needs to be installed. A hole should be drilled in the boat’s stern to allow the servo’s push-rod to connect to the bucket.

The computer architecture of the smart boat platform can be improved once the mechanical platform yields consistent results. Autonomous navigation code can be written for waypoint missions using this real-time data (possibly leveraging the ArduPilot library). In addition, the ESP32-CAM module often employs an external, high-gain, 8dB WiFi antenna to extend the device’s range. However, this antenna is physically large and I have yet to test it to determine if it actually improves the system’s range.

Please see my GitHub repository for the latest versions of my project files [11].

In conclusion, the smart boat project is meant to develop a new marine research platform that can access areas that were previously inconvenient or impossible to reach. The design of the smart boat platform should be adapted to meet the criteria of the specific research goal.


https://github.com/meirinberg/SmartBoat.