ECE445 Final Report

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Abstract

Though submarines play a significant role in history and the modern world, there have been no graduation projects in water until now. As a result, we designed a submarine model from scratch to fill the blank area in the underwater fields of the graduation design and to support future students in exploring the possibilities of underwater devices. The report introduces our design process, theoretical calculation, and verification methods in four parts: mechanical subsystem, remote-control subsystem, power subsystem, and stability subsystem, to provide future students with a detailed user manual either for further research or for maintenance. Our design is featured in compatibility, easy maintenance, and user-friendliness. Possible improvements from our point of view are also clarified in the conclusion.

Keywords: Submarines, Waterproof, Signal processing, MCU, Automation

Contents

1. Introduction

1.1 Purpose

Though the remote-control mechanical device is a popular topic for graduation design, the device in water is still a blank area, either because of the high testing risks or the high testing environment requirements. However, devices in water like submarines play a crucial role in modern science and should not be ignored [1]. As a result, our project Submarine Model aims to design a submarine model that could operate in water (i.e., move in water freely in control; signals sending and receiving), expanding the possibilities of graduation design and offering the students a versatile solution for exploring applications in water such as underwater ecosystem research and water quality monitoring, which could deepen their understanding of marine and aquatic environments.

1.2 Functionality

Propulsion: The submarine model can sink to a depth of 0.5m, resurface from a depth of 0.5m, and float at any depth within 0.5m. The submarine model can move horizontally at a speed visible to the naked eye (i.e., left or right, back or front). This part enables the movement of the submarine model.

Control: The submarine model operates according to the commands of a remote controller (i.e., sink, resurface, move front/back, and so on) and communicates with the user by a Bluetooth module with data detected by sensors (i.e., velocity, acceleration, and depth). This part enables the user on the ground to control the submarine model in water.

Mechanics: The submarine model has an appearance with a reasonable fluid resistance coefficient (i.e., it can move in a comparably energy-efficient way) and is waterproof (i.e., it can work in water for 30+ mins). This part enables the electronic components to work normally in water.

1.3 Subsystem Overview

Figure 1.1 shows the four main subsystems. The Mechanical subsystem functions as the outer shell and waterproof capabilities. The drainage component is closely linked to the Stability subsystem, which enables the submarine's vertical movement (i.e., sink and resurface). Additionally, the propellers are connected to the Power subsystem, which handles the submarine propulsion. The Control subsystem serves as the central hub that connects and coordinates the operation of all other subsystems. It manages the functioning of various modules and receives remote commands. Based on the signals received by the Microcontroller Unit (MCU), the Control subsystem can command the movement by controlling the Power subsystem and ensure the stability of the submarine by controlling the Stability subsystem. Figure 1.2 shows the overall design of the submarine model.

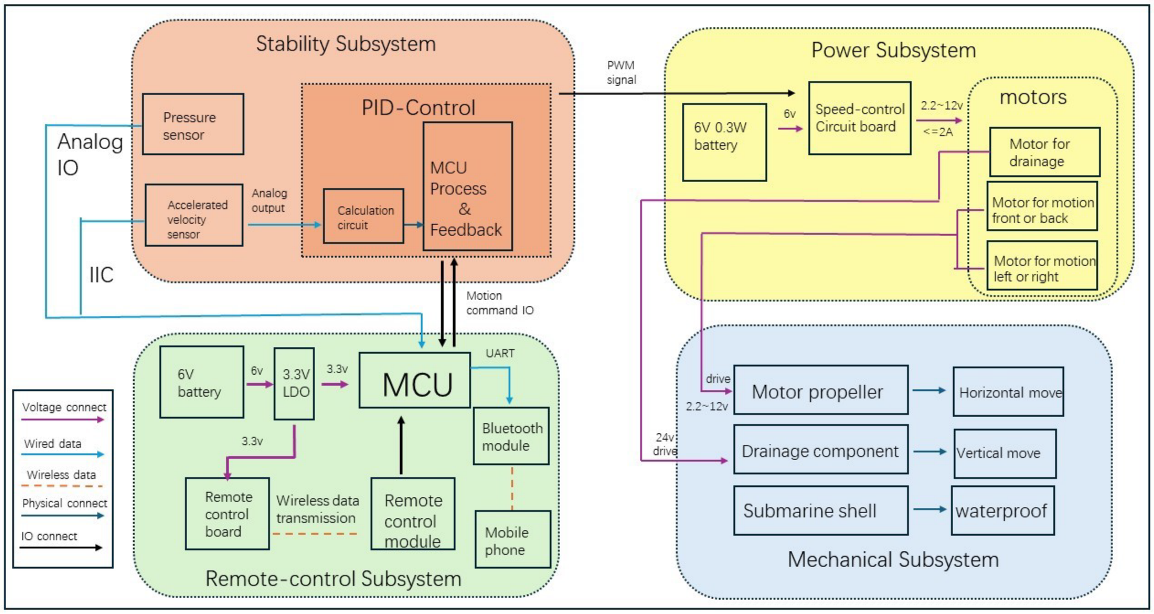

Figure 1.1 Block Diagram

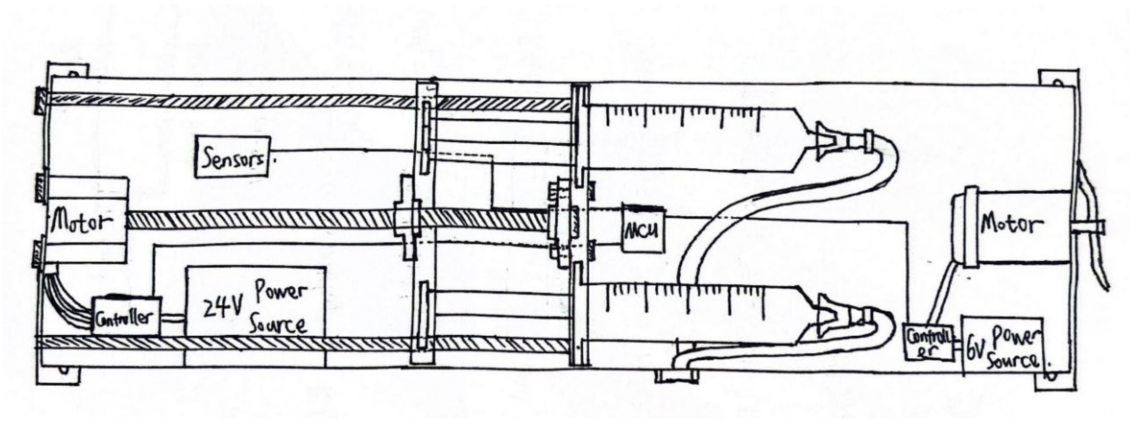

Figure 1.2 Submarine Model

2. Design

2.1 Mechanical Subsystem

The mechanical subsystem primarily comprises two components: the hull structure and the ballast system. Regarding the hull, its pivotal roles encompass isolation and immobilization. It's imperative to ensure that all hull components, excluding the ballast system, are effectively shielded from external water. Simultaneously, stability within the hull must be maintained. To achieve this, we propose utilizing a 100 mm diameter (approximately 3.94 inches), 40 cm long acrylic tube as the hull framework. A 110 mm diameter (about 4.33 inches) cover plate will be cut to seal the hull, and waterproof glue and o-rings will be employed to ensure water resistance at the junction between the cover plate and the hull. Additionally, 3D-printed parts will be utilized to secure circuit boards, motors, and other components within the hull.

The net weight of the submarine model was approximately 1.4 kg (shown in Figure 2.1). We need to add counterweights (shown in Figure 2.2) to balance the whole model and make the total weight approximately equal to 3.14kg.

For the ballast system, we plan to employ a combination of 42-60 stepper motors and silk rods to actuate injectors for water absorption and drainage. A T8 trapezoidal screw will facilitate the push-pull mechanism, while a T5 screw will be utilized to affix the syringe to the motor.

For the propulsion system, we use two DC brush motors as a source of left-right propulsion, and a brushless motor as a source of front-rear propulsion. Zhicong designed some connectors to fix the motor to the hull and the linkage for the drivetrain.

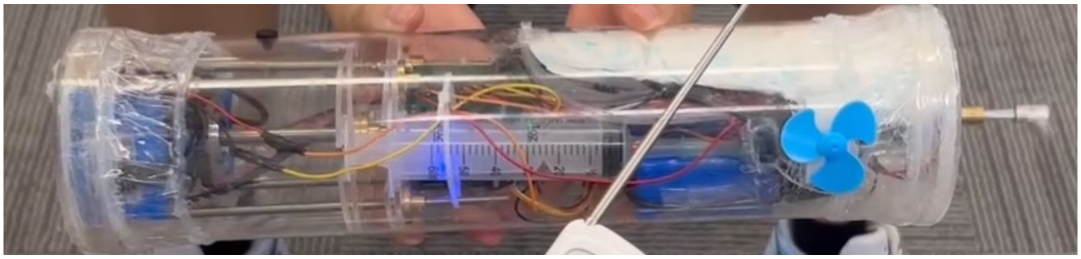

Figure 2.1 Submarine Model

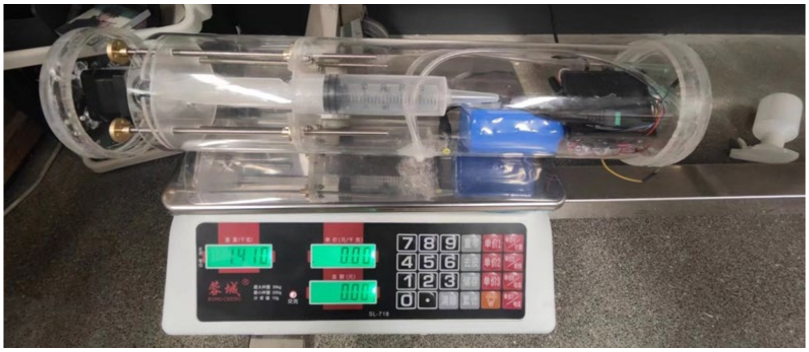

Figure 2.2 Net Weight of Submarine Model

Figure 2.3 Counterweights

2.2 Remote-Control Subsystem

As for remote control, we need to use a remote control module to give the order of motion to the submarine. We need to control distance at least 50 centimeters to realize remote control. The control signal will be delivered to the MCU control part. Figure 2.4 shows the remote-control RX-Q8 module, which is combined with the transmitter and receiver. The schematic shows the module is integrated with an 8-pin decoder, which can output 0 or 3.3V according to the pressed button of the transmitter. The command is sent through 433MHz electromagnetic wave, and the experiment shows it can work under 50cm of water. These eight pins will connect with the GPIO pins of the MCU, such that the MCU can read the command of the remote controller.

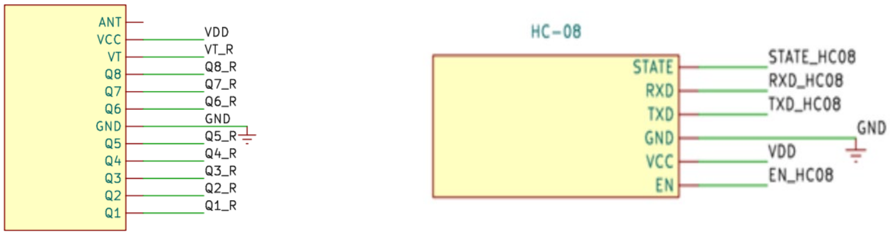

Figure 2.4 Circuit Schematics of Remote-Control Module RX-Q8 (Left) & Bluetooth Module HC-08 (Right)

In addition, we use an HC-08 chip, a Bluetooth 4.0 chip to transmit sensors' data from MCU to our mobile phone to illustrate the state of the submarine and receive more commands from a mobile phone. Figure 2.4 shows the Bluetooth module is connected to the MCU by the UART interface. We can just use RXD and TXD pin foot to communicate about what data it sends.

2.3 Power Subsystem

The power part handles the propulsion of horizontal movements. It includes a battery (2000mAh, 0-2.5A, 5V [2]), and 3 motors (1-6V, 0.35-0.4A, 17000-18000rpm [3]) to enable corresponding propellers to motivate the model to move front or back, left or right. A control unit manages the operation of the motors based on the signal received from the remote controller. See Figure 2.5. Moreover, as the propellers should be in the water, the waterproofing problem should be carefully handled, as a connection part with the cover part.

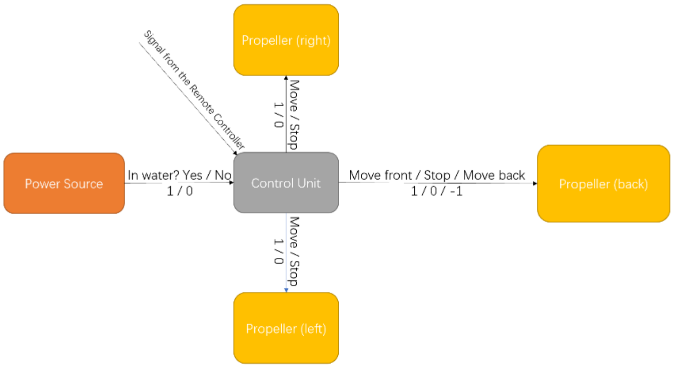

Figure 2.5 Block Diagram for Power Subsystem

The first version of the control unit uses four MOS switches (4 NMOS, voltage, current) and one speed-controlling board. See Figure 2.6. However, it did not work as expected (updated on April 12th: when pressing the corresponding buttons of the controller, the propellers did not always work) because the MOS switches do not work stably in this circuit design [4].

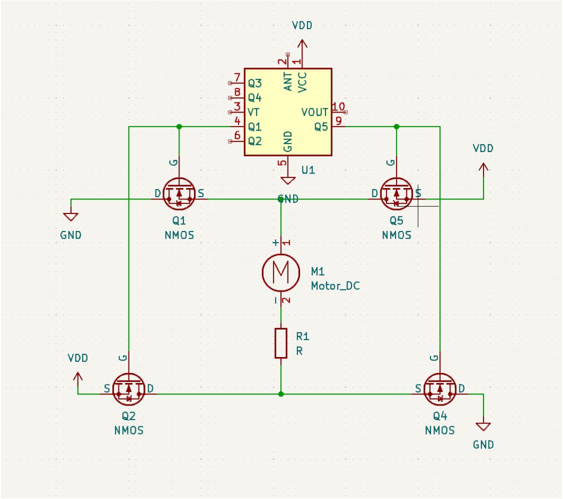

Figure 2.6 Circuit Diagram of Power Subsystem (V1)

The revised version improves the stability of the switches [5]. See Figure 2.7. It utilizes the characteristics of NMOS and adds some resistances to protect the circuit. The revised version passed all the tests (updated on April 18th: tests 1-5 passed).

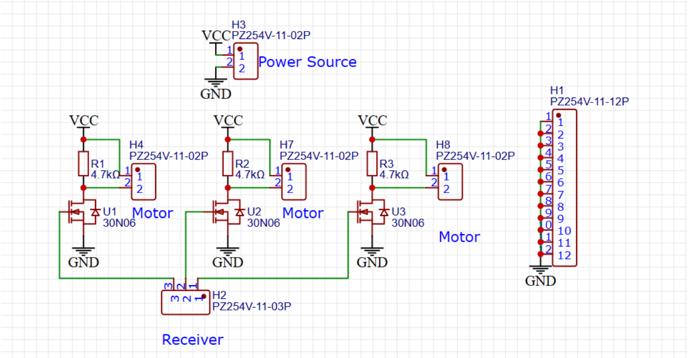

Figure 2.7 Circuit Diagram of Power Subsystem (V2) [5]

However, we then realized that the submarine model cannot be stable when rotating if only one propeller works on one side [6]. As a result, the third version is designed [6], which enables the submarine model to move back/front and right/left stably with one propeller rotating forward and the other rotating reversely. See Figure 2.8.

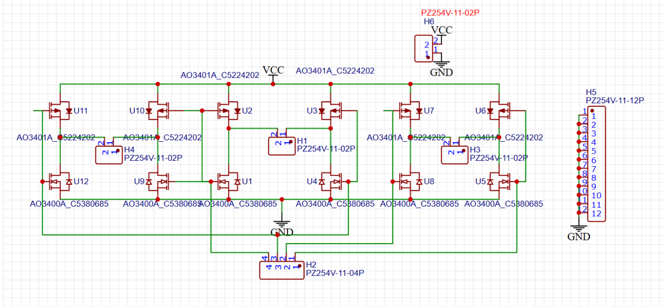

Figure 2.8 Circuit Diagram of Power Subsystem (V3) [6]

2.4 Stability Subsystem

In our design, the purpose of the stability subsystem is to ensure the stable navigation of the submarine underwater. This subsystem plays a crucial role in facilitating the submarine's buoyancy, controlling its descent, and maintaining a stable hover at a specific horizontal plane. We achieve this by processing data obtained from various sensors and collaborating closely with the power unit through the control system to achieve stable vertical movement of the submarine.

To meet the high-level requirements set forth for the submarine's operation underwater, it is imperative to provide a highly detailed and quantitative block description of the Stability subsystem. We must understand how the stability subsystem contributes to the overall design objectives, including ensuring stable navigation, controlling descent, and maintaining hover stability.

Stability control is of great importance to the submarine in our design project. This is because this subsystem will directly affect the balance and motivation of the submarine underwater. From basic physics, we can learn that for different buoyancy forces, we can have different underwater states of the submarine. In this way, whenever the buoyancy of the submarine is equal to the force of gravity, then we can make sure that the submarine stays underwater at a specific depth and makes a stable suspension when needed. For the balance of the submarine, we have to control the adjustment of the buoyancy force, this is because different buoyancy force also has different balances. Also, by changing the buoyancy in the suspended state, we can also change the submarine's suspended height. This can be achieved by allowing the submarine to move first and then return to its original balance. Therefore, we have to make sure that the submarine is able to change its tank capacity in a stable way and achieve what we need.

Based on this requirement, our main goal is to develop a better stability control system. The need for this system is not only to be able to keep the submarine balanced but also to ensure that the submarine can move and drive underwater and move properly. So I had to design algorithms to regulate the buoyancy and suspension of the submarine through sensors and then process the data through the MCU. We have to balance the buoyancy with the gravity and the center of gravity of the submarine so that the submarine can reach the desired goal, which is to adjust the depth.

Furthermore, in my design process, I do not just pay attention to the passive buoyancy suspension adjustments, I also use some other methods to get the instructions. I also integrated the active control system. This active control system will allow the submarine to actively adjust depth when it needs to. This includes improved performance of the water tank and more flexible underwater movement for the submarine.

With these designs and the subsequent testing described above, our ultimate goal is to develop a stability control system for the submarine. We can greatly improve the overall performance of the submarine project by using our integrating our different subsystems.

2.4.1 Hardware Design for Stability

For this part, we will use an MPU-6050 sensor. Because we found in our calculations that the accelerometer we're using measures the value of gravitational acceleration, and because the direction of gravity cannot perfectly align with the XYZ axes, we need to manually confirm the direction of gravitational acceleration. So, we choose to use the sensor MPU6050 by using the MCU. This sensor not only measures linear acceleration but also has three gyroscopes, which can be used to calculate the values of its Euler angles. In this scenario, we can calculate the direction of gravitational acceleration under the initial conditions and then correct the subsequent direction of acceleration.

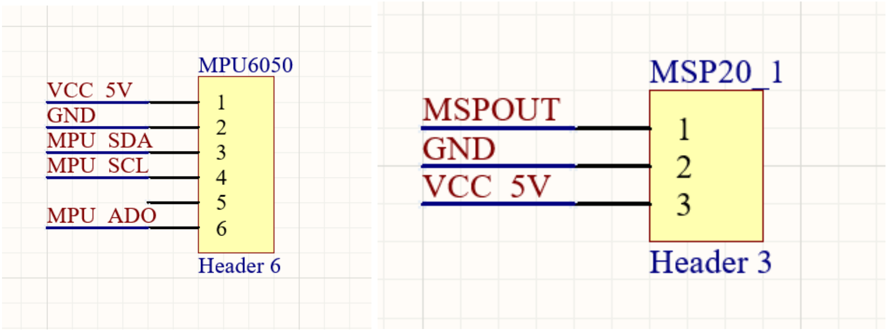

Figure 2.9 MPU6050 Pin Plan (Left) & MSP20 Water Depth Pin Plan (Right)

For MPU6050, SCL and SDA are the digital output of I2C. It will output a digital signal related to the accelerator of the chip. The I2C part and the MCU pin plans can be seen in the MCU part below.

In addition, we also intend to use a simple water pressure sensor. This sensor can provide an analog signal output indicating the current water pressure at the submarine's position. This can help us determine the current underwater depth, which will aid us in achieving the stability of the submarine during the underwater process.

In Figure 2.9, the MSPOUT pin is the analog output pin, and the output of this pin will increase as the water pressure increases. Based on our measurements, we found that the output analog voltage value of this pin is roughly proportional to the depth. Through the relationship that we can obtain from the measurement, we can determine the correlation between the required voltage and the depth.

2.4.2 Euler Angle Linear Algebra Calculation Design

In the previous section, we mentioned that we will use Euler angles to transform acceleration or other vectors into different coordinate systems.

Euler angles are a way to describe the orientation of a rigid body in three-dimensional space. They consist of three angles: roll, pitch, and yaw. Roll describes rotation around the longitudinal axis (the x-axis); pitch describes rotation around the lateral axis (the y-axis); yaw describes rotation around the vertical axis (the z-axis), and together, these angles uniquely describe the orientation of an object in three-dimensional space.

Assume the Eulr Angle is (θ, ϕ, ψ) for the axis of (x, y, z), then if we want to transfer the Euler Angle of $(0,0,0)$ to the Euler Angle (θ, ϕ, ψ), we have:

$$Rx = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\theta & -sin\theta \\ 0 & sin\theta & \cos\theta \end{bmatrix}, Ry = \begin{bmatrix} cos\phi & 0 & sin\phi \\ 0 & 1 & 0 \\ -sin\phi & 0 & \cos\phi \end{bmatrix}, Rz = \begin{bmatrix} cos\psi & -sin\psi & 0 \\ sin\psi & cos\psi & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{2-1}$$

The new vector from the original vector (a, b, c) will be:

$$\begin{bmatrix} a' \\ b' \\ c' \end{bmatrix} = RxRyRz \begin{bmatrix} a \\ b \\ c \end{bmatrix} \tag{2-2}$$

Based on this algorithm, we can transform any vector into any Euler angle configuration. If we take the initial gravitational acceleration as a reference, we can adjust subsequent acceleration vectors using Euler angle transformations to accommodate changes in the direction of gravity. If the gravity we measure is (g_x, g_y, g_z), we need to turn it to $(0,0,g_0)$. With this method, we can transform all scenarios into a unified coordinate system.

At the beginning of the submarine's operation, we need to convert the measurement coordinate system to the world coordinate system. Thus, we need the world coordinate system result to be:

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix}^{w} = \begin{bmatrix} 0 \\ 0 \\ g_0 \end{bmatrix} \tag{2-3}$$

If we want to achieve this result, we can cross the values of only the z-axis with the results of the sensor. Using this cross-product method, we can obtain the transformation between the world coordinate system w and the initial coordinate system of the sensor A:

$$\begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} \times \begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} -y \\ x \\ 0 \end{bmatrix} = A_x\,; \quad \begin{bmatrix} -y \\ x \\ 0 \end{bmatrix} \times \begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} xz \\ yz \\ -x^2 - y^2 \end{bmatrix} = A_y; \quad \begin{bmatrix} x \\ y \\ z \end{bmatrix} = A_z \tag{2-4}$$

Combining these three axes together, we can get that:

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix}^{w} = R_A^w \begin{bmatrix} x \\ y \\ z \end{bmatrix}^{A} \tag{2-5}$$

Where the transformation array is:

$$R_A^w = \begin{bmatrix} \frac{A_x}{\|A_x\|} & \frac{A_y}{\|A_y\|} & \frac{A_z}{\|A_z\|} \end{bmatrix} \tag{2-6}$$

In each subsequent transformation, denoted by B for the new sensor coordinate system, we have measured Euler angles (θ, ϕ, ψ) for R_B^A:

$$R_B^A = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\theta & -sin\theta \\ 0 & sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} cos\phi & 0 & sin\phi \\ 0 & 1 & 0 \\ -sin\phi & 0 & \cos\phi \end{bmatrix} \begin{bmatrix} cos\psi & -sin\psi & 0 \\ sin\psi & cos\psi & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{2-7}$$

And the result for world coordinate system should be:

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix}^{w} = R_A^w R_B^A \begin{bmatrix} x \\ y \\ z \end{bmatrix}^{B} \tag{2-8}$$

Where $\begin{bmatrix} x \\ y \\ z \end{bmatrix}^B$ represents the values of the sensor acceleration along the xyz axes measured at the current moment. These values can be directly read, so through these two matrices, we obtain the true acceleration of the submarine in the world coordinate system. At this point, subtracting the acceleration obtained during the initial initialization allows us to derive the submarine's acceleration relative to the water.

2.4.3 Close Loop Control System Design

In order to meet the requirements for the normal operation and suspension of a submarine in water, we need to provide a more detailed description of the analytical subsystem associated with suspension stability. This is because in this subsystem we utilize acceleration sensors to measure the acceleration of the submarine in all three directions (x, y, z), which is critical for assessing its suspension stability. This task can be difficult to achieve, so the first step in our design approach is to fulfill the basic suspension requirements. This will not require much in terms of stability, as this is only the initial stage of the design. Then, in the second step, we aim to achieve stable suspension and remain in a fixed position below the surface of the water. This will be more challenging, but very valuable as this aspect is related to the use of control systems.

The accelerometer sensors provide data on the submarine's acceleration, which is then analyzed using mathematical formulas to evaluate its suspension stability. Specifically, we make certain assumptions: assume the submarine mass is m, the acceleration due to gravity is g, the depth of the submarine is h, the density of water is ρ, the volume of the submarine excluding the tanks is V_0, and the volume of the tanks is $S \times x$, where S is the cross-sectional area of the tank and x is the drainage height of the tank. We control the value of x through the motor. Thus, we can have:

$$\rho g(V_0 + S \times x) = mg - m\ddot{h} \tag{2-9}$$

Assume $\dot{y} = \frac{\ddot{h}}{g}$, $y(t = 0) = 0$, which means that the submarine's initial vertical velocity is 0. Thus, we can have $y(t = +\infty) = 0$. By controlling the value of x, we can achieve this. We can use a PID system for this part.

In the water chamber tank, the control of the height x of the drainage is realized by means of a motor, which allows us to adjust it as needed. By controlling x and analyzing the data provided to us by the accelerometers, we can effectively control the stability of the submarine through our control system.

So in our design process, we used a combination of motors and MCU parts that worked with our control system to reach the stability analysis. We have used the control system to control the speed of the motor and the angle of rotation and we want to get the stability result in this way.

In order to control the motor, we used a method where the output value of the MCU is proportional to the range of rotation of the motor. This is because the maximum speed of the motor is fixed, and the maximum speed is not large enough. Therefore, we increased the rotation range to achieve the effect of controlling the variation of the water tank.

We use “Sigmoid function” or “Logistic function” for this relation:

$$S(x) = \frac{L}{1+e^{-k(x-x_0)}} \tag{2-10}$$

The Sigmoid function approaches zero for very small input values, approaches a maximum value for very large input values which is L, and exhibits a relatively fixed slope for values between the small and large inputs. Consequently, when input data falls within a normal range, the output approximates a proportional relationship. However, for input values that are significantly higher than or lower than the range, upper and lower limits are applied to ensure bounded outputs.

Our PID controller comprises integral and derivative components. This is because the two quantities we measure are acceleration and distance (i.e., water depth). Hence, these two quantities serve as the derivative and integral parts of velocity. By adjusting the values of the parameters: K_i and K_d, we can obtain the desired PID output.

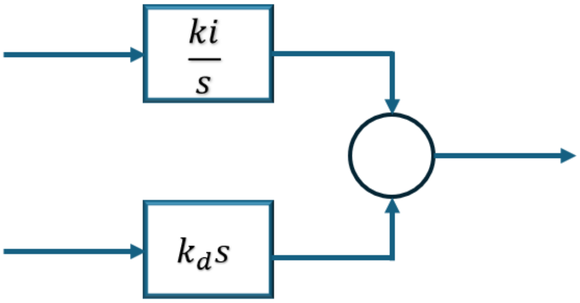

Figure 2.10 PID Control System

2.5 Microcontroller Unit Subsystem

The microcontroller unit subsystem is the core subsystem to receive the command and control the motion of motors with the analysis of sensors. We selected STM32F103ZET6 as our MCU. The MCU is connected to the receiver of the remote controller, Bluetooth module, pressure sensor, acceleration sensor, stepping motor drive module, and DC brushless motor drive module. The MCU needs to read the command signal from the remote control module and Bluetooth module. It also needs to initialize the sensors, read, and process the data from the sensor, apply PID control, and then generate a control signal to drive the motion of motors. The stepping motor is used to change the water volume in the drainage system. MCU needs to provide three signals to control the stepping motor: enable, direction, and PWM. MCU can enable the motor by setting EN to 0V. The direction signal can be set to GND or VCC which corresponds to two directions of the stepping motor. PWM signal is used to control the speed and duration of the motor. We can increase the rotation speed by increasing the frequency of PWM and change the duration by setting the number of cycles of PWM because the experiment shows 200 cycles of PWM signal equals one cycle of rotation of the stepping motor. Besides the stepping motor, the MCU also needs to generate a PWM signal to the DC brushless motor which takes responsibility for moving forward and backward. We can change the duty cycle of the provided PWM signal to realize the clockwise, counterclockwise, and halt state of the brushless motor.

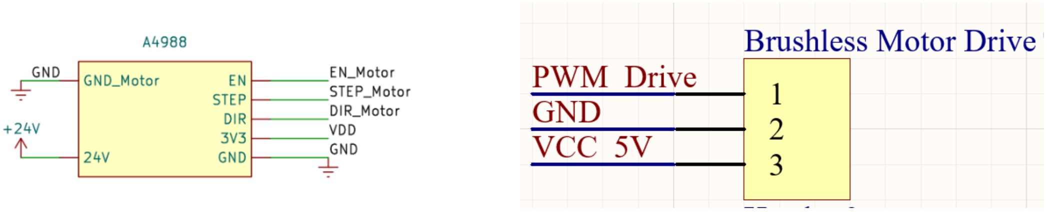

Figure 2.11 Module Schematics of Step Drive (Left) & Brushless Motor Drive (Right)

To save space in the submarine and improve the stability of circuit connection, we designed a PCB to replace wires between MCU and modules. Figure 2.11 shows the schematics and the PCB layout design of the MCU subsystem. In the PCB design, the circuit require two kinds of voltage: 3.3V and 5V. We choose 5V battery and a 3.3V Linear Dropout Regulator which convert 5V to stable 3.3V. When designing the MCU circuit, we reference from the official datasheet [7], which provides how power supply, resonant crystals and other components connect to the pins of MCU

3. Design Verification

3.1 Stability Subsystem

For the verification of this part, our initial focus is on accurately measuring acceleration and water depth. The algorithm already provides correct world coordinate system acceleration readings, and we have established a proportional relationship between water depth and output voltage.

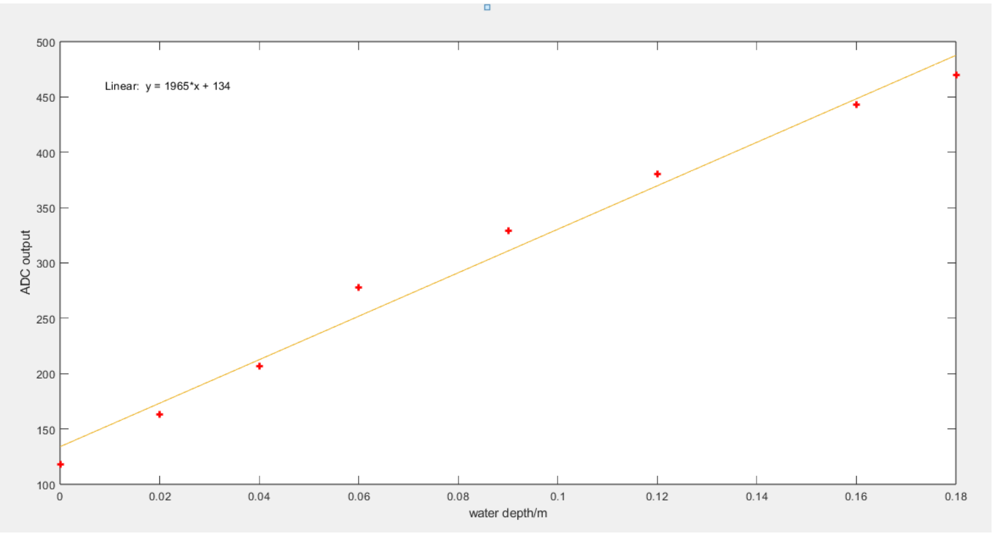

Figure 3.1 ADC output of MSP20

The submarine's diving depth is ensured. It can descend at least 8 centimeters below the water surface and still resurface safely. Moreover, the error range during suspension is guaranteed. The acceptable range of error when descending to the specified depth is also ensured.

In addition to that, we can implement basic suspension functionality. Through the PID system, we can dynamically adjust the volume of the ballast tank to automatically control the system's acceleration.

3.2 Power Subsystem

Measure the output signals of the control unit with signal controlled using an oscilloscope and compare them with data in theory. The control unit can respond properly according to the signal received (0V-0± 0.1V, 1V-3.3±0.1V). Test 1 passed.

Power the propellers with certain voltages to see if they reach the spinning speed of 17000-18000rpm. The propellers can work under the output voltage range (1V-6V) of the power source. Test 2 passed.

Immerse the connected parts in the water 50cm under water for 10s and then see if the device inside the model is dry. The connected parts of propellers and motors proved to have good waterproofing abilities 50cm under water. Test 3 passed.

Press the buttons on the remote controller and see if the propellers work as expected. The propellers reacted as the remote controller commands. All tests passed.

3.3 Remote-Control & MCU Subsystem

Requirements of Remote-Control and MCU subsystem can be found in R&V Table 8 and Table 11. We need to verify that remote transmission and reception can be realized using remote controller with frequency 433Mhz and Bluetooth module with frequency 2.4Ghz at least half a meter underwater. First, we perform theoretical calculations and simulations as shown below:

TEM waves will decay through water, so we need to analyze how much the power of TEM waves will decrease through 0.5m water. In our design, we use a 433MHz transmitter and a 2.4GHz Bluetooth module. Assume the transmitter is on the surface of water. After looking up the datasheet of tap water, tap water has the parameters below: $\sigma = 0.05S/m, \epsilon_r = 81$, $\mu_r = 1$. Then we calculate:

$$\text{loss tangent} = \frac{\sigma}{\omega\varepsilon} \tag{3-1}$$

The loss tangent is 0.0256 for 433MHz wave and 0.004623 for 2.4GHz, so both are imperfect dielectric.

The propagation constant for imperfect dielectric $\alpha = \frac{\sigma}{2}\sqrt{\frac{\mu}{\varepsilon}} = 1.04647$, which is irrelated to frequency.

Because the energy of electromagnetic waves is proportional to the intensity of the electric and magnetic fields, which is the strength of the wave vector, we can get:

$$E(z,t) = E_0 e^{-\alpha z} \cos{(\omega t - \beta z + \varphi)} \tag{3-2}$$

and the energy is proportional to $e^{-2\alpha z}$, where z is the depth underwater.

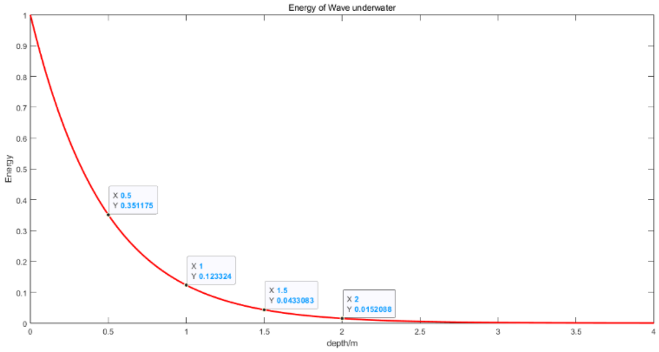

Figure 3.2 Energy Decay Simulation

Figure 3.2 shows the energy decay versus depth underwater. To receive the valid data, we will receive 35% power under 0.5m water and we cannot transmit data through tap water exceeding 2 m with around 1.5% power. Theoretical calculations verify transmission under 0.5m can work.

We also conducted a launching experiment. We submerged the submarine to the bottom of the test swimming pool (more than half a meter deep) and used the remote control to issue instructions such as forward and backward, left and right steering, and floating. The corresponding motor can make corresponding actions within 0.5 seconds. At the same time, our mobile phone can also receive the readings of the water pressure sensor and acceleration sensor through the Bluetooth module. This underwater experiment verified that remote control can be achieved half a meter underwater.

We also need to verify MCU can control and drive the motion of the stepping motor and DC brushless motor. We have verified the brushless motor can rotate in different directions according to the duty cycle of the PWM signal in frequency 70kHz, which is shown in Table 1. In the domain of clockwise rotation, the increase of the duty cycle of the PWM signal results in higher speed. In the domain of counterclockwise rotation, the decrease of the duty cycle of the PWM signal results in higher speed.

State/ Direction	Frequency	Domain of duty cycle
Halt	70kHz	[9.5%, 9.9%]
Clockwise	70kHz	[10.0%, 10.5%]
Counterclockwise	70kHz	[8.9%, 9.4%]

Table 3.1 Mapping Relation between Motor Direction and Duty Cycle of PWM

Figure 3.3 shows the PCB circuit connection between MCU and other modules. We have verified the work of the circuit by testing the remote control both in the air and underwater. Figure 3.3 shows we tested the submarine model underwater. We have verified the work of the Bluetooth module, pressure sensor, and acceleration sensor by sending the sensors' data through the Bluetooth module to our phone. The received data shows the data are proper. In the underwater test, we put our submarine 0.5m underwater and press the button of the remote controller, the corresponding motor can rotate, and the submarine can move accordingly. Specifically, the step motor rotates and absorbs water causing the submarine diving when pressing button 5 and expelling water when pressing button 6. Press 7 and 8 can drive the brushless DC motor to rotate and cause the submarine to move forward and backward. This has verified MCU can read and process the remote control and drive the motors in the correct direction. Also, the reaction time of the submarine is within 1s, which meets requirements and MCU can process quickly.

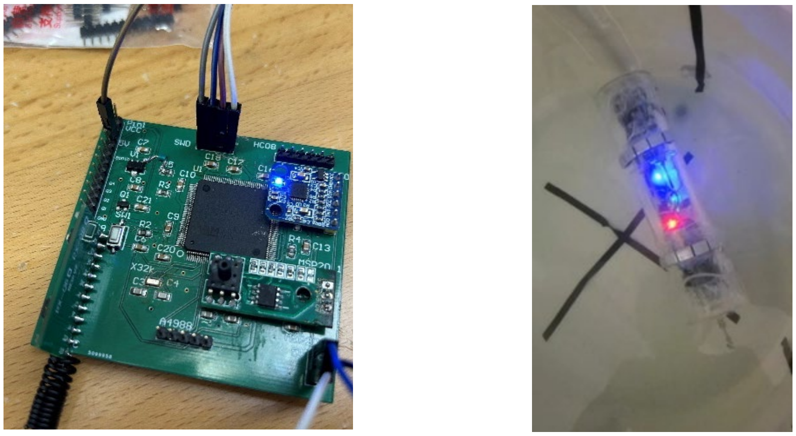

Figure 3.3 PCB Circuit Connection (Left) & Submarine Model Underwater Test (Right)

3.4 Mechanical Subsystem

Requirements of the Mechanical subsystem can be found in R&V Table 7. For the most important waterproof system, we need to conduct an underwater test for our submarine model. (shown in Figure 3.3

submarine model underwater test) Under ideal conditions, we need to ensure that the interior of the hull is as isolated as possible from the external water environment, in order to ensure the safety of the internal circuit and the stability of the ballast system. In the previous tests, we found that the hull was still leaking, mainly because we carried out underwater tests before the waterproof glue set. In the final demo, we will carefully glue all possible leaky areas and wait for the glue to cure before launching the test.

For the ballast system, we will carry out separate and integral tests. We will independently test to verify the feasibility of the mechanical transmission. After the assembly was completed, we completed the feasibility verification of the transmission device, which proved that our design was reasonable. (shown in Figure 3.4 ballast system) Then, after the complete assembly, we also conducted the launch test of the ballast system. The test results show that the design and assembly of the system are satisfactory, and it can enable the submarine to sink, float, and levitate. However, due to material and design limitations, we cannot completely maintain a vacuum inside the needle, which also leads to the adjustable range of the ballast system being much less than the ideal state.

For the propulsion system, the results of the underwater test show that our design can achieve a good left and right turn and forward function, but due to the non-streamlined shape of the hull, we can’t achieve a perfect backward function. (shown in Figure 3.4 propulsion system) In the future, we will add a deflector to the rear of the hull to achieve this function.

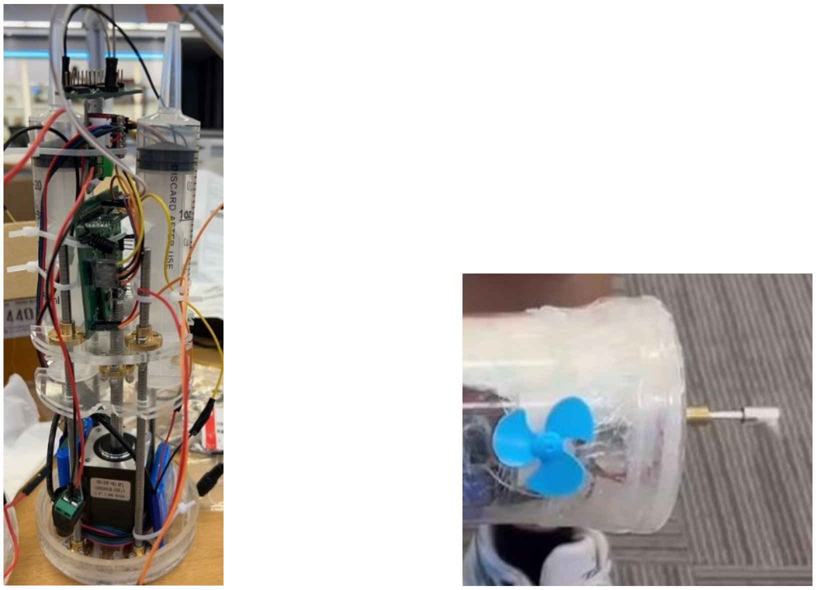

Figure 3.4 Ballast System (Left) & Propulsion System (Right)

4. Costs & Schedule

4.1 Parts

Part	Manufacturer	Retail Cost (￥)	Bulk Purchase Cost (￥)	Actual Cost (￥)
Motor + Propeller	Beike Trading Co., Ltd	7.20	0	7.20
Speed Regulating Motor	Zhuoye Micro Motor Factory	20.34	0	20.34
Batteries	Changying Information Technology Co., Ltd	4.95	0	4.95
PCB V1	Jiepai Information Technology Co., Ltd	8.00	0	8.00
MOSFET	Promoting Century Electronics Co., Ltd	6.60	0	6.60
Pin Header	Kobe Micro Semiconductor Co., Ltd	2.63	0	2.63
MOSFET	Kobe Micro Semiconductor Co., Ltd	8.98	0	8.98
PCB V2	Jiepai Information Technology Co., Ltd	8.00	0	8.00
Resistance	Limao Electronic Technology Co., Ltd	1.50	0	1.50
PCB V3	Jiepai Information Technology Co., Ltd	21.00	0	21.00
Total		89.20		89.20

Table 4.1 Power Subsystem Costs

Part	Manufacturer	Retail Cost (￥)	Bulk Purchase Cost (￥)	Actual Cost (￥)
Remote controller	Shenzhen Wanhong Technology	28.00*4	0	112.00
5V battery	Zhongli Energy Technology	40.00*2	0	80.00
Bluetooth HC-08	Guangzhou HC Technology	22.80*4	0	91.20
MSP-20	Studing electronic	26.80*4	0	107.20
MPU6050	Keyes Official Store	36.86*4	0	147.44
ADXL335	Zave flagship store	29.80*1	0	29.80
ADXL345	Zave flagship store	9.50*1	0	9.50
Electronic components for soldering	Lichuang Mall	262.01	0	262.01
Total		799.85	0	839.15

Table 4.2 Remote-Control & MCU Subsystem Costs

Part	Manufacturer	Retail Cost (￥)	Bulk Purchase Cost (￥)	Actual Cost (￥)
Submarine toy	Luoerle store	113.28	0	113.28

Acrylic tube	Shanghai jiabo plexiglass factory	120.00	0	120.00
Barrel syringe	Biduoshi medical device store	22.88	0	22.88
42 step motor	Huayang motor store	193.91	0	193.91
Trapezoidal screws and nuts	Huaxiang transmission equipment production center	59.00	0	59.00
Waterproof glue	Shouli home furnishing store	6.90	0	6.90
Brushless motors and related components	Supersonic boat model shop	163.50	0	163.50
Optical shaft processing	Lishui ruide CNC	132.00	0	132.00
Total		811.74		811.74

Table 4.3 Mechanical Subsystem Costs

Part	**Manufacturer**	**Retail Cost (￥)**	**Bulk Purchase Cost (￥)**	**Actual Cost (￥)**
Magnets	Chang'an Hengxin Magnet Business Department	17.81	0	17.81
Turntable	Jinxin Acrylic New Plastic Wholesale Department	7.50	0	7.50
Sanitary Towel	Yihou Cheng Daily Necessities Co., Ltd	5.01	0	5.01
Siphon Tube	Shangyige Flagship Store	5.60	0	5.60
Total		35.92		35.92

Table 4.4 Other Costs

4.2 Labor

Labor = $18/h * 10h * 12 weeks * 4 members = $8640

4.3 Schedule

Week 1	March 11-14
Cover	Design and purchase shell and sink tank, and prepare for underwater sealing testing.
Remote Controller & MCU	Do the working test of the remote-control module 50cm underwater. Learn for ADXL345 sensor.
Stability & Sensors	Testing the Basic Properties of Sensor Chips: MSP20 and MPU-6050
Propeller	Power system and motor purchase; Conceive of magnetohydrodynamic thruster.
Week2	March 15-21
Cover	update shell and sink tank design.
Remote Controller & MCU	Test the IIC interface and ADC interface for sensors using an oscilloscope.
Stability & Sensors	Writing code for activating sensor; Attempt to connect the sensor with MCU and use MCU to control the sensor.

Propeller	The propeller part completes the individual test.
Week3	March 22-28
Cover	Underwater sealing testing, design, and assembling ballast system.
Remote Controller & MCU	Use MCU output PWM signals to control the speed of the motor. Realize the connection of MCU and ADXL345 sensor (acceleration sensor).
Stability & Sensors	Testing the Sensor for water depth; Integrate Sensor with the MCU.
Propeller	Complete waterproofing Test and connection with remote controller.
Week4	March 29 - April 4
Cover	Solve the leak problem and test the ballast system. Consider the distribution of the center of gravity.
Remote Controller & MCU	Realize the control speed of the motor by remote controller. Integrate acceleration sensor and speed control module.
Stability & Sensors	Integrate depth and acceleration sensors for the PID system.
Propeller	Design the PCB of the propeller-control circuit and print the PCB.
Week5	April 5 -11
Cover	Complete installation of shell and sink tank, prepare for sinking and floating experiment.
Remote Controller & MCU	Integrate the remote control with the motor speed control. Study and write the code for Bluetooth module HC-08.
Stability & Sensors	Using MCU code to control the Sensor (MPU6050). Get data and try to calculate velocity.
Propeller	Test the printed PCB circuit.
Week6	April 12-18
Cover	Complete the Sinking and floating experiment. Try Fluid simulation modeling.
Remote Controller & MCU	Test the use of Bluetooth Module and design the PCB to integrate the connection between MCU and modules. Complete the sink test with a remote control in the submarine.
Stability & Sensors	Collect data about sensors (water depth sensors); Write code to try calculating speed to use PID.
Propeller	PCB tests passed. Complete the remote controller part. Feasibility test of propellers with magnets passed.
Week7	April 19 - 25
Cover	Design electronic component fasteners and improve tail power system (High-power motor).
Remote Controller & MCU	Complete the PCB design of the MCU subsystem and prepare to solder and test the printed PCB.
Stability & Sensors	Calculate acceleration and velocity and obtain correct outputs using the MCU. Use Filter to Remove Noise
Propeller	In-water test complete.

Week8	April 26 – May 2
Cover	Complete assembling.
Remote Controller & MCU	Solder the electronic devices on PCB and test the work of MCU subsystem on PCB. Add a PCB circuit in the body of the submarine model.
Stability & Sensors	Complete the algorithm design and make the submarine reasonably stable
Propeller	Reverse circuit design.
Week 9	May 3 - 9
Cover	Hull beautification and prepare for the final demo.
Remote Controller & MCU	Test the remote control in the whole system and prepare for the final demo.
Stability & Sensors	Adjust parameters and further optimize algorithms and outputs
Propeller	Reverse circuit test.

Table 4.5 Time Schedule and Milestone

5. Conclusion

5.1 Accomplishments

The submarine model can sink to a depth of 0.5m, resurface from a depth of 0.5m, and float at any depth within 0.5m. The submarine model can move horizontally at a speed of 10 cm/s front/back, 0.007 rad/s left/right. The submarine model can respond to the commands of a remote controller (i.e., sink, resurface, move front/back, and so on) and communicates data detected by sensors (i.e., velocity, acceleration, and depth) with the user. The submarine model has an appearance with a reasonable fluid resistance coefficient, which is comparably energy-efficient and can work in water for 30+ mins.

5.2 Uncertainties

The sinking and resurfacing speed is relatively slow (0.0135m/s). Its floating is not stable and requires skillful operation, which is not user-friendly. The Bluetooth module sometimes may have a problem dealing with the sensor data and, end up showing garbled data on the user end. The back movement is not energy-efficient now because of its appearance which blocks the water flow. There is still some water leakage problem when the model stays longer than 30 minutes in water.

5.3 Ethical considerations

In our design process, we must consider the ethical guidelines of the project. This is because no matter what kind of project it is, we must make sure that it is ethically sound. According to the IEEE Code of Ethics [8], we need to ensure that the highest standards of safety are followed in the design, manufacturing, and testing of the project. According to the original text presented by the IEEE: “to uphold the highest standards of integrity, responsible behavior, and ethical conduct in professional activities” [8]. In addition to this, IEEE has to ensure the need for privacy protection in the project during the process of the project, this is because the personal privacy of the users is very important. The collection, storage, and processing of information, resources, and data in the project must be strictly adhered to.

In terms of safety, since our project is related to electrical circuits and electronics, we have to make sure that the circuits are safe as well as prevent short circuits. We also need to prevent electrocution because the voltage sources we use have higher voltage components. We should make strict measures for the circuit pins to ensure the safety and stability of the circuits, like measuring the resistance between pins. A combination of measures can be taken to minimize the risk in the motor and in the various parts of the circuit to ensure that it does not pose a danger to the personnel and the testers.

Another huge source of risk is the fact that we need to use energized devices underwater. This means that we must isolate our projects from all types of high-voltage power sources, the most dangerous of which are 110V or 220V AC power sources. We have to make sure that high-voltage electricity does not come close to our devices during testing and in all kinds of processes because it is very dangerous. Due to the special characteristics of underwater devices, we will find that we must ensure that we have very effective waterproofing. We must regularly test the waterproofing and use all means to solve the leakage problem.

5.4 Future work

For the Control Part, with the communication between the submarine model and the user achieved, far more functionalities are possible. For example, we can add more sensors such as temperature sensors, ion concentration sensors, and so on. Cameras added can help the user to see the environment around the model. It is fantastic that if we have sonar and related algorithms implemented, we can achieve automatic obstacle avoidance. Or if we can have algorithms dealing with the signal intensity detected, we can ensure that the submarine model will not be out of the control range.

For the Mechanical Part, we can add a more streamlined design to decrease the fluid resistance coefficient and thus, further improve the energy efficiency. We can also pull out the charge cables of the batteries to make the charging process easier.

For the Propulsion Part, propellers can be redesigned to be more efficient and if we can substitute the wires with the magnetic field, waterproofing abilities would be more reliable.

As far as we can see, there is much more magical work to do with our submarine model. And we believe there are more interesting possibilities waiting for exploration.

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Appendix A Requirement and Verification Table

Requirements	Verifications	Verification status (Y or N)
1)The submarine hull can make sure that everything except the ballast system, is isolated from the outside water.	1) Submerge the cabin underwater, first stand still for 10s, then move back and forth randomly and vigorously for 10s to detect any water ingress into the hull of the boat	N
2)The submarine hull and its components can be kept relatively stationary in motion and rest.	2) Submerge the cabin underwater, first stand still for 10s, then move back and forth randomly and vigorously for 10s, to detect whether there is any displacement of the parts inside the vessel	Y
3)The submarine ballast system can implement stable and fast water intake and discharge.	3) Turn on and operate the stepper motor and observe whether the screw can drive the end of the syringe in a smooth push-pull motion and observe whether the syringe body is offset from the motor.	Y
4)The submarine can keep its balance while floating in the water. 5) The submarine can float and sink completely and remain suspended.	4) During all these tests, the hull pitch Angle is maintained at 10 degrees	Y

Table A-1 Requirements & Verifications for Mechanical Subsystem

Requirement	Verification	Verification status (Y or N)
The Submarine can receive the motion command through a transmitter under 50 cm of water.	a) If the submarine can move according to the remote controller, the below test can pass. b) Connect the LEDs with the output decoder pins of the remote-control module. If the receiver receives the motion command, the corresponding LED should light up. c)put the submarine underwater around 50 centimeters, press the command button, and observe whether the corresponding LED light is within delay 2s.	Y

The submarine can send the sensors' data to mobile equipment, and we can demonstrate the state of the submarine to mobile devices.	a) Put the submarine underwater around 50 centimeters. Our mobile device can receive the data and show the sensors' data like the depth of the submarine and accelerate data. b) Use the program in MCU that sends sentences to mobile devices continuously. Gradually sink the submarine underwater. Observe the received data on the mobile device and measure the depth at which we cannot receive the sentences by the ruler and compare the measured depth with the target depth of 50cm.	Y

Table A-2 Requirements & Verifications for Remote-Control Subsystem

Requirement	Verification	Verification status (Y or N)
1. The control unit can respond properly according to the signal received (0V-0± 0.1V, 1V-3.3±0.1V).	Measure the output signals of the control unit with signal controlled using an oscilloscope and compare them with data in theory.	Y
2. The propellers can work under the output voltage range (1V-6V) of the power source.	Power the propellers with certain voltages to see if they reach the spinning speed of 88rpm.	Y
3. The connected parts of propellers and motors should have good waterproofing abilities (50cm under water).	Immerse the connected parts in the water 50cm under water for 10s and then see if the device inside the model is dry.	Y
4. The propellers react as the remote controller commands.	Press the buttons on the remote controller and see if the propellers work as expected.	Y

Table A-3 Requirements & Verifications for Power Subsystem

Requirements	Verifications	Verification status (Y or N)
1. The submarine's diving depth should be ensured. It should be able to descend to at least 8cm below the water surface and still float back to the surface.	Measurements should be taken using a ruler or other length measuring tools.	Y
2. The error range in suspension should be ensured. The vertical variation in suspension should not exceed 12 centimeters and should be maintained for at least 5	Measurements should be conducted using a timer and length-measuring tools. Measurements should be taken at different heights, either randomly or at regular intervals of depth.	Y

seconds.		
3. The submarine should be able to descend to the specified depth. The error should not exceed 20 centimeters.	Measurements should be taken using a ruler or other length measuring tools.	Y

Table A-4 Requirements & Verifications for Stability Subsystem

Requirement	Verification	Verification status (Y or N)
1. In general, MCU should ensure all the interfaces (IIC, UART, ADC) and sensors work. MCU can read data, process all the data, and output some data. MCU needs to generate PWM waves to control the speed of motors. Meanwhile, all the electric components need a 3.3V power supply and 3.3V IO connection, and the MCU needs to output the appropriate voltage.	a) We plan to connect all the sensors to MCU pins. We can measure the outputs of sensors by oscilloscope and determine the functionality works. b) Test the ADC interface with pressure sensors. Connect pressure sensors with MCU. Pressure sensors can generate varied voltage values linearly between 0V and 5V according to the varied pressure, and MCU could read the data with ADC, demonstrated by sending data to mobile devices. c) Test the UART interface of the Bluetooth module. And Bluetooth module can be tested by receiving correct data like sentences on mobile phones. d) Test the PWM signal generated by MCU to control motor speed. The oscilloscope can display the PWM waves and record the frequency of PWM and speed of motors, then compare the relationship between frequency and motor speed. e) Test the voltage connected between components by voltmeter and compare the voltage value with the desired value according to the datasheet.	Y
2. The MCU needs to process the remote-control signal and generate a motor control signal, so the motor can react according to the remote controller. The drainage motor should drive the tank to suck or expel the water according to the remote command.	a) Put the submarine underwater around 50 centimeters, we can press the moving up, down, front, back, left, and right buttons, record the rotation of motors and their direction and compare the motion with the button press. b) press button 5, MCU should generate a control signal to drive the motor to rotate and cause the submarine's ballast tank to suck in water so that the submarine could dive. c) press button 6, MCU should generate a control signal to drive the motor to rotate in the counter direction causing the submarine's ballast tank to expel water so that the submarine could surface.	Y
3. The data needs to be processed quickly enough to ensure the	The code needs to be optimized enough. We can test the efficiency that the submarine can implement command within delay 3s. We can test	Y

	quick reaction of the submarine. The reaction should not be realized more than 3s.	delay by recording the time between pressing the command button and the reaction moment of the submarine.	

Table A-5 Requirements & Verifications for Microcontroller Unit Subsystem

Appendix B PCB Design

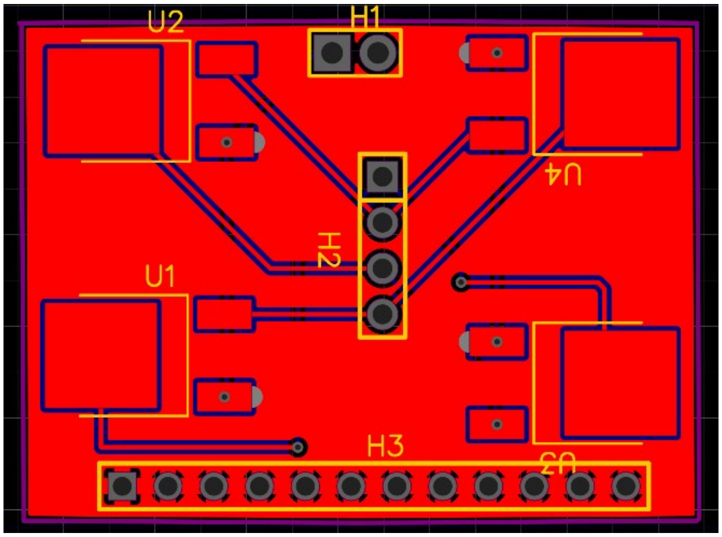

Figure B-1 PCB Design of Power Subsystem (V1)

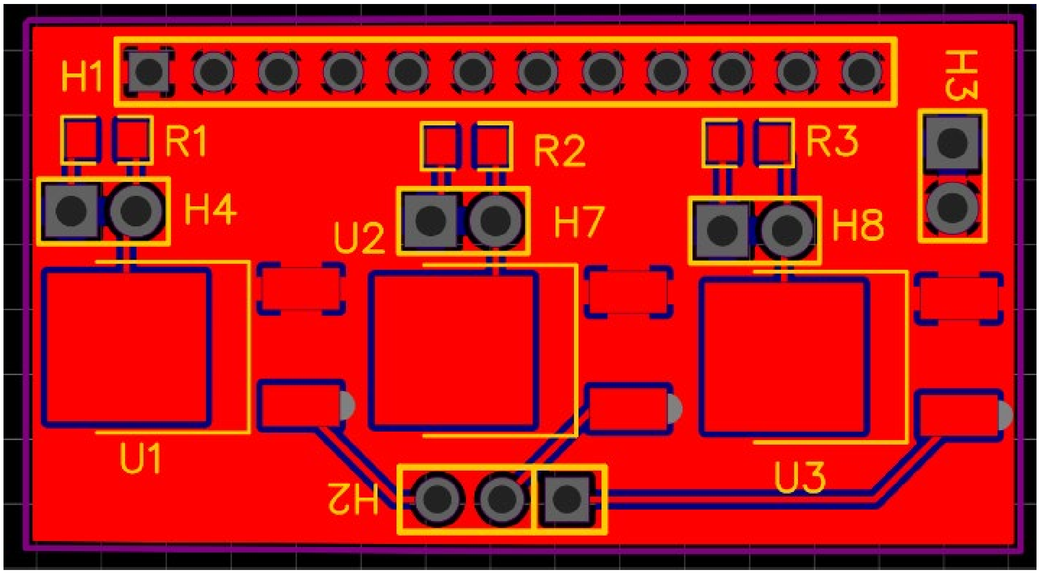

Figure B-2 PCB Design of Power Subsystem (V2)

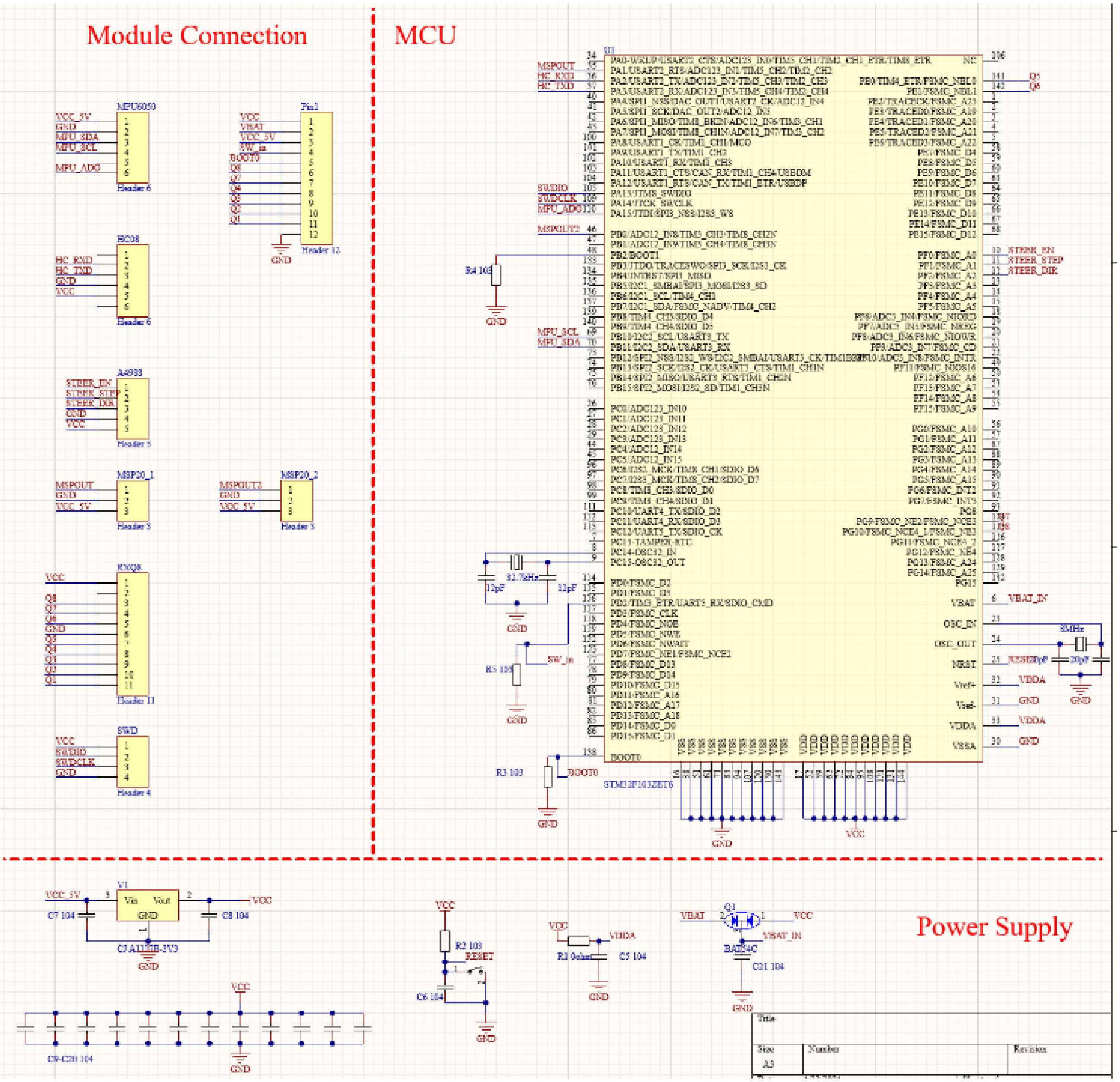

Figure B-3 MCU Subsystem Circuit Schematics

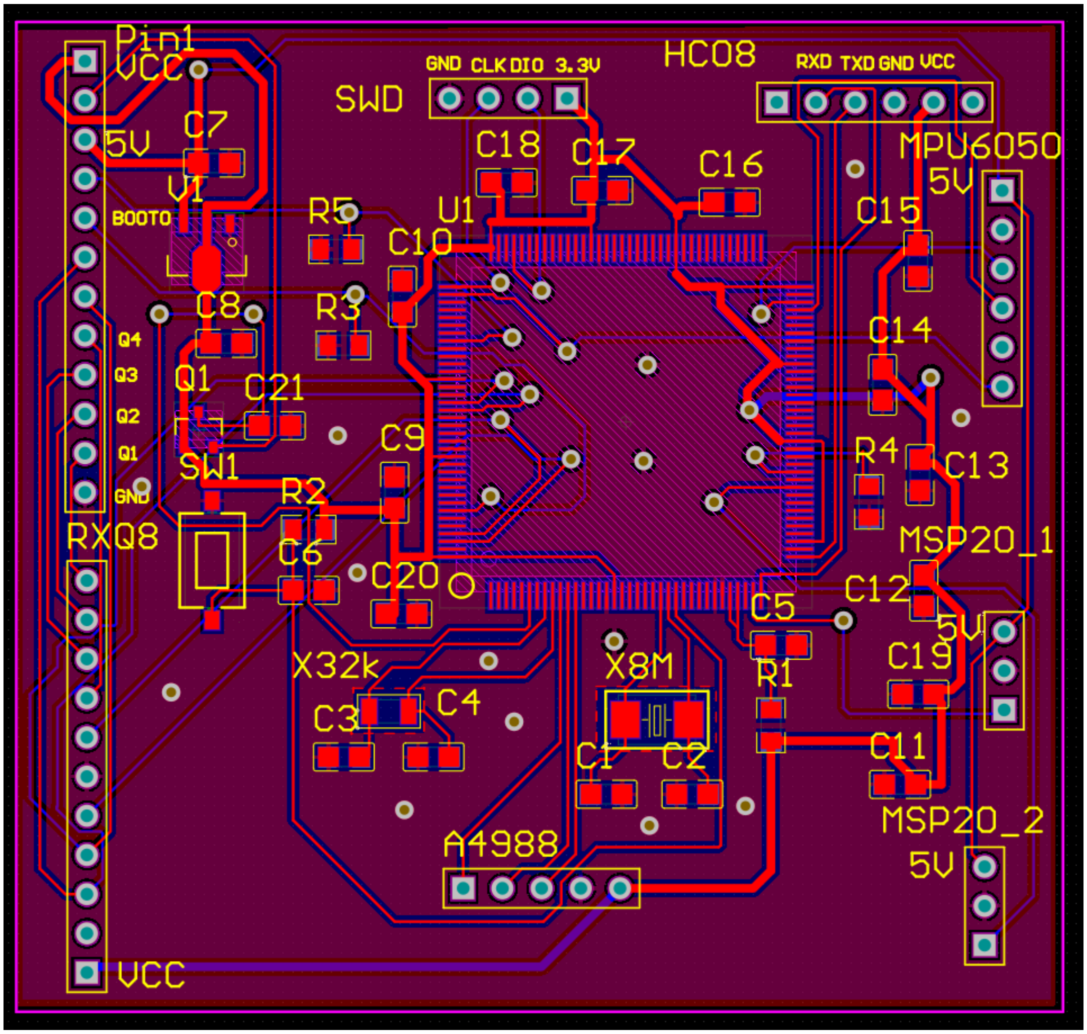

Figure B-4 PCB Design of MCU Subsystem

Appendix C Code and Project

The Link of the Project:

https://github.com/Taotu02feather/ECE445_STM32_Code_Public