ECE445 Final Report

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Project No. 6

Abstract

Our team's project is the development of a submarine model. Built upon the integration of microcontroller units and sensors, we emphasize methods in waterproofing and motor design. The project adopts a comprehensive approach to underwater vehicle design, highlighting the integration of electronic and mechanical components. Additionally, we address challenges in sensor integration and algorithm development for performance optimization. Future efforts will focus on further sensor integration and algorithm refinement to enhance the model submarine's capabilities. Through this project, we showcase the multifaceted nature of underwater vehicle design and underscore the importance of balancing electronic and mechanical elements.

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 under water.

1.3 Subsystem Overview

Figure 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 propulsion of the submarine. 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 2 shows the overall design of the submarine model.

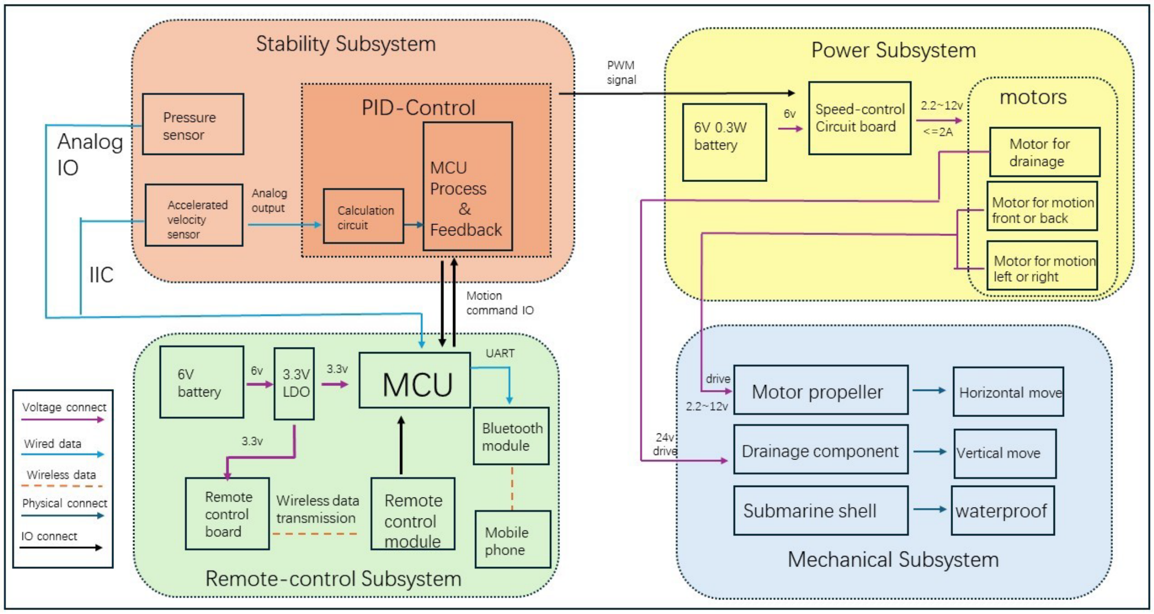

Figure 1 Block Diagram

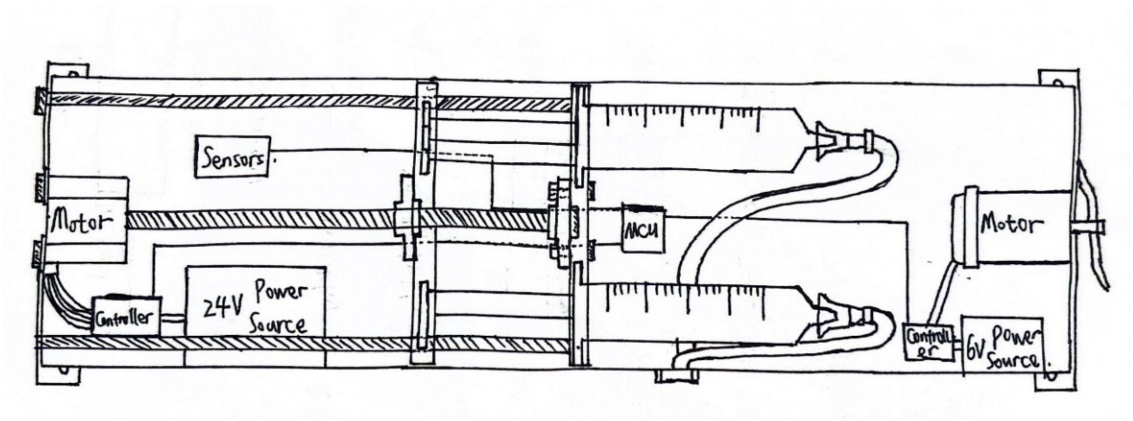

Figure 2 Submarine Model

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 4). We need to add counterweights (shown in Figure 5) 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, a brushless motor as a source of front-rear propulsion. And I designed some connectors to fix the motor to the hull and the linkage for the drivetrain.

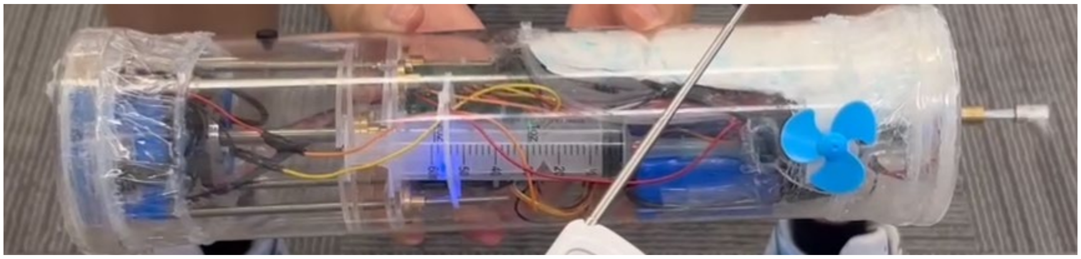

Figure 3 Submarine Model

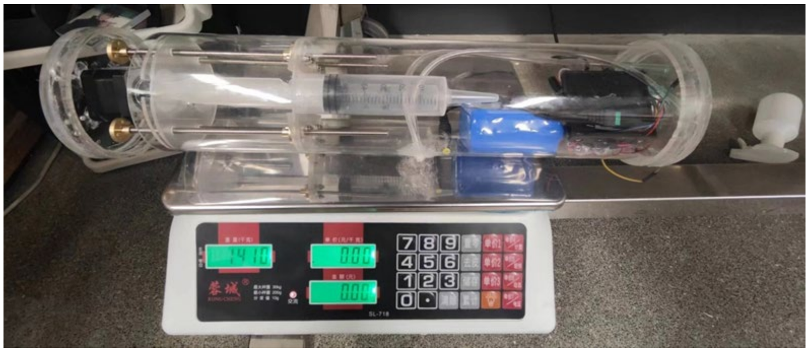

Figure 4 Net weight for submarine model

Figure 5 Counterweights

2.2 Remote-Control Subsystem

As for remote control, we need to use remote control module to give the order of motion to submarine. We need to control distance at least 50 centimeters to realize remote control. And the control signal will be delivered to the MCU control part. Figure 6 shows the remote-control RX-Q8 module, which is combined with 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 transmitter. The command is sent through 433MHz electromagnetic wave, and the experiment shows it can work under 50cm water. These eight pins will connect with the GPIO pins of MCU, such that MCU can read the command of remote controller.

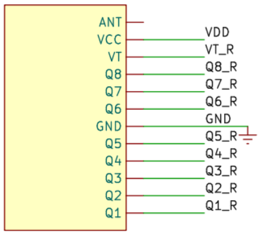

Figure 6 Remote-control module RX-Q8 circuit Schematics

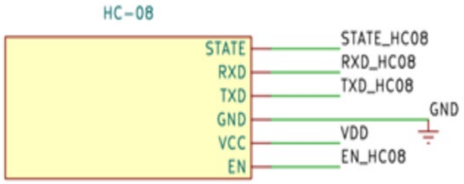

Figure 7 Bluetooth module HC-08 circuit Schematics

In addition, we use 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 mobile phone. Figure 7 shows the Bluetooth module is connected to MCU by 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 8. Moreover, as the propellers should be in the water, the waterproofing problem should be carefully handled, as a connection part with the cover part.

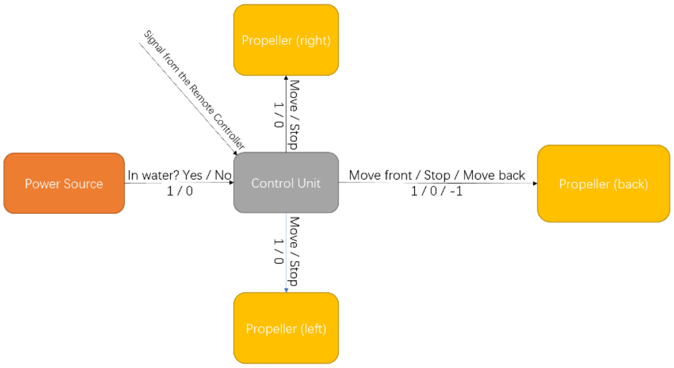

Figure 8 Block Diagram for Power Subsystem

The first version of the control unit uses four MOS switches (4 NMOS, voltage, current) and one speed-controlling board. See Figure 9. 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].

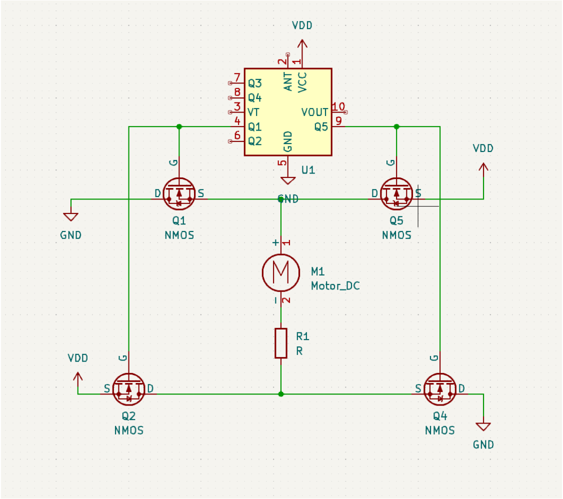

Figure 9 Circuit Diagram of Power Subsystem (V1)

The revised version improves the stability of the switches [5]. See Figure X. 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).

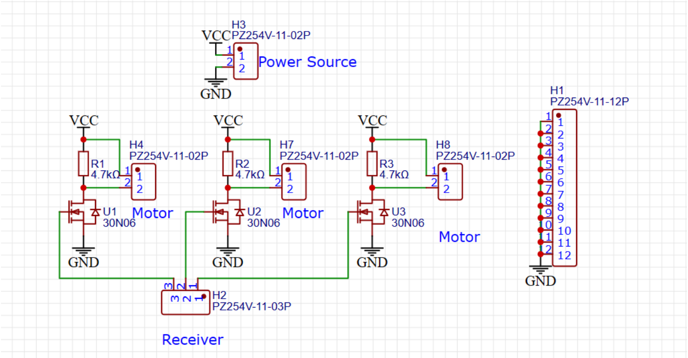

Figure 10 Circuit Diagram of Power Subsystem (V2) [5]

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 11.

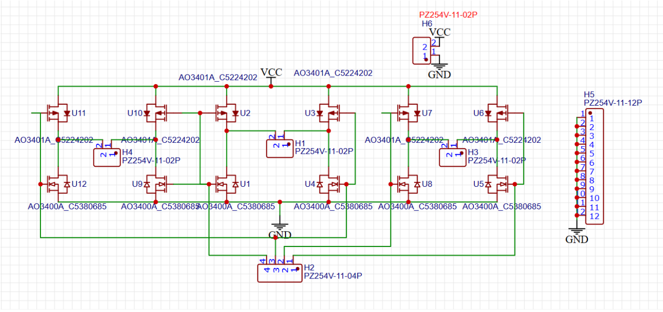

Figure 11 Circuit Diagram of Power Subsystem (V3) [6]

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 paramount for submarines, directly influencing the balance and maneuverability of the submarine underwater. Achieving buoyancy aims to ensure that the submarine can maintain a specific depth in the water and stabilize its floating when required. Effective control of the buoyancy adjustment system is crucial to maintaining the submarine's balance in the water, allowing it to descend to the desired depth while maintaining a suspended state. We also need to ensure that the submarine can descend and in a controlled manner when necessary. Adjusting the tank and other systems allows the submarine to descend to the desired depth.

Expanding on this, our primary objective is to develop a sophisticated stability control system that not only ensures the submarine's equilibrium but also enhances its maneuverability underwater. This entails implementing advanced algorithms and control mechanisms to precisely regulate the submarine's buoyancy in real-time. We aim to achieve a fine balance between buoyancy and weight distribution, enabling the submarine to maintain its desired depth effortlessly.

Furthermore, our focus extends beyond passive buoyancy adjustments. We intend to integrate active control mechanisms that allow the submarine to adjust its depth when needed. This involves optimizing the performance of the ballast tank system and incorporating responsive actuators to facilitate swift and precise movements underwater.

Through meticulous design and rigorous testing, we aim to develop a stability control system that not only meets but exceeds the stringent requirements of submarine navigation. By ensuring seamless integration with other subsystems and employing robust verification procedures, we strive to deliver a solution that enhances the overall performance and safety of the submarine.

2.4.1 Hardware Design for Stability

For this part, we will use 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 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.

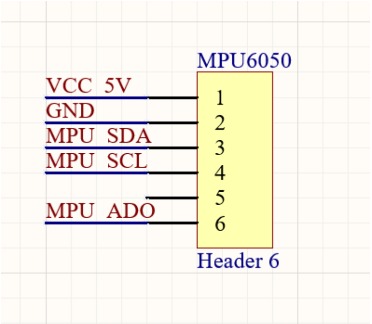

Figure 12 MPU6050 Pin Plan

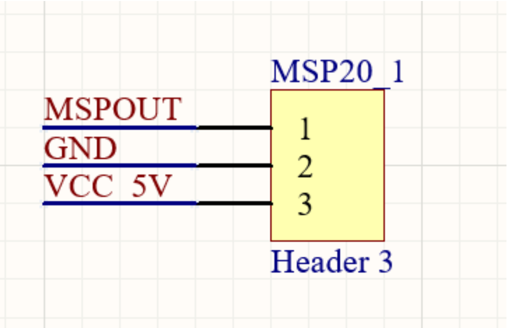

Figure 13 MSP20 Water Depth Pin Plan

For MPU6050, SCL and SDA are the digital output of I2C. It will output 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 analog signal output indicating the current water pressure at the submarine's position. This can help us understand the current underwater depth, aiding in achieving the stability of the submarine during submersion.

In Figure 13, the MSPOUT pin is the analog output pin, and the output of this port will increase as the water pressure rises. Based on our measurements, we found that the output analog voltage values are roughly proportional to the depth. Through the corresponding relationship, we can determine the relationship 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 they together, these angles uniquely describe the orientation of an object in three-dimensional space.

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

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

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

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

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:

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

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:

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

Combining these three axes together, we can get that:

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

Where the transformation array is:

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

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

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

And the result for world coordinate system should be:

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

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

To meet the requirements for the normal operation and suspension of the submarine in water, we need to provide a highly detailed and quantitative block description for the analysis subsystem related to suspension stability. This subsystem utilizes accelerometer sensors to measure the acceleration in all three directions (x, y, z) of the submarine, which is crucial for assessing its suspension stability. This task will be quite complex, so our first step in the design approach is to fulfill the basic buoyancy and suspension requirements. This will not demand too much in terms of stability since it is just the initial phase of the design. Then, in the second step, we aim to achieve suspension and maintain a fixed position below the water surface. This will be more challenging but highly valuable. Additionally, in subsequent design phases, we can utilize the translational acceleration for other control purposes.

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:

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

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.

The control of the drainage height x is achieved through the motor, allowing us to adjust it as needed. By controlling x and analyzing the accelerometer data, we can effectively assess and adjust the suspension stability of the submarine.

To further validate and support our design decisions, our plan includes relevant data analysis and considerations regarding the motor and chip components. This involves calculating the motor's rotational speed and minimum rotation increments, among other factors. Additionally, we will analyze from the perspective of the control system to ensure its stability. This will ensure that our design decisions are justified and aligned with the overall design goals dictated by the high-level requirements.

For controlling the motors, we employ a method where the output is directly proportional to the rotational range of the motor. This is because the maximum rotational speed of the motor is fixed, and the rotational speed is not very high. Hence, we increase the range of rotation to achieve the desired effect in controlling the changes in the water tank.

We employ the "Sigmoid function" or "Logistic function":

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

The Sigmoid function approaches zero for very small input values, approaches a maximum value for very large input values, and exhibits a relatively steep slope for intermediate values. Consequently, when input data falls within a normal range, the output approximates a proportional relationship. However, for input values that significantly exceed the range, upper and lower limits are imposed 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 for velocity. By adjusting K_i and K_d, we can attain the desired PID output.

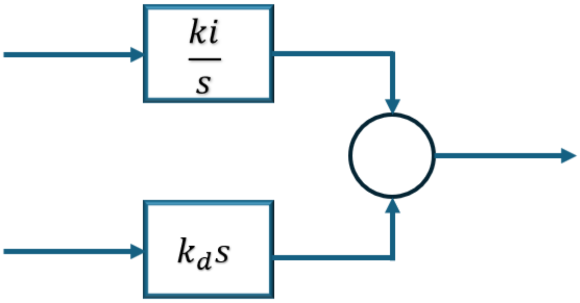

Figure 14 PID Control System

2.5 Microcontroller Unit Subsystem

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 receiver of 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 remote control module and Bluetooth module. It also needs to initialize the sensors, read, and process the data from sensor, apply PID control and then generate control signal to drive the motion of motors. The stepping motor is used to change the water volume in drainage system. MCU need provide three signals to control stepping motor: enable, direction and PWM. MCU can enable the motor by setting EN to 0V. Direction signal can be set to GND or VCC which corresponds to two direction of stepping motor. PWM signal is used to control the speed and duration of 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 to one cycle of rotation of stepping motor. Besides stepping motor, MCU also need generate PWM signal to DC brushless motor which takes responsibility for moving forward and backward. We can change the duty cycle of provided PWM signal to realize the clockwise, counterclockwise and halt state of the brushless motor.

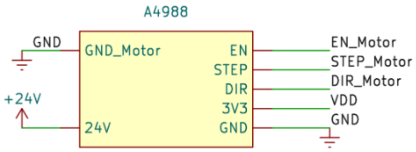

Figure 15 Step drive module Schematics

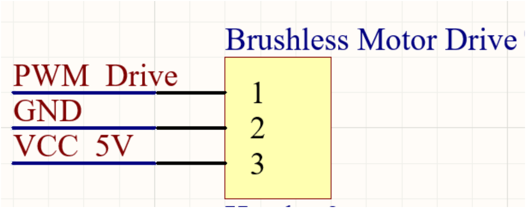

Figure 16 brushless motor drive module Schematics

To save space for the circuitry inside the submarine and enhance the stability of circuit connections between modules, we have designed a PCB to connect the remote controller, sensors, and two motor driver modules. Figure 15 shows the schematics of MCU subsystem and Figure 16 shows the PCB layout design of MCU subsystem. In the PCB design, we have considered providing two voltage options, 3.3V and 5V, for the modules, with voltage conversion achieved through a 3.3V LDO. The working circuit for the STM32F103 chip is referenced from the official datasheet [7], providing the MCU with circuit designs for 3.3V power supply, crystal oscillator, RESET, and other functionalities.

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.

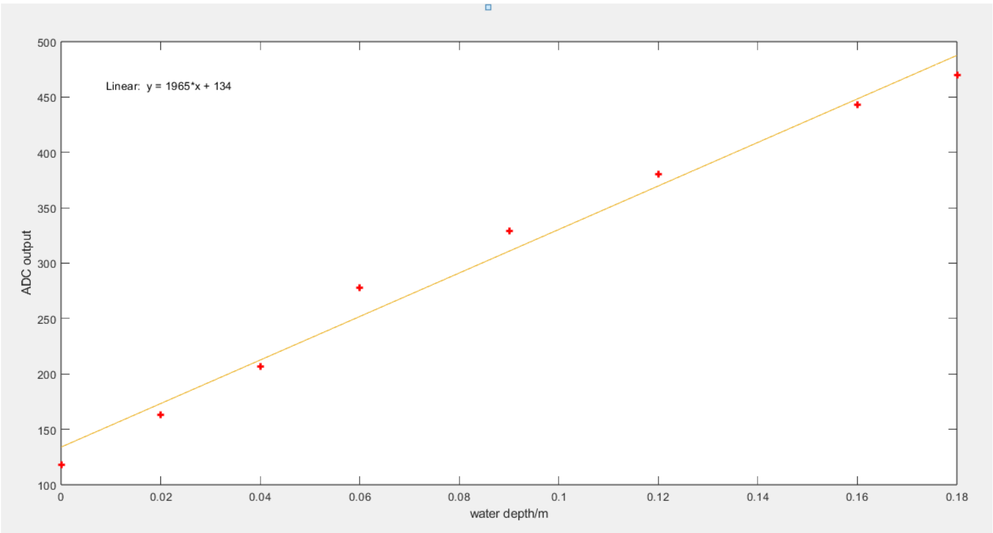

Figure 17 ADC output of MSP20

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 Table8 and Table 11. We need to verify that the 433MHz remote controller and the 2.4GHz Bluetooth module can achieve remote transmission and reception in water depths of at least half a meter. Firstly, we conduct theoretical calculations and simulations.

TEM waves will decay through water, so we need to analyze how much power of TEM waves will decrease through 0.5m water. In our design, we use 433MHz transmitter and 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:

$$\text{loss tangent} = \frac{\sigma}{\omega\varepsilon} \tag{4}$$

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, so we can get:

$$E(z,t) = E_0 e^{-\alpha z} \cos(\omega t - \beta z + \varphi) \tag{5}$$

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

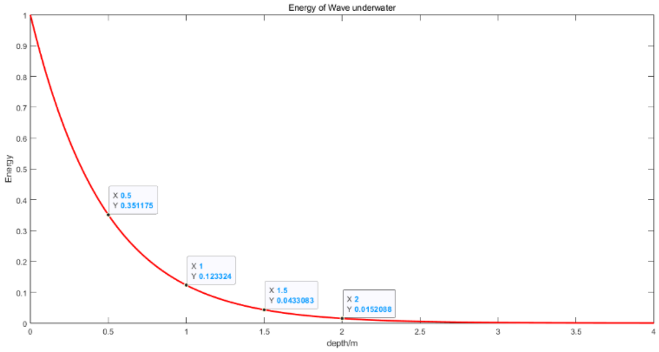

Figure 18 Energy decay simulation

Figure 18 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 underwater experiments by submerging the submarine to the bottom of a test pool (greater than half a meter deep). Using the remote controller, we issued commands for forward, backward, left turn, right turn, and ascent. The corresponding motors responded with the appropriate rotation within 0.5 seconds. Additionally, our mobile phone was able to receive readings from the water pressure sensor and accelerometer through the Bluetooth module. This underwater experiment validated the feasibility of remote control at a depth of half a meter underwater.

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

Figure 19 shows the PCB circuit connect 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 20 shows we tested the submarine model underwater. We have verified the work of Bluetooth module, pressure sensor and acceleration sensor by sending sensors' data through 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 remote controller, the corresponding motor can rotate, and the submarine can move accordingly. Specifically, the step motor rotates and absorb water causing the submarine diving when press button 5 and expel water when press button 6. Press 7 and 8 can drive brushless DC motor rotate and causing the submarine moving forward and backward. This has verified   MCU can read and process the remote control and drive the motors in correct direction. Also, the reaction time of submarine is within 1s, which meets requirements and MCU can process quickly.

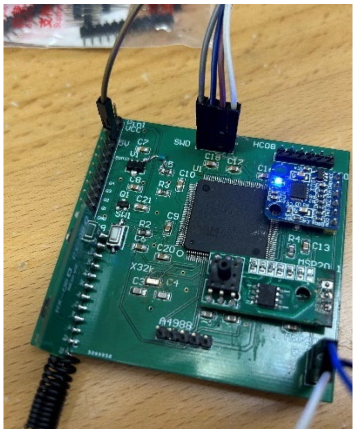

Figure 19 PCB circuit connection

Figure 20 Submarine model underwater test

3.4 Mechanical Subsystem

Requirements of Mechanical subsystem can be found in R&V Table 7. For the most important part-water proof system, we need to conduct underwater test for our submarine model. (shown in Figure 20 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 21 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 is 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 22 propulsion system) In the future, we will add a deflector to the rear of the hull to achieve this function.

Figure 21. Ballast system

Figure 22. Propulsion system

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 2 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 3 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		811.47	0	811.47

Table 4 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

Table 5 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, 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 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 individual test.
Week3	March 22-28

Cover	Underwater sealing testing, design and assemble ballast system.
Remote Controller & MCU	Use MCU output PWM signals to control the speed of 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 ballast system. Consider the distribution of the center of gravity.
Remote Controller & MCU	Realize the control speed of motor by remote controller. Integrate acceleration sensor and speed control module.
Stability & Sensors	Integrate depth and acceleration sensor for 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 writing 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 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 sink test with 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 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 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 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 6 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 xx (TBD) front/back, 0.007rad/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 (TBD), 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 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 the appearance which blocks the water flow. There is still some water leakage problem when the model stays longer than 30mins in water.

5.3 Ethical considerations

Analyzing the ethics and safety aspects of the project is paramount. Adhering to the IEEE Code of Ethics [8], we must ensure that the design, manufacturing, and testing processes of the project strictly adhere to the highest safety standards to safeguard the well-being and health of all project participants. Moreover, it is imperative to guarantee that any collection, storage, and processing of personal data involved in the project strictly comply with stringent privacy protection requirements to uphold users' rights to personal privacy.

In terms of safety, prioritizing the safety of circuits is paramount to prevent short circuits or electric shocks. We will implement stringent measures, including robust insulation and protective measures, to ensure the stability and safety of the circuits. Additionally, comprehensive measures will be taken to mitigate risks associated with equipment such as motors, ensuring they do not pose any threat of injury to classmates. This may involve installing safety covers, implementing safe operating procedures, and adhering to strict safety protocols to mitigate any potential hazards.

Another risk is that we are combining electricity and water. We must ensure that high voltage, such as 220V, never gets anywhere close to our experimentation with water. Due to the unique situation of submarines, waterproofing and electrical issues are of paramount importance. We need to utilize high-quality waterproof materials and sealing techniques to ensure the submarine's hull, critical components, and all connections have excellent waterproofing performance. Additionally, regular waterproof performance testing and inspections should be conducted to promptly identify and rectify any potential leakage issues. Contingency plans should be considered to address emergencies or unforeseen events. Regarding the electrical system, certified electrical components and wiring should be used to ensure the reliability and stability of the system. Furthermore, strict electrical safety standards, including proper waterproofing and insulation measures, must be implemented to prevent short circuits and electrical shock accidents. By adhering to these safety measures and recommendations, we can effectively address waterproofing and electrical issues in submarine design, thereby maximizing the safety of team members and equipment.

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 sensor, ion concentration sensor and so on. Cameras added can help the user to see the environment around the model. It is more 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 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 charging process easier.

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

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

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Appendix A Requirement and Verification Table

Requirements	Verifications
1)The submarine hull can make sure that everything except the ballast system, is isolated from the outside water. 2)The submarine hull and its components can be kept relatively stationary in motion and rest. 3)The submarine ballast system can implement stable and fast water intake and discharge. 4)The submarine can keep its balance while floating in the water. 5) The submarine can float and sink completely and remain suspended.	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 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 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. 4) During all these tests, the hull pitch Angle is maintained at

Table 7: Requirements & Verifications for Mechanical Subsystem

Requirements	Verifications
1) The Submarine can receive the motion command through transmitter under 50 cm water. 2) Submarine can send the sensors' data to mobile equipment, and we can demonstrate the states of the submarine in mobile devices.	1) a) If submarine can move according to the remote controller, the below test can pass. b) Connect the LEDs with output decoder pins of remote-control module. If receiver receive the motion command, corresponding LED should light up. c)put the submarine underwater around 50 centimeters, press the command button, observe whether the corresponding LED light within delay 2s. 2) a) Put submarine underwater around 50 centimeters. Our mobile device can receive the data and show the sensors' data like depth of submarine and accelerate data. b) Use the program in MCU that send sentences to mobile devices continuously. Gradually sink the submarine underwater. Observe the received data on the mobile device and measure the depth that we cannot receive the sentences by ruler, compare the measured depth with target depth 50cm.

Table 8: Requirements & Verifications for Remote-Control Subsystem

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

Table 9: Requirements & Verifications for Power Subsystem

Requirements	Verifications
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. 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 seconds. 3) The submarine should be able to descend to the specified depth. The error should not exceed 20 centimeters.	1) Measurements should be taken using a ruler or other length measuring tools. 2) 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. 3) Measurements should be taken using a ruler or other length measuring tools.

Table 10: Requirements & Verifications for Stability Subsystem

Requirements	Verifications
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 need generate PWM waves to control the speed of motors. Meanwhile, all the electric components need 3.3V power supply and 3.3V IO connect, MCU need output appropriate voltage. 2) MCU need process remote control signal and generate motor control signal, so the motor could react according to the remote controller. The drainage motor should drive tank suck or expel the water according to the remote command. 3) The data needs to be processed quickly enough to ensure the quick reaction of the submarine. The reaction should not be realized more than 3s.	1) 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 value linearly between 0V and 5Vaccording 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 Bluetooth module. And Bluetooth module can be tested by receiving correct data like sentences in mobile phone. d) Test 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 connect between components by voltmeter and compare the voltage value with the desired value according to datasheet. 2) a) Put the submarine underwater around 50 centimeters, we can press moving up, down, front, back, left, and right button, record the rotation of motors and its direction, compare the motion with the button press. b) press the button 5, MCU should generate control signal to drive motor rotate and causing the submarine's ballast tank to suck in water so that the submarine could dive. c) press the button 6, MCU should generate control signal to drive motor rotate in counter direction and causing the submarine's ballast tank to expel water so that the submarine could surface. 3) The code needs optimized enough. We can test the efficiency that the submarine can implement command within delay 3s. We can test delay by record the time between pressing the command button and the reaction moment of the submarine.

Table 11: Requirements & Verifications for Microcontroller Unit Subsystem

Appendix B PCB Design

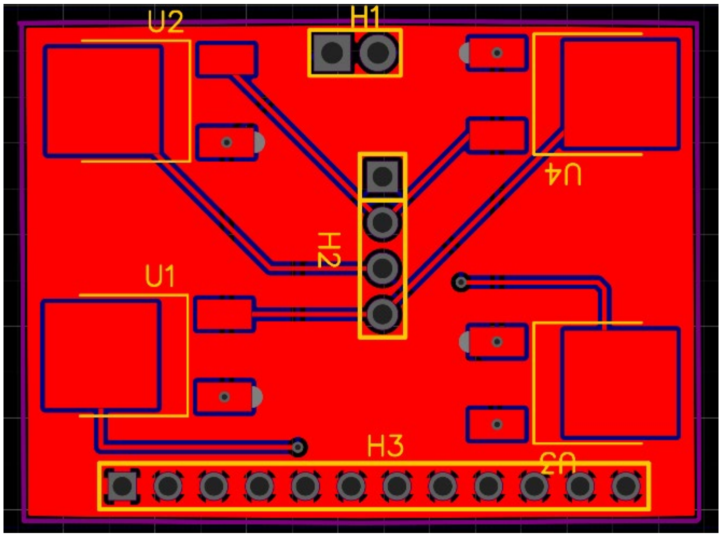

Figure 23 PCB Design of Power Subsystem (V1)

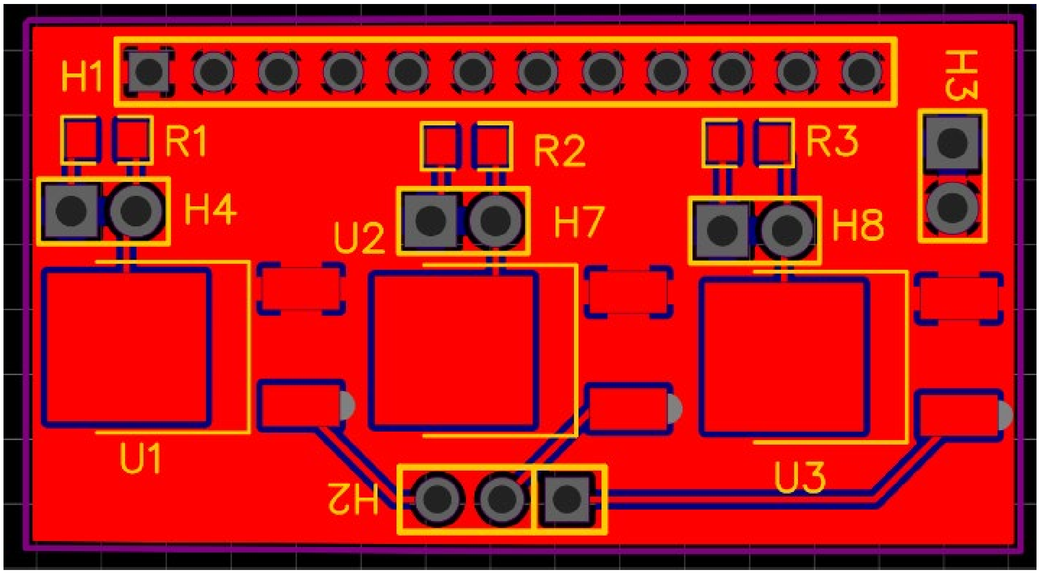

Figure 24 PCB Design of Power Subsystem (V2)

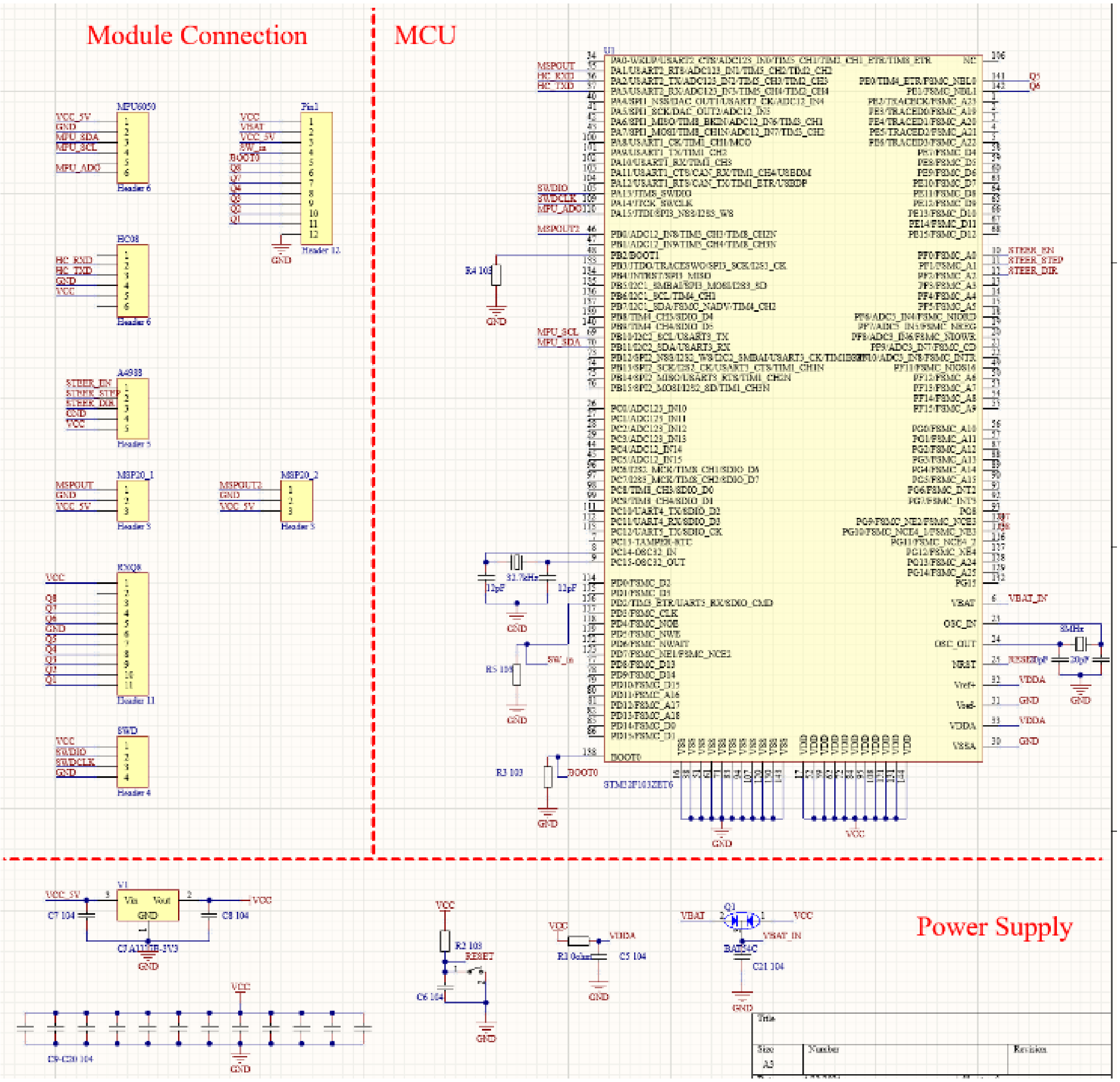

Figure 25 MCU subsystem circuit Schematics

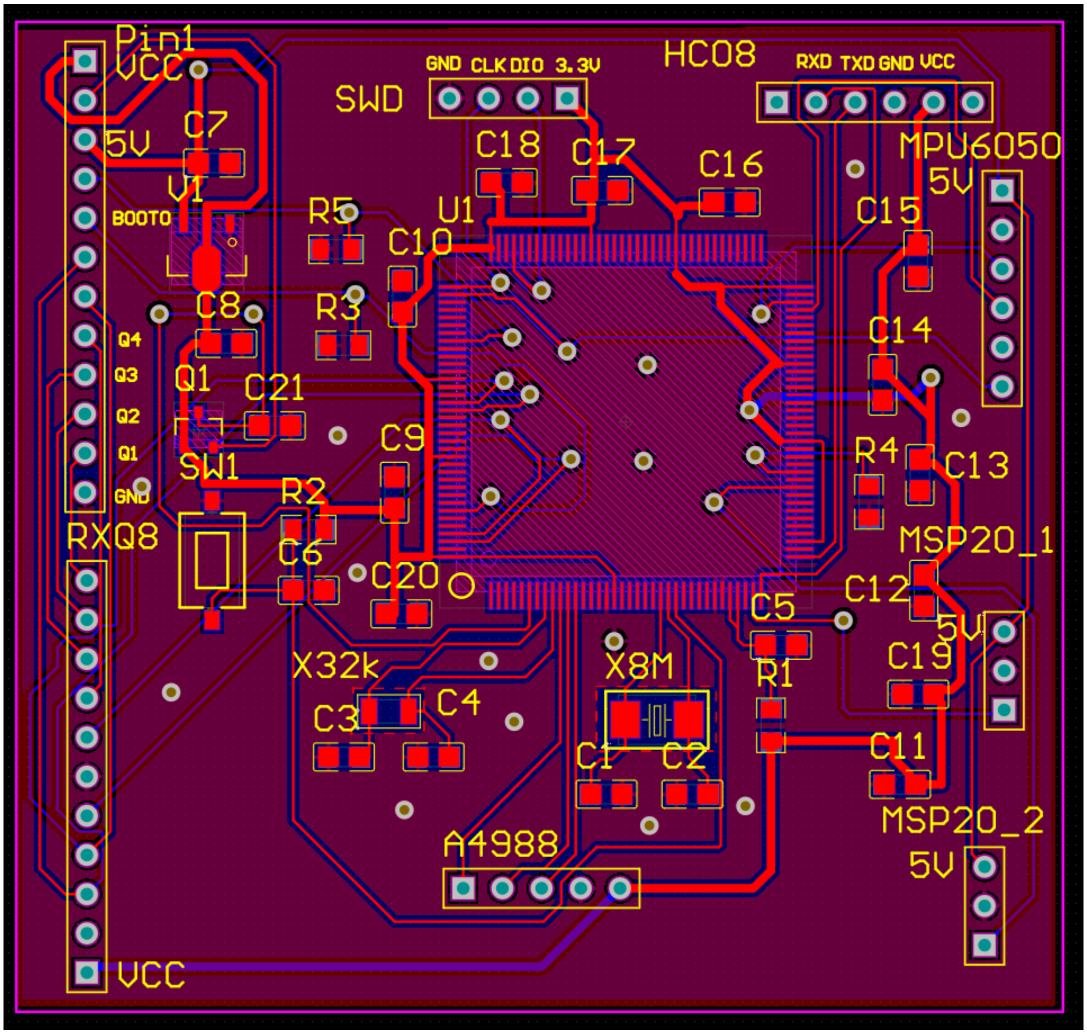

Figure 26 PCB Design of MCU subsystem