ECE 445

SENIOR DESIGN LABORATORY

Design Documents

A Transformer

Jingcheng Liu - EE (jl138)

Haobo Li - EE (haoboli2)

Tinghua Chen - ECE (tinghua3)

Shiqi Yu -ECE (shiqiy2)

Sponsor : Rakesh Kumar

TA: Xiaoyue Li

03/24/2023

1 Introduction

1.1 Problem

In some cases or scenarios, some locations or areas are inaccessible to people, such as narrow pipes and crevices in collapsed buildings, so we need adaptive robotics to reach these areas instead of us and do some of the work for us. The robotics that we will introduce and build is Modular Self-Reconfigurable Robotics (MSRR), which are able to connect to each other and change their configuration in order to create new robots or structures.

With its features, MSRR can be used in many scenarios like space exploration, disaster response, undersea inspection, education, entertainment and art. For example, It can be used for space exploration missions, where they can reconfigure themselves to adapt to different tasks and environments, and they can also repair themselves and replace damaged modules. In disaster scenarios, MSRR can adapt to changing environments or narrow and complex landform, help with search and rescue missions. In the undersea scenarios, MSRR can also work and help with inspection or building piers and tunnels. The other aspect application of MSRR is education, entertainment and art. For example, MSRR can be programmed to create interactive artworks and installations because it can be assembled and reassembled to create different configurations.

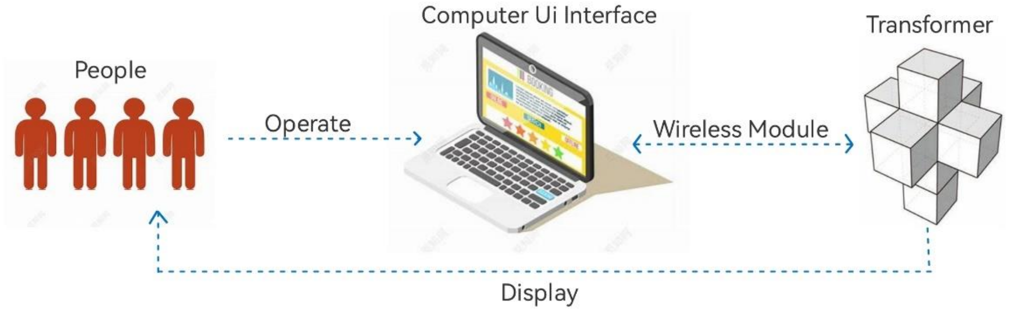
1.2 Solution

We are aiming to build a modular block system with self-reconfigurable features. Our solution will include easier lighter devices, fluent transformation and easy-to-operate interface. It’s an innovation in the field of MSRR, especially in education, entertainment and art. More concisely, we will use electromagnet to control the mechanism of block robotics. Different block robots are controlled by a central host computer through wireless signals. MCU in block robots receive signals from wireless module and control the circuit to apply positive or negative current to the electromagnet to control the rotation or suspension of the block entity.

A 3D printed cube and 12 metal sticks on the edges. Metal sticks on the edge serve as hinges to attach different cubes during the rotation. When the joint surfaces of the two blocks need to be changed, the hinges form a tight connection between them, allowing the blocks to flip over smoothly without falling apart. The wireless module transmits command signal from host computer to block robots. After the signal is received at the remote side, MCU in block robots will process this signal and convert it to control signals on its ports. Electrical circuits will get input signal from an MCU port, then use it to control the state or polarity of 6 electromagnets on the block surface or 8 electromagnets on the corner which have 5v voltage and 3kg force. The change in polarity of electromagnet is used to complete the rotation and deformation of the robot.

When the modular block robotics come into application, we can also install different modules on different block, but they are further study and exploration which are not included in this project.

1.3 Visual aid:



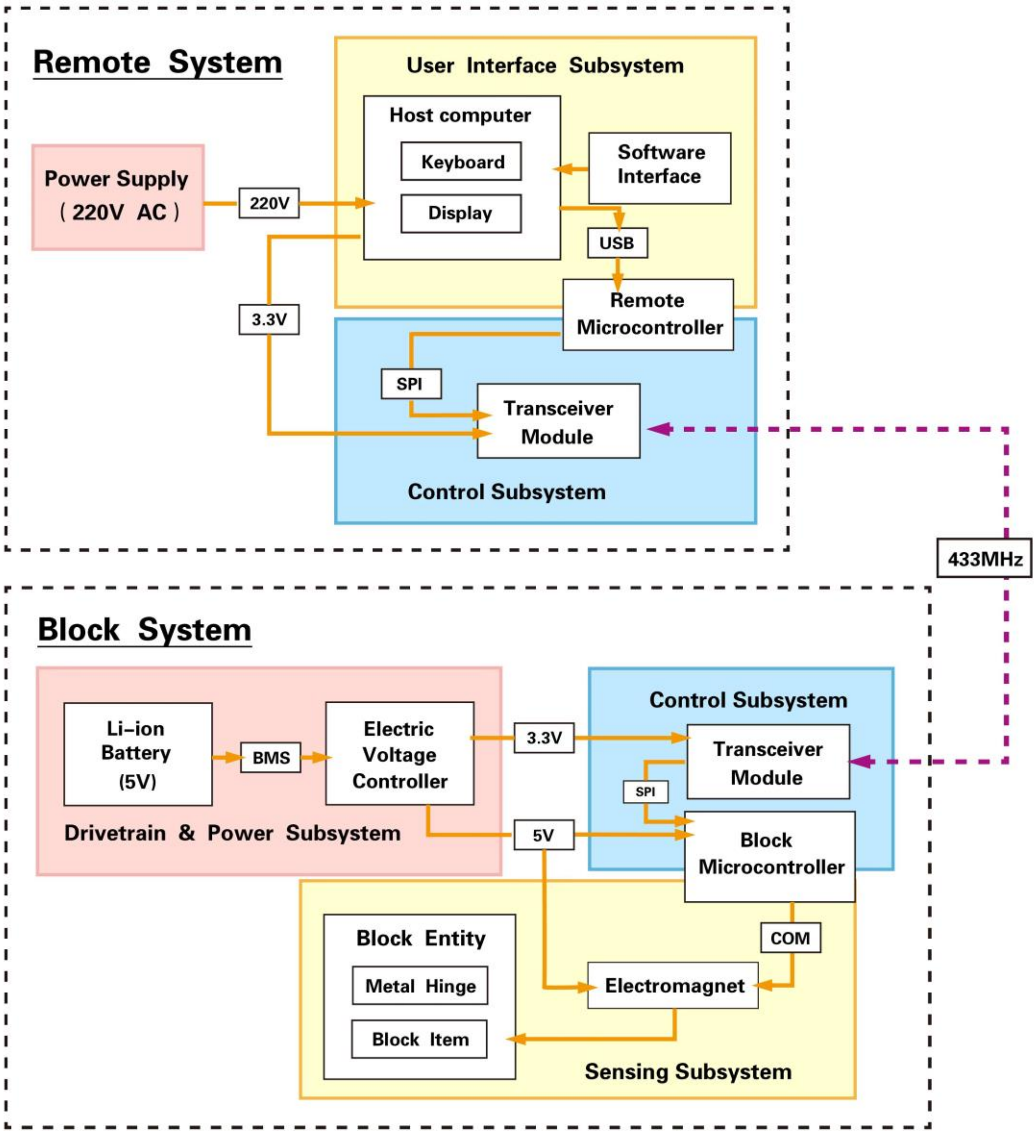
1.4 High-level requirements list

1. Compact and portable: The control units within each mechanical entity are compact, capable of integrating wireless modules, control circuits and electromagnets, and each mechanical entity is smaller than $216^{cm^3}(6^{cm} * 6^{cm} * 6^{cm})$ in size and lighter than 1kg.
2. Flexibility: Each mechanical entity can achieve a 90° flip and a 180° flip in four directions (Front, back, left and right).
3. Separability: At least three mechanical entities can be controlled by the control system, and these mechanical entities are not affected by each other.
4. User-friendliness: The computer control interface is clear and concise so that users can clearly operate the transformer.

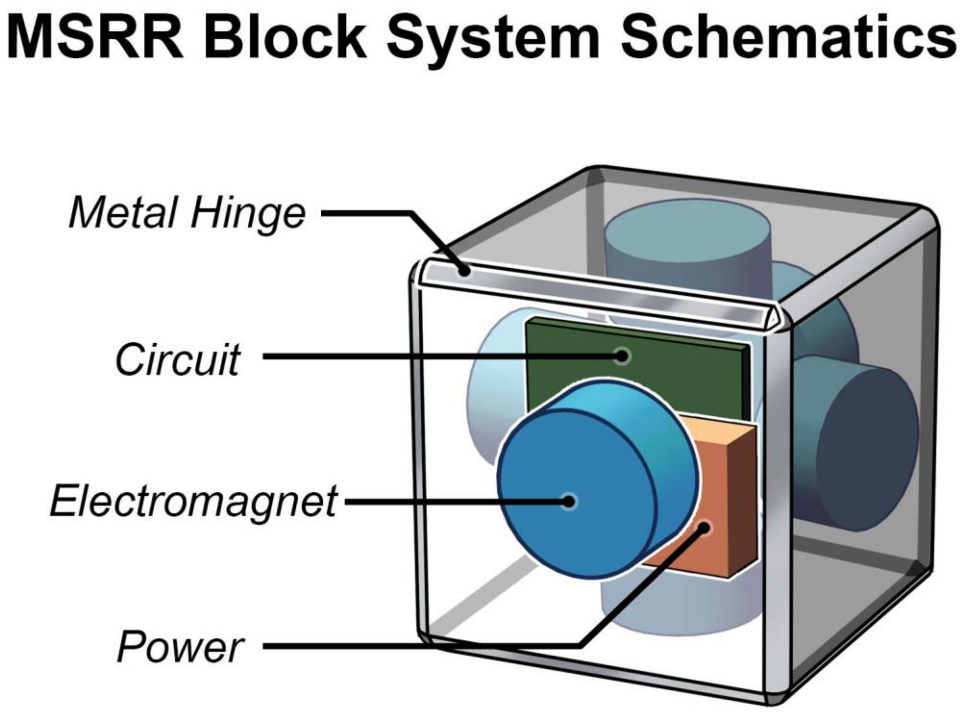
2 Design

In order to make the whole system works successfully, all the systems and subsystems should work well, for the remote system is basically completed on personal computer (PC), with a USB interface to send the instructions on PC to the Transceiver Module, so that the USB interface must be able to supply at least 3.3 V DC voltage to the Remote Microcontroller to make it work normally. And the Transceiver Module must be able to send the control signal at 433 MHz or 2.4 GHz to the receiver part.

And for the block part, the Li-ion battery must supply a steadily 5V voltage for at least 30 minutes, so that the experiments and demo can goes smoothly. And the microcontroller should decode the signal get from the transceiver module and send a instruction to control the positive or negative voltages of the electromagnet to control the electromagnet's polarity.



The physical design shown below contains one eclectromagnet on each face, so in total it has six eclectromagnets, and each edge contains a metal hinge, and inside it there is the Li-ion battery and the circuit board, the detailed parameters we will talk at 2.3 Material part.



2.1 Remote system

2.1.1 Power Supply subsystem

For the Power subsystem must be able to supply a stable 220 V AC voltage so that the computer can work normally. And the USB interface must be able to supply at least 3.3 V DC voltage to the Remote Microcontroller to make it work normally. And the Transceiver Module has a work voltage at 2V-12V.

a. Computer battery

At the time of demo, the computer may be need to work without charging, so we should test the work time of the computer battery

requirement	verification
Work at least 1 hour with power off	Fully charge the battery, unplug the power, and record the working time of the computer in the hot state, if this time is larger than one hour, then it meets our requirements.

b. Other components

We need to simple test the components to check whether they work well

requirement	verification
Work under normal operating voltage	Place the component in the normal working voltage and working environment to see if it works properly, if it works properly, then it meets our requirements.

2.1.2 User Interface

For the User Interface subsystem, it must be able to recognize the instructions entered by the user's keyboard, and send it to the Remote Microcontroller by USB interface, and the software must run smoothly.

a. Aduino Software

requirement	verification
Can transfer the written code into the aduino module	1. Write a test aduino code(Example: let the lights flicker). 2. Transfer the code into aduino module. 3. Power on, observe whether the lights flicker. 4. If the lights flicker, then it meets our requirements.

2.1.3 Control

For the Control subsystem, the Send-Transceiver Module must be able to recognize the instruction from the Remote Microcontroller, and send the control signal at 433 MHz or 2.4 GHz to the right block, we may have ten or more blocks so the Transceiver Module must be able to send the control signal to special block or it must be able to send a special signal that all the blocks can receive.

a. Send-Transceiver Module

requirement	verification
recognize the instruction from the Remote Microcontroller, and send the control signal at 433 MHz or 2.4 GHz to the right block	1. Use it to send out a sinusoidal signal 433 MHz. 2. Receive the signal and pass it into filter at 400MHz-450MHz filter interval. 3. Obverse the frequency domain of the signal after passing through the filter. 4. Also obverse the frequency domain of the noise after passing through the filter. 5. Compare them, if there is only a raised part at about 433MHz, and the noise

	doesn’t have this part, then it meets our requirements.

b. Serial Port Monitor

requirement	verification
connect to the Transceiver Module and send command to it to generate wireless signals. It is connected to the computer, we use Serial Port Monitor to control the module.	USB com port monitor, connects com port with the USB on the computer. So we can directly send command to the transceiver module.

2.2Block system

2.2.1 Drivetrain & Power subsystem

For the Drivetrain & Power subsystem, we would like to use a Li-ion Battery, to make the whole system run normally, it must have a stable output voltage of 5 V, and the output current should be 0-2A, and the battery capacity should larger than 5000 mAh to ensure that all the experiments and demonstrations can be carried out properly. BMS is circuit protection device, and it must be able to cut off the circuit when the current is larger than 2 A, and the Electric Voltage Controller must be able to recognize the control signal sent by the microcontroller, to supply a positive or negative voltages to the electromagnet to control the electromagnet's polarity.

a. Li-ion Battery

requirement	verification
Supply a steadily 5V voltage for at least 30 minutes	To test it, we will first set up a simple circuit, just the li-ion battery and a 50 Ω resistor, and measure the voltage at both ends of the resistor by voltmeter, and continuously observe for 30 minutes, if the voltage can keep steadily at about 5V, then it meets our requirements.

b. BMS(Battery Management System)

requirement	verification
cut off the circuit when the current is larger than 2 A	Connect the battery to the sliding rheostat and slowly reduce the resistance value, at this time the current will gradually increase, and measure the current value when the circuit is cut off, if this value is about 2A, then it meets our requirements.

c. Electric Voltage Microcontroller

requirement	verification
recognize the control signal sent by the microcontroller, and supply a positive or negative voltages to the electromagnet to control the electromagnet's polarity.	1. Connect the voltage controller to the circuit. 2. Measure the positive and negative voltage at both ends of the resistor. 3. Send a signal to the voltage controller through the microcontroller. 4. Measure the positive and negative voltage at both ends of the resistor again. 5. If the voltage reversed, then it meets our requirements.

2.2.2 Control

For the Control subsystem, the Receive-Transceiver Module must be able to recognize the control signal at 433 MHz or 2.4 GHz, and send the instruction to Microcontroller of the block.

a. Receive-Transceiver Module

requirement	verification
Recognize the control signal at 433 MHz or 2.4 GHz, and send instruction to Microcontroller of the block.	1. Use the Send-Transceiver Module to send a test signal at 433 MHz or 2.4 GHz 2. View the processing records of the microcontroller, if there is a record of the test signal, then it meets our requirements.

2.2.3 Sensing

For the Sensing subsystem, the nano MCU must be able to decode the instruction send by Receive-Transceiver Module, and control the voltage and polarity of electromaget. And it needs a voltage supply of 5 V and a current not lager than 1 A.

a. MCU(Microcontroller of the block)

requirement	verification
decode the instruction send by Receive-Transceiver Module, and control the voltage and polarity of electromagnet	1. Set up the circuit with all the components in, but change electromagnet as resistor. 2. Observe the voltage at both side of the resistor, find whether it is positive or negative. 3. Send a test signal to Receive-Transceiver Module 4. Observe the voltage again

	5. If the positive or negative of the resistor's voltage changes, then it meets our requirements.

2.3 Material

And for the block it self, it's made by 3D-print, and the density of the printed material is 1.24g/cm^3, and the thickness of the face should be less than 2 mm, so that the weight of the box itself can less than 150 g, and to decrease the weight, our preliminary determination of the thickness is 1 mm. And we have six electromagnets fixed on its six faces, each electromagnet weighs 25 g, and needs a 5 V voltage supply and current not larger than 0.22A, and each electromagnet can supply a 3 KG magnetic force, we also have 12 hinges on the each edge, the role of the hinges is to enhance the magnetic force between the two different blocks and facilitate rotation, and each hinges is made of iron and weights 0.7 g, with length of 8 cm and diameter of 1.2 mm.

a. Electromagnets

requirement	verification
It can work normally at a voltage of 5V and provide a magnetic attraction force not less than 3kg	Switch the power on, let the two electromagnets attract each other, hang the weight on one side of the electromagnet, and record the mass of the weight until it falls off. If the weight is larger than 3kg, then it meets our requirements.

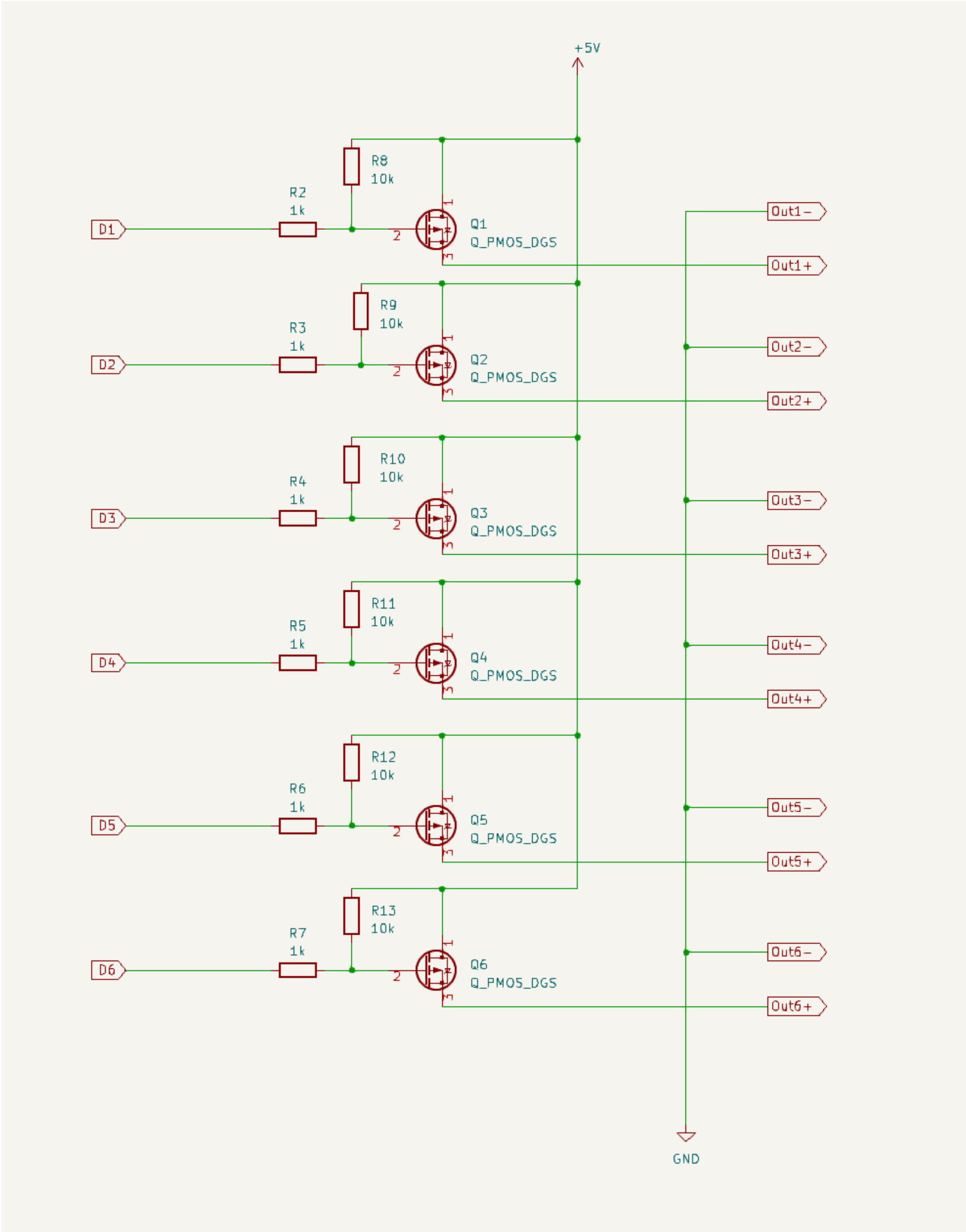
b. Other components

The materials we need are purchased online, so we should make sure that the parameters are accurate.

requirement	verification
The parameters are accurate	For simple weighing with an electronic scale, if the weight of a block is no larger than 500g, then it meets our requirements.

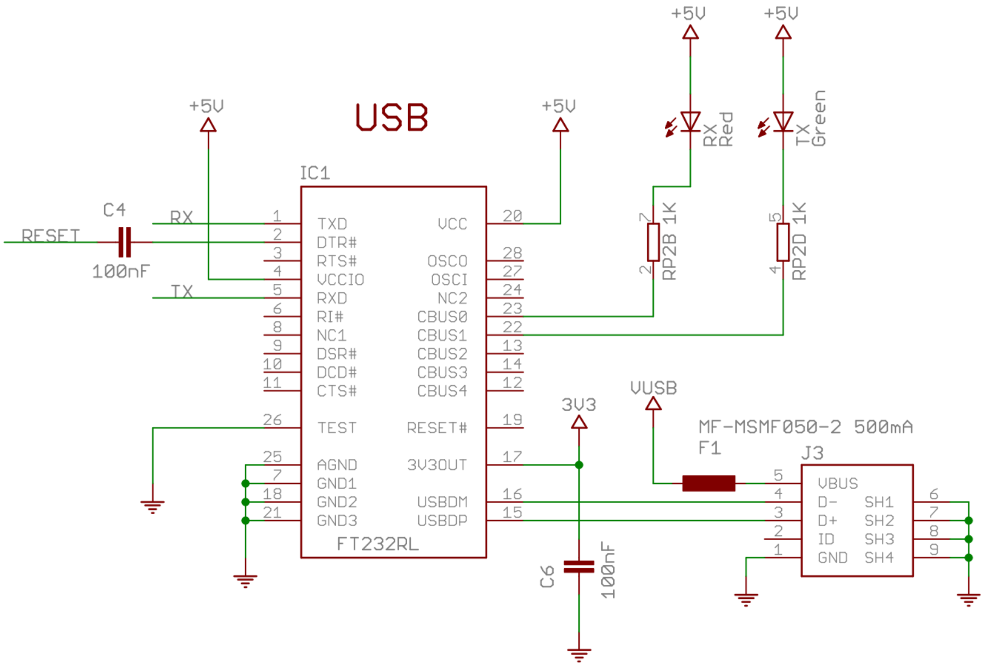
2.4 Schematics

Power Supply

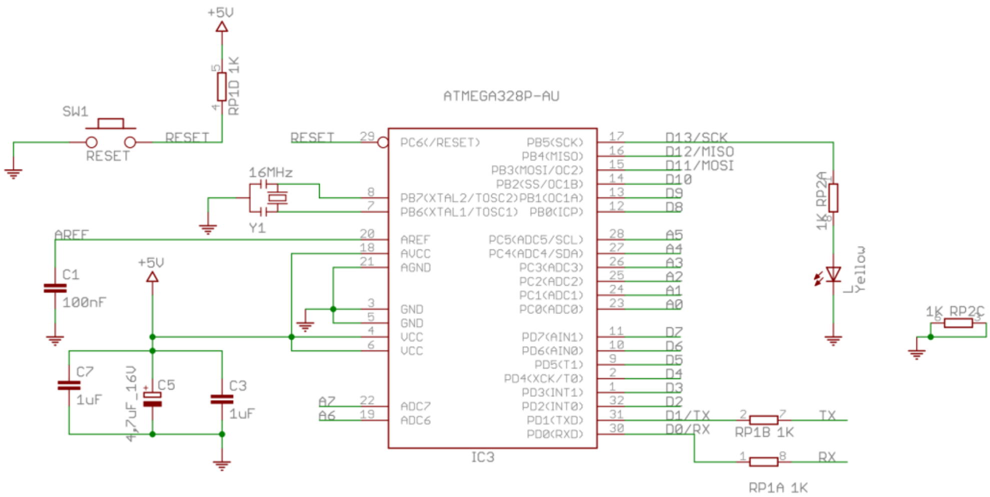


+5V
R8
10k
R2
1k
D1
Q1
Q_PMOS_DGS
Out1−
Out1+
R9
10k
R3
1k
D2
Q2
Q_PMOS_DGS
Out2−
Out2+
R10
10k
R4
1k
D3
Q3
Q_PMOS_DGS
Out3−
Out3+
R11
10k
R5
1k
D4
Q4
Q_PMOS_DGS
Out4−
Out4+
R12
10k
R6
1k
D5
Q5
Q_PMOS_DGS
Out5−
Out5+
R13
10k
R7
1k
D6
Q6
Q_PMOS_DGS
Out6−
Out6+
GND

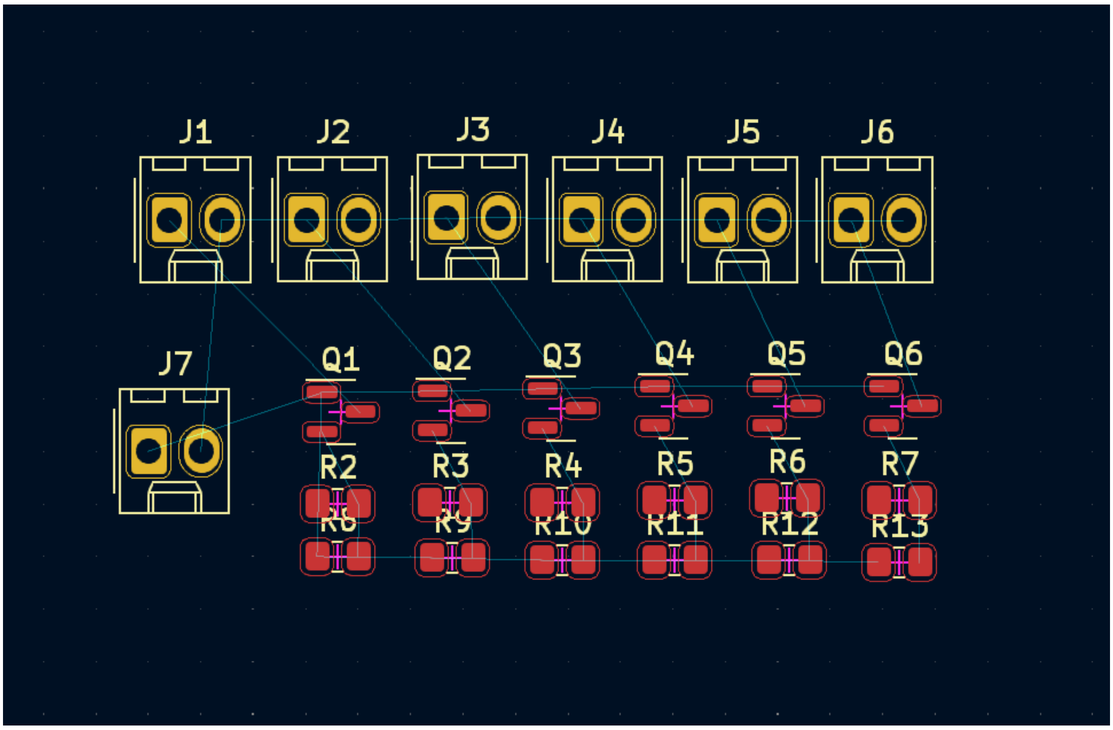
USB



Microcontroller



2.5 PCB Board Layout

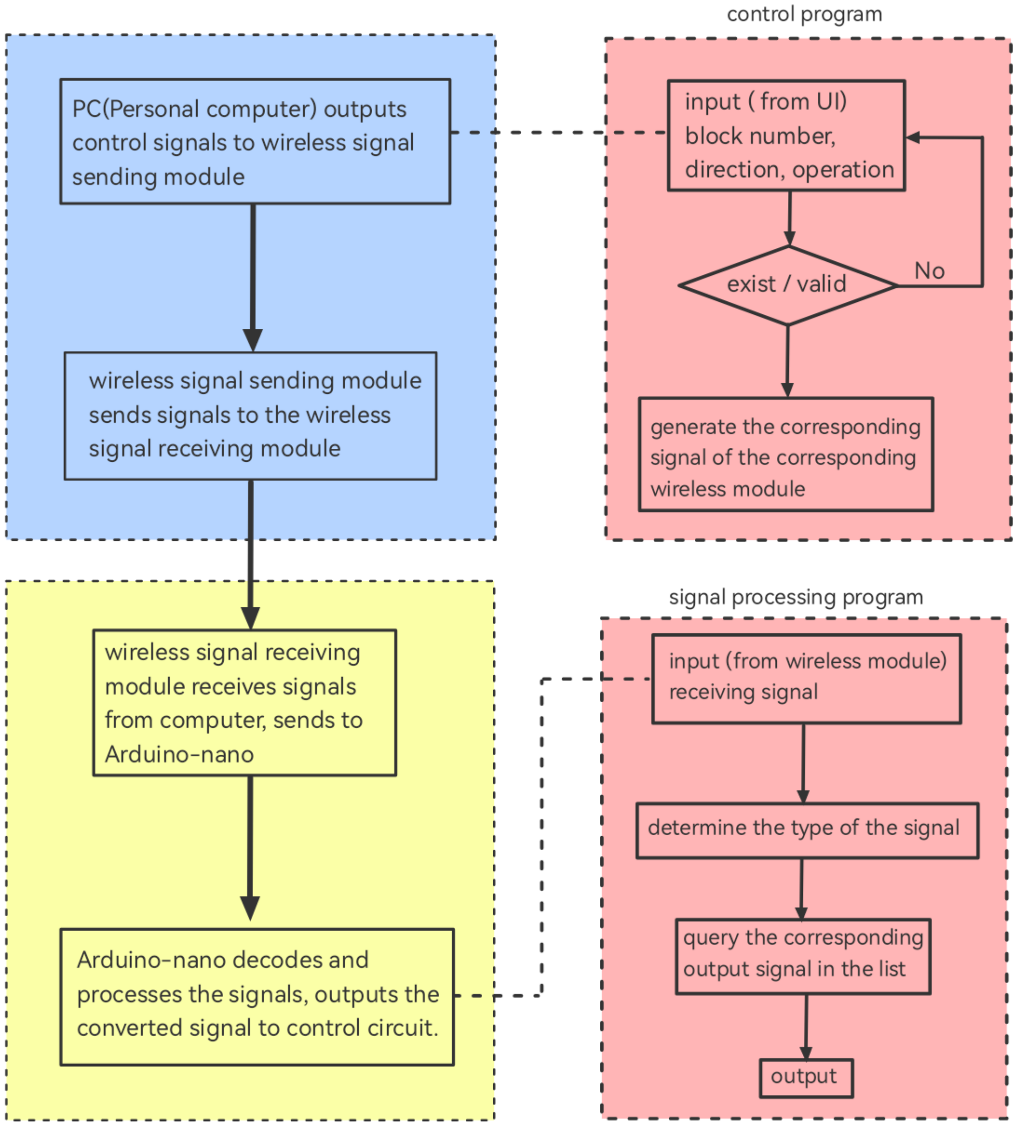


2.6 Software

This software includes two parts: control and signal processing program and User interface. Control and signal processing program is mainly used to control the input and output of signals. The User interface acts as the medium used to connect the user to the control and signal processing program.

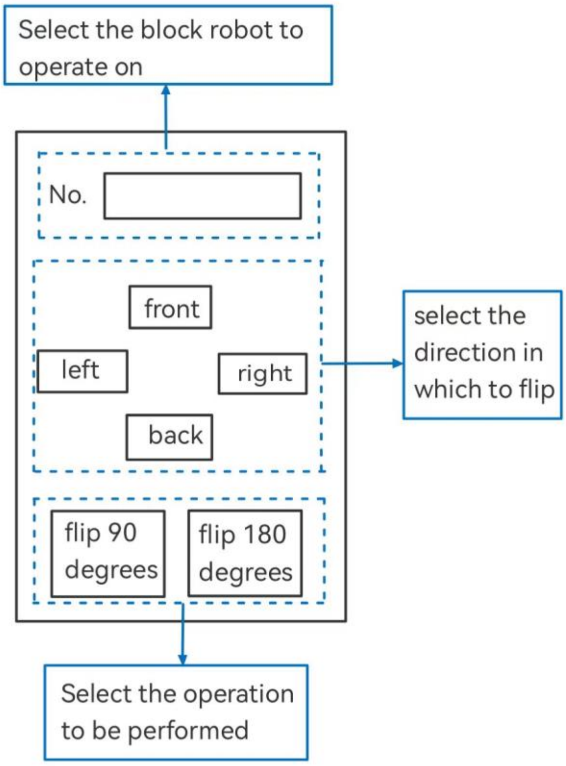
2.6.1 Control program and Signal processing program

The function of the control program is to receive the user interface information as input, and then generate the corresponding signal output to the wireless signal sender. The function of the signal processing program is to analyze the signal received by the receiver of the wireless module, determine the corresponding object and operation of the signal, and then output the corresponding circuit analog signal of the object and operation.



2.6.2 User interface

The design of the user interface is mainly divided into three parts: block number, direction and operation. The user sends the block number and the operation to be operated to the control program through the user interface. The user interface connects the user with the control program, which facilitates the user to operate multiple block robots.



2.7 Tolerance Analysis

In our design, the key point is that our electromagnet is able to attract and move the block in different transforms. We have two configuration of the electromagnet, one is on the surface, one is on the corner. If the power of magnet is enough, we can install the electromagnet on the surface, which is easy to control and we can make the block smaller. Installing the magnet on the corner can give a larger momentum but makes the block larger and harder to control. In our tolerance analysis, we will use mathematical analysis to demonstrate the feasibility of several transforms in our design.

At first, we know the Biot-Savart Law and Ampere's Law:

$$B = \frac{\mu_0}{4\pi}\int_L \frac{I\,\boldsymbol{dl} \times r}{|r|^3} \qquad (1) \qquad F = \int_C I\,\boldsymbol{dl} \times B \qquad (2)$$

So the force between two loop current can be written as:

$$F_{21} = \frac{\mu_0}{4\pi} I_1 I_2 \oint\oint \frac{dl_2 \times (\boldsymbol{dl_1} \times (r_2 - r_1))}{|r_2 - r_1|^3} \qquad (3)$$

$$F_{12} = \frac{\mu_0}{4\pi} I_2 I_1 \oint\oint \frac{dl_1 \times (\boldsymbol{dl_2} \times (r_1 - r_2))}{|r_1 - r_2|^3} \qquad (4)$$

Through formula simplification, we can get the following:

$$F_{12} = -\frac{\mu_0}{4\pi} I_2 I_1 \oint \oint \frac{r_1 - r_2}{|r_1 - r_2|^3} dl_1 \cdot \boldsymbol{dl_2} \quad (5)$$

For the convenience of calculation, we regard the solenoid as a multiple loops current. For details, we can have a electromagnet with the current of 0.22A and 500 turns, 20mm width and 15mm length. The electromagnet has an iron core and the magnetic force is 3kg when the magnets are attached together. By formula (5) we can assume that the magnetic force of the electromagnet is proportional to the inverse of the square of the distance.

Then we can calculate the coefficient of the magnetic force k, and the corresponding relative permeability μ_r.

$$\mathrm{k} = \frac{\mu_r \mu_0}{4\pi} I_2 I_1 \quad (6)$$

Through calculate the integral when the electromagnets are attached together, integral along the axis of magnets, we can get the coefficient k is equal to 1.132×10^{-5} and the relative permeability μ_r is equal to 2338.99.

And then we count the weight of the block system and its contents, which consists of block entity, electromagnets, PCB and transceiver, iron sticks, circuits and battery. And the side length *a* of block is about 10cm.

Item	Weight
Block entity	78g
Electromagnets	6*25g
PCB and transceiver	5g
Iron sticks	12*0.7g
Circuits	3g
Battery	100g
Total	344g

According to formula (5) and (6), we can assume that the magnetic force between two magnets is approximately inversely proportional to the square of the distance. That's what we should know in the our project design. When the distance between two magnets is in the level of 5cm, the force between them is about 1/10 with respect to the origin. We can only push the magnet when they are attached together, because the attract force when they are separated alone are very small. So when we design our project, we may have limited operations and transforms. We can make sure that we can do 90 degree transforms, but we need to do experiment and select more powerful electromagnet during our project design process.

3 Costs

The expected hourly salary for each of our members is $15, we expect the member to do about 10 hours work each week(2hours for 4 days and 1 hour for 2 days), and we expected that we need use 10 weeks to finish the project, so the cost should be:

4（people）× $15（salary per hour）× 10（hours per week）× 10（weeks）= $6000

And for each block of model robot, the cost of materials are:

Materials	**Costs**
Electromagnet × 6	$0.943(¥6.6) × 6
5V Li--ion battery	$5.143(¥36)
Send/Receive-Transceiver Module	$0.778(¥5.45) × 2
Aduino nano V3.0 ATMEGA328P	$2.229(¥15.6)
Iron hinges	$1(¥7)
3D-print materials	$1.371(¥9.6)
3D-print cost	$1.429(¥10)
Total cost	$18.506(¥128.7)

We plan to make 10 blocks, so the total cost is $185.06(¥1287)
So the total cost include the labor is $6185.06(¥43287)

4 Schedule

Week	Jingcheng Liu	Haobo Li	Tinghua Chen	Shiqi Yu
3/13/23	Mathematical analysis and equipment selection.	Electronic component procurement	Project feasibility investigation	Ethics and safety consideration
3/20/23	Experiments on transceiver module. Connect the transceiver module on the computer and master the skills to use the module.	Experiments on the electromagnets. Finish the selection of the type of power supply and electromagnets.	Design the circuit and voltage controller and test its availability. Master the skills to use the transceiver module.	Wireless module transceiver test. Decode the transceiver signal and control the analog output signal.
3/27/23	Test other feasible driving methods, PCB design version 1	The design of the internal drive system of the block.	Master the skills to use the Arduino-nano and wireless module.	Continue work on Wireless module transceiver test.
4/3/23	Finish and order PCB version 1 and 3D printed entity	Design the structure of the mechanical entity. Combine interior with exterior design.	Circuit design for Arduino-nano and wireless module, work on block control program	Combine wireless module and Arduino-nano, work on block control module
4/10/23	Assemble all the components and test the basic functionality	Installation of mechanical entity and basic functionality test.	Continue work on block control program	Design and build the user interface
4/17/23	Functional validation experiments and PCB design version 2	Improve design of mechanical entity and functionality validation	Test the availability of the block control programs.	Combine control program with User Interface

4/24/23	Finish and order PCB version. Functionality validation experiments	Troubleshoot problems encountered in actual operations	Control programs improve and test. Fix problems in test.	Test the availability of User Interface test and improve.
5./1/23	Prepare for demo and begin final report	Prepare for demo and begin final report	Prepare for demo and begin final report	Prepare for demo and begin final report

5 Ethics and Safety

5.1 Ethics

Protection of Privacy of others: With its minimized size, MSRR has a promising future to finish various tasks at environments where humans cannot easily reach. We should therefore notice the possibility that such a microsized MSRR can be used to complete tasks such as collecting and even steal other’s private information without being noticed by a human. According to IEEE Code of Ethics I.1, invasion of other people’s privacy is strictly prohibited [1]. Therefore, we must be sure to add related code of conduct that prevents the MSRR from privacy invasion if the MSRR is produced and released in the market. One possible technical solution is to add additional signals that are easy to be noticed, such as alarms and blinks, when the MSRR is collecting information from the environment.

5.2 Safety

Safety issues when assembling MSRR: First, soldering operations will be very frequent as we will build up our PCBs, test them and refine them for many times. Therefore, frequent use of flux, soldering Iron and other soldering devices might hurt people high temperature. The operators must stay focused and follow the soldering guidelines. Second, since our MSRR robot will use a 3D printed shell, we must be careful not to hurt ourselves by its rough edges. To prevent possible injury, one solution is that we can polish the sharp edges with sandpaper and add rounded corners to our shell design.

5.3 Possible health issues

Though the intensity of electromagnetic field generated in our MSRR should not be too large, we should notice that exposure to man-made EMF can have negative effects on health. According to a research conducted by the U.S.Navy in 1984, exposure to unnatural electromagnetic frequencies can cause health problems such as changing hormone levels and cause sterility in male animals [2]. Further experiments need to be conducted if we would like to use microsized MSRR (such as medical robot) to be used in the medical operations.