Zhejiang University/University of Illinois Urbana-Champaign Institute

Senior Design Report

A TRANSFORMER

By

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Abstract

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 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.

This paper presents design principles for our modular robots, as blocks that can help stimulate children's interest in robots in the educational field, can be used as a decoration that can transform shapes, and can be used as a base model for modular robots that can explore tight spaces in the future.

The reconfiguration is done using dynamic connection and disconnection of modules and rotations of the degrees of freedom. For the hardware framework, we present the mechanical design of our modular robots and an active connection mechanism based on physical plugging method. For the software framework, we designed a user interface to control one or more of our modular robots. At the same time, we use the wireless communication module to realize the robot control. The control method is based on forward kinematics and reverse kinematics. Further we discuss how our modular model can be improved and how it can be extended as a base model.

Key words: MSRR; Modular Self-Reconfigurable Robotics; transformer; mechanical design

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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. In addition, we also thought about how we could inspire children to learn about robots through robots that act like building blocks. Or how to make your home have an accessory that can change shape at will. The robotics that we will 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, and can effectively solve our problem.

1.2 Background

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.

1.3 Motivation

We would like to create modular robots where the modules can be assembled freely, and our modular robots can be transformed into a desired form through a series of operations, or can be transformed between several different forms. We plan to stimulate children's interest in learning robots by building modular robots like building blocks, which can also be used as art decoration through various ways of assembly and deformation.

The reconfiguration is done using dynamic connection and disconnection of modules and rotations of the degrees of freedom. For the hardware framework, we present the mechanical design of our modular robots and an active connection mechanism based on physical plugging method. For the software framework, we designed a user interface to control one or more of our modular robots. At the same time, we use the wireless communication module to realize the robot control. The control method is based on forward kinematics and reverse kinematics. Further we discuss how our modular model can be improved and how it can be extended as a base model.

1.3.1 Visual aid

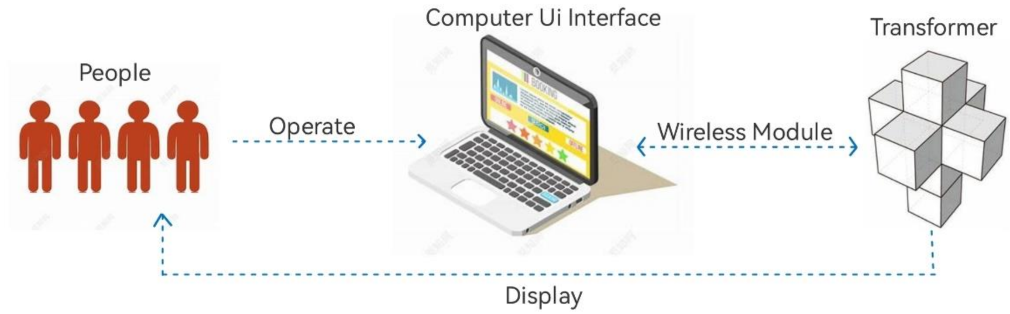

Figure 1 Visual Aid

1.3.2 High-level requirements

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 $3375cm^3(15cm * 15cm * 15cm)$ in size and lighter than 1kg.

Flexibility: Combinations of blocks can be transformed into many different configurations.

Separability: At least three mechanical entities can be controlled by the control system, and these mechanical entities are not affected by each other.

User-friendliness: The computer control interface is clear and concise so that users can clearly operate the transformer.

2 Literature review

To gain insight into the overall design of MSRR block units and their interconnections, a thorough literature review of existing MSRR projects was conducted.

Fig. 2.1 showcases the internal design of Roombots by the Swiss NCCR in Robotics. Each Roombot has dual rotation axes while 3 main motors are distributed across two Roombots. Within each module, a comprehensive motor and gearbox structure connects the upper and lower half-sphere modules of the Roombot. The detailed design of the motor and gearbox arrangement is in the right portion of Fig. 2.1. This design incorporates two stages of gear structures and a hollow axis for accommodating wire to passage through the slip ring. The implementation of gears and pinions enables motor speed and torque conversion while allowing flexibility in motor placement within the half-sphere module because the rotation axis of the motor no longer need to be put at the center of the rotation axis of the Roombot.

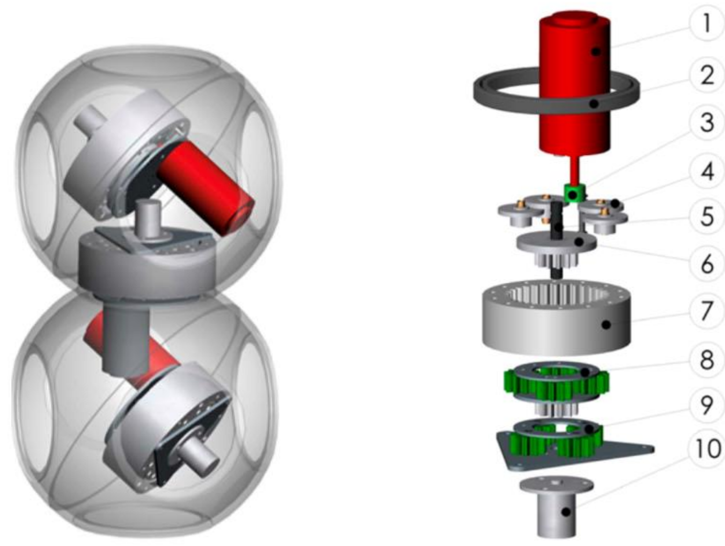

Figure 2 The interior structure of two Roombots. *Note.* By Sproewitz, A., Billard, A., Dillenbourg, P., & Ijspeert, A. J. (2009)

To enhance the flexibility of MSRRs during transformations, the ability for the robot blocks to actively connect and disconnect to each other in a stable way is crucial. Fig. 2.2 illustrates the ACM (Active Connection Mechanism) employed in Roombots, which utilizing two mechanical latches that enable a robot module to firmly grasp onto its neighboring module. This design approach employs a hermaphroditic concept, allowing the connection plate to engage with any other connection plate, regardless of whether it possesses a motor, a gearbox or not. The right section of Fig. 2.2 provides a detailed depiction of the active connection mechanism's components on each face of a Roombot module, excluding the motor and gear box structure depicted in Fig. 2.1. Two latches and the corresponding holes are symmetrically positioned in a four-way configuration and actuated by a slider connected to a mini motor gearbox.

By substituting an active connection plate with a passive connector plate (lacking the latch and motor structure, featuring only holes), the weight of the Roombots can be reduced. Consequently, for each pair of Roombots composed of two robot modules, six passive connector plates and four ACM plates are used instead of using the maximized 10 ACM plates on each face. This also enables easier assembly while not affecting their functionality of connection.

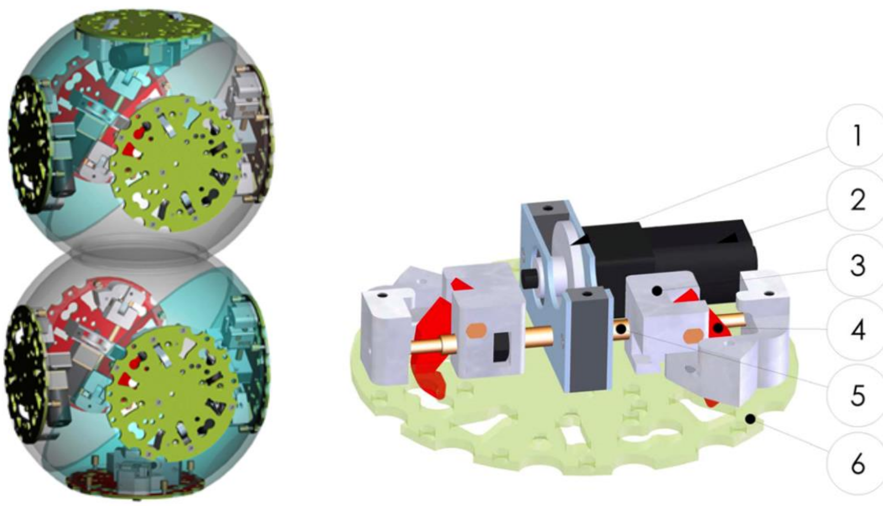

Figure 2.2 The ACM on 5 faces of each Roombot. *Note*. By Sproewitz, A., Billard, A., Dillenbourg, P., & Ijspeert, A. J. (2009)

3 Methodology

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 servos to control the mechanism of block robotics. Different block robots are controlled by a central host computer through wireless signals. Arduino nano in block robots receive signals from wireless module and control the rotation of servos.

It consists of two hemispherical shells and an intermediate connector. The wireless module transmits command signal from host computer to block robots. After the signal is received at the remote side, Arduino in block robots will process this signal and convert it to control signals on its ports. Electrical circuits will get input signal from an Arduino port, then use it to control the rotation of servos. Rotation of different servos on different axes is used to complete the rotation and deformation of the robot.

3.1 Design criteria

When designing our project, we mainly follow the following criteria:

Functionality: We hope that our project can achieve deformation through the combination of different modules and operations such as rotation, and can adapt to various scenarios.

Safety: In case of faults caused by overvoltage or short circuit, the project will automatically power off in a timely manner and will not cause fires due to overheating.

Flexibility: Different modules can be connected freely, and one or more modules can be controlled to rotate simultaneously.

Stability: The project can run stably for a long time, and is not easily tilted or fallen.

Easy to use: The project should be easy to operate and understand, and it is best to create a simple and clear UI interface for easy use by various groups.

Low cost: The project should have relatively low maintenance and repair costs.

Humanized design: The project should be as neat and beautiful as possible.

3.2 Alternatives considered

We revised our design during the progress. For the power-driven system, we found the electromagnet force is too weak and the distance is nearly zero. So we turned to some mature device like servos as the power driven device. And for the connection part, the magnet is too large and not powerful enough, so we attempted alternative mechanical connections, like claws with strings, gears or latches. But we found that the mechanics in such a small space is hard, delicate, and complex. The 3D print claw may be not tight and cannot support the weight of blocks. So we gave up the unreliable designs and use screws for connection. For the shape of block entity, we changed from cubes to spheroid. Two half shell are connected on the middle surface. The cross section is like a hexagon. We made it a cube like sphere, in order to avoid collisions during rotation.

3.3 Design decisions

If we use electromagnet as driving device, we can make the volume of our project smaller, but the force of electromagnet is greatly restricted by distance, so the operations of our project will also be greatly restricted by distance, which means it can't support some of the operations.

If we use servo as driving device, it can provide enough force to support the entire system's operation, but our project will be much larger and heavier, which may limit the application scenarios of our project.

If we use a cuboid shell, our project will have good stability but can only perform horizontal rotation or flipping. However, if we use a spherical shell, our project can perform tilted rotation, but the stability of the device will be lower and will require more stable connection methods.

3.4 Justification for the final design

We ultimately chose to use a servo as the driving device, although this choice will increase the volume and weight of our project and affect its use in some narrow scenarios, it can well accomplish the originally designed actions and has a wider range of applications compared to using an electromagnet as the driving device.

We ultimately chose to use a spherical shell, although the stability of our project will be reduced, but our project can use tilted rotation instead of less stable flipping, which can increase the stability of the device to a certain extent, and the circular plane can also maximize the stability of the device.

3.4.1 Block diagram

Our system is mainly divided into two parts, remote system and block system. The remote system mainly consists of three parts, power supply, user interface and sender in transceiver module. The block system is mainly composed of three parts: mechanical design, control module and receiver in the transceiver.

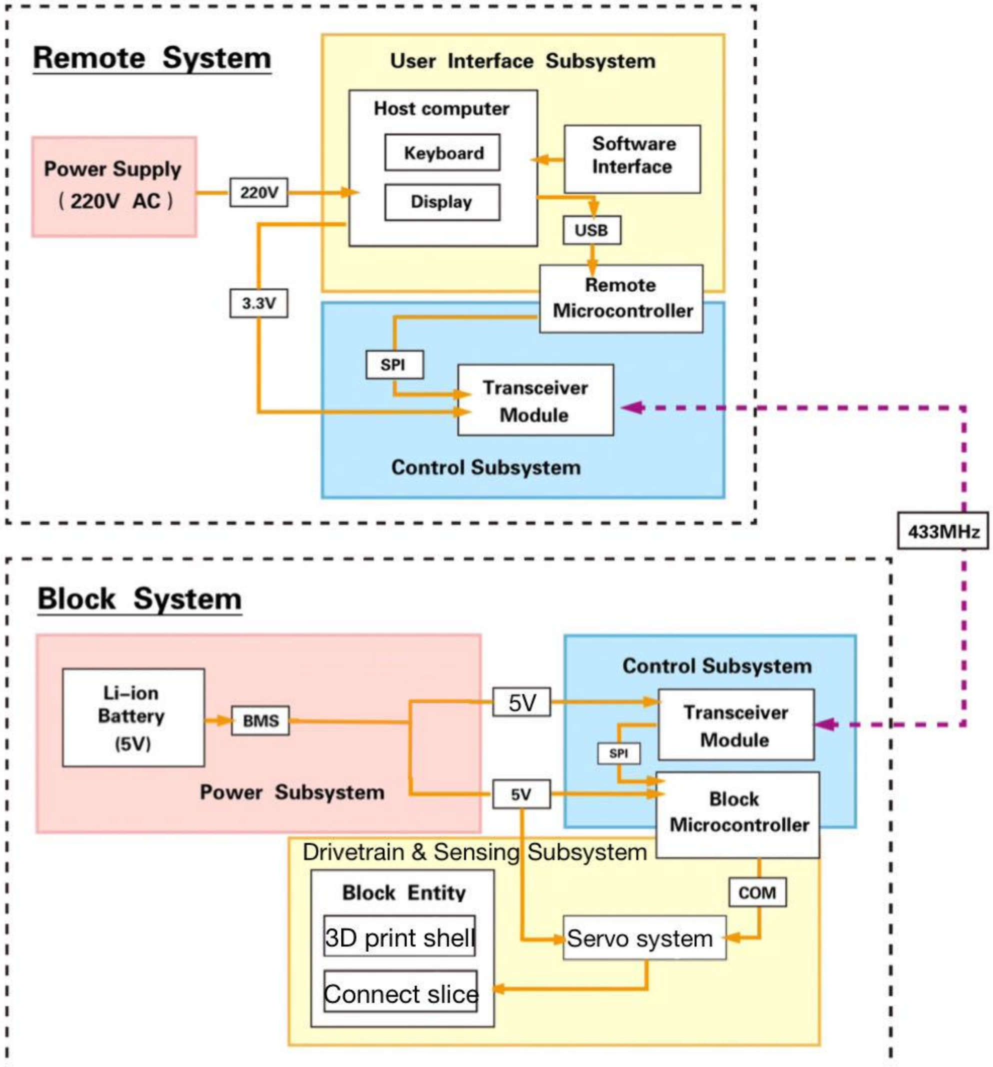

Figure 3 Block Diagram

4 Results

The robot is designed to like a worm which can crawl on the floor or attach to a base like robot arm. It is able to transform to lines, squares and ‘L’. The robot can be applied to collect something with a claw or detect something with a camera, since it has a flexible shape and kinematic. If the number of robots is larger, maybe they can take care of themselves, move, or replace parts or configure themselves.

4.1 User Interface

The web page is based on the HTML and FLASK framework in python and html. We use the flask to construct the back-end function and use html to create the front end of the UI. For the front end, we use ‘form’ tags in HTML for request-response between client and server via the 'GET' and 'POST' methods. In other words, we use this method to transfer the data entered by the client and submitted to the web page to the back end, so that the back end can control the system based on this information. As for the back end, we build a back-end program connected to the front end through the FLASK framework. The back-end program processes the user's related instructions and sends the instructions to the sender.

Figure 4 shows our UI interface. We respectively used blue, the representative color of Zhejiang University, and dark blue and orange, the representative color of University of Illinois Urbana-Champaign, as the interface colors. On the left is the instruction window to implement the forward kinematics. Users are free to choose which block they want to change and the corresponding servo’s rotate degree. Then users send 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. The user selects and enters relevant information, which is temporarily stored in the network buffer after the submit button is pressed. The back-end program uses the 'GET' or 'POST' method to get the information in the buffer and process the information. The middle section records the user's historical operation data. After processing the user's input, the back end encodes and sends the processed data on the one hand and feeds it back to the front-end on the other hand. The middle section records all the operations carried out so that the user can have a clear understanding of the current mechanical configuration. The right part is a few buttons we set, users can use these buttons to connect multiple modular robots to change to a specific form.

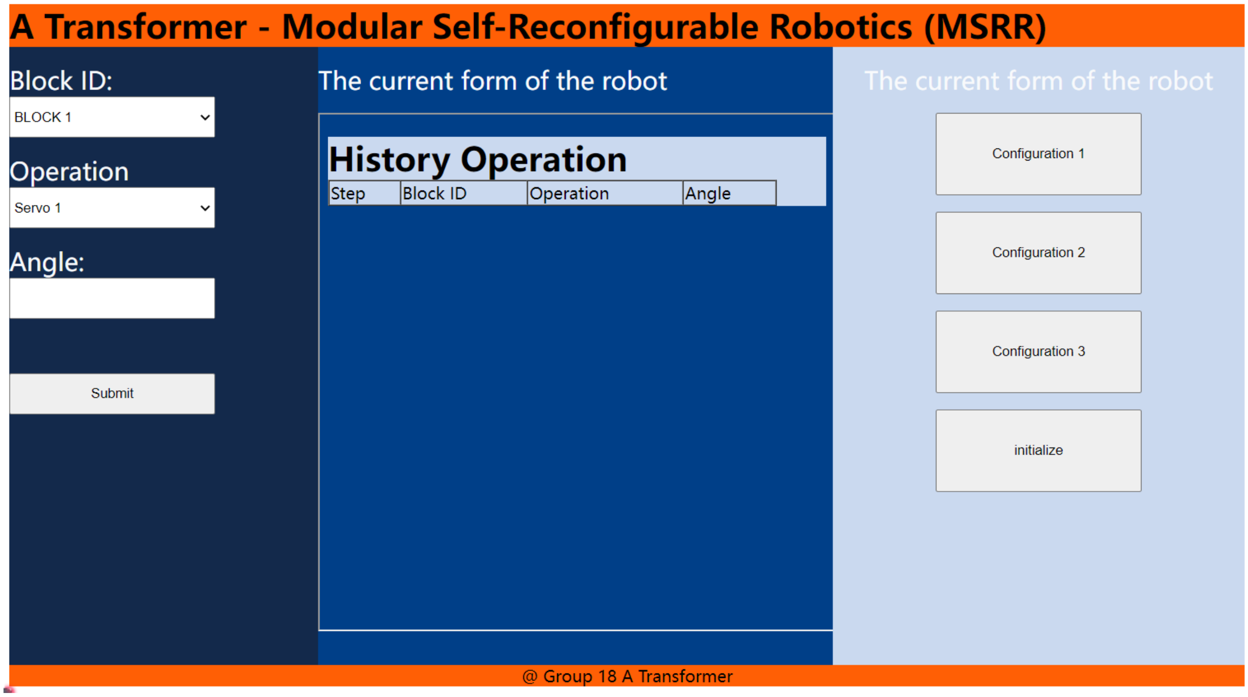

Figure 4 User Interface - Web Application. This is what our UI looks like.

4.2 Mechanical design

The initial phase of the design process involves conceptualizing the basic shape and dimensions of our MSRR robot block. Ideally, the block should resemble a sphere intersected by a cube, resulting in six circular faces that ensure stability when placed on a flat surface. The radius of each face should be equal to or less than sqrt (2)/4 of the cube that intersects it so that the division of a block to its upper and lower part while maintain the same size of each of its face is possible. Fig. 5.1 and Fig. 5.2 depict the computation and elucidation of the dimensional relationship.

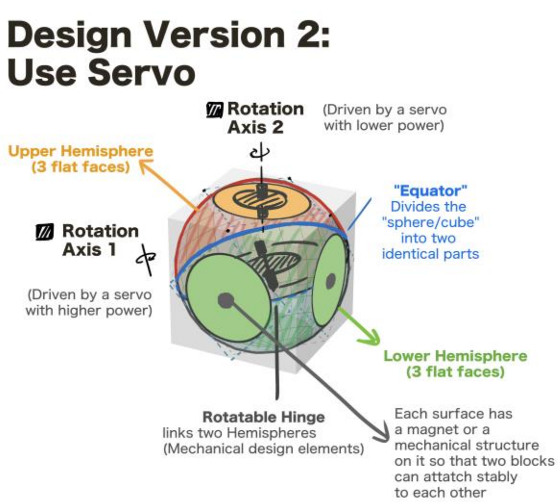

Fig. 5.1 A sketch for our 2nd version of MSRR block

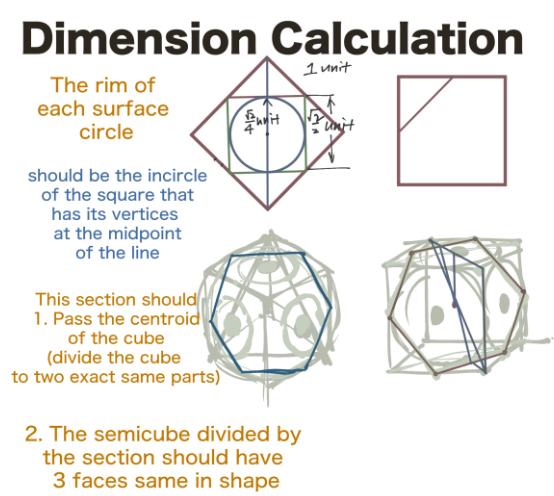

Fig. 5.2 Dimension Calculation

In the latest version of the upper half-sphere and connection plate pair, I chose to change the circular plate into a strip shape. Through testing, we discovered that after multiple rotations, the connection between the plate and the half-sphere tended to loosen. To address this issue, I redesigned the connection between the sphere and strip, ensuring that the plate remains securely embedded within the half-sphere and firmly connected using screw-nut pairs. The stair-like structure of the connection strip is for the sake of saving more space for another servo to be put in the upper half-sphere.

The figure 5.1 is the basic structure of a block. It consists of two hemispherical shells and an intermediate connector. The intermediate connector connects one hemispheric shell to a servo in the other hemispheric shell so that the two hemispheric shells can rotate relative to each other. The assembled block is shown in the figure 5.1. Once the block is assembled, it can be connected by an intermediate connector, shown in figure 5.2. This intermediate connector connects one block housing to the servo in the other block, which allows the two blocks to rotate relative to each other.

Figure 6.1 Method of connection between block robots

Figure 6.2 The connection of two hemispheres

4.3 Transceiver (wireless) module

We use 433MHz transceiver modules, “T1” and “R1”, one transmitter connected to the computer and multiple receivers on the blocks. We use a simple strategy, one versus all strategy. Because we have no demand of privacy or secrecy, each block can receive the same command sent from the transmitter. The receiver module on the block will receive the signal and the MCU will decode the command into device id, operation and degree. The receiver module has three pins, VCC, DATA and GND.

For the convenience and precision, we use the protocols in RCSwitch library. This library is used to control 433MHz transceiver modules. We can customize pulse length, Sync bit, wave form for “0” bit and “1” bit. These settings are for enhancing the precision of transmitted signals.

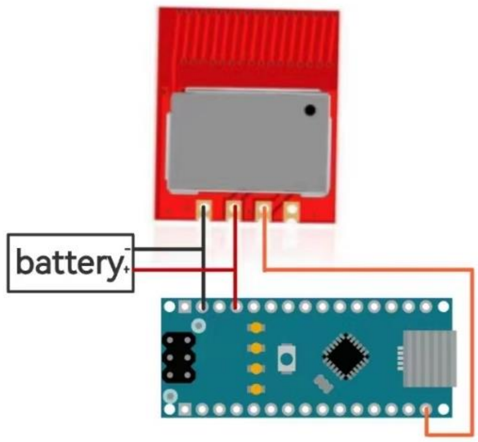

Figure 7.1 Circuit connection diagram of the sending module and Arduino

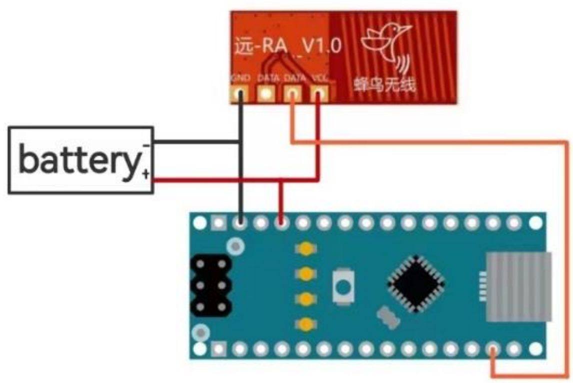

Figure 7.2 Circuit connection diagram of the receiving module and Arduino

4.4 Control system

For the customized shape in our transformer, we wrote an algorithm to calculate the servo degrees according to the shape we ordered. It's about exponential coordinate, screw theory and backpropagation. Since our robotics are modular, we designed a remote-control system, one computer controlled multiple blocks. Command bits are transmitted from computer sender to the receiver on the block. So, we got MCU and control circuit on each of the blocks.

We use PWM servo for our project. The PWM signal is controlled by the MCU. The servo uses a 3ms PWM. For the 360 degrees mode, the PWM means the rotate speed and direction. For the 180-degree mode, the PWM means degrees of servo. We used 360-degree mode, because we hope the robot has for transforms.

Table 1 System Requirements and Verifications

PWM Wave Length	motor speed
0.5ms	**Reverse**
1.5ms	**Static**
2.5ms	**Forward**

4.4.1 Forward Kinematic

Mapping from theta of servos to the position of blocks, we use exponential coordinate and screw theory. We have eight servos, so we have eight screw axes.

For a screw axis, we have a rotate axis w and the reference velocity v. Then we can screw matrix and compute the exponential coordinate. M is the initial transform matrix. So we can derive the transform matrix with θ by the product of the series of exponential matrix effectors. Give us the Product of Exponentials (PoE 2-4).

$$v = -w \times q \tag{1-1}$$

$$[S] = \begin{bmatrix} [w] & v \\ 0 & 0 \end{bmatrix} \tag{1-2}$$

$$e^{[S]\theta} = \begin{bmatrix} R & p \\ 0 & 1 \end{bmatrix} \tag{1-3}$$

$$T(\theta) = e^{[S_1]\theta_1} e^{[S_2]\theta_2} \dots e^{[S_{n-1}]\theta_{n-1}} e^{[S_n]\theta_n} M \tag{1-4}$$

4.4.2 Backward Kinematic

We have forward kinematic mapping from theta to position of blocks, so we have backward kinematic mapping from position to theta, for the control of servos. This process is done on Pytorch and by backpropagation. The input is the theta of eight rotate axis and the output is the position of four blocks. To solve the inverse kinematic problem, we use the optimization strategy. We compute the error of current state and the destination state, take the derivative and backpropagate the error to the parameter of thetas. Then reduce the error and begin the next loop. We need about 1000 epochs to get accurate thetas, and the error can be always reduced under 1e-03. For the high robustness, our explanation is that the moving sight of each servo are interconnected with each other, so we can always find the gradient of global minimum. And we ordered the position of each blocks, so the theta can be also solved along the axis.

```
y:  [ 0.  0. 10.  0.  5. 15.  0. 10. 20.  0. 10. 30.]
Forward kinematics calculating:

epoch: 0 loss: 37.500000
epoch: 500 loss: 0.029596
epoch: 1000 loss: 0.004536

position
[ 2.10e-02 -1.70e-02  1.00e+01  1.07e-01  4.97e+00  1.50e+01 -7.70e-02
  1.02e+01  2.00e+01  2.50e-02  9.95e+00  3.00e+01]
theta
[ 0.13  0.01 -0.14 -2.09 -0.01  2.02 -0.05  0.22]

[0, 0, 0, -120, 0, 120, 0, 0]
```

Figure 8 Training process of backward kinematic and result

4.5 Other tests and verifications

4.5.1 Electromagnet

To test the electromagnet, we need to do a very fine measurement, but it's difficult for us to find good measuring tools. So, we use a simpler way to test it. We add some weights on one of the electromagnets, then we slowly decrease the distance between two electromagnets until they attract each other, and by this way I get some data shown below:

Table 2 The Relationship of Distance & Force

Distance	0	1mm	5mm	>5mm
Force	3kg	0.5kg	0.02kg	0

4.5.2 motor

When we test motor, we found that for MG995, there is an obviously disparity between the force needed for the motor to start and for the motor to keep running, so when we cut off the circuit, the motor won't immediately stop because of rotational inertia, so when our block rotating inclined, the rotation angle may become larger, this will cause the block splicing to be unstable, so I do analysis to calculate the rotational inertia of the motor MG950:

We know that to calculate the rotational inertia, we need to know the mass of the motor and the diameter of the gear, the mass of MG950 is 55g, and the gear diameter of MG950 can't be measured, but we know the side length of the motor, so we can know the gear diameter is no larger than 40 mm, so the equation to calculate rotational moment of inertia is:

$$\mathrm{J} = \frac{1}{2}\mathrm{mD}^2 = \frac{1}{2} \times 55\mathrm{g} \times (20\mathrm{mm})^2 = 1.1 \times 10^{-5}\,\mathrm{kg} \cdot \mathrm{m}^2 \quad (2)$$

About how rotational moment of inertia action on the angle we haven't finished it yet, but I did some experiments to help us verify my outcome, and it can also give us some help.

In the experiment, we let the motor to rotate certain degree and measure the actual degree, by compare the difference, we estimate an error angle, and that's the table of the data:

Table 3 Experiment data

Set angle	Actual angle
90	102
90	101.5
90	101
180	192
180	190
180	190

4.6 Cost

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 (3)

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

Table 4 Cost of Materials

Materials	**Costs**
MG996R motor × 2	$4.4(¥31)
5V 900mA Li--ion battery × 2	$5.14(¥36)
Send/Receive-Transceiver Module × 2	$1.546(¥10.9)
Aduino nano V3.0 ATMEGA328P × 2	$4.46(¥31.2)
Pins × 2	$0.012(¥0.084)

Solder cost	\$0(¥0)
3D-print cost	\$0(¥0)
Total cost	\$15.558(¥109.184)

4.7 Schedule

Table 5 Schedule of Individual work

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 Discussion

5.1 Strengths

First of all, our design has high flexibility and adaptability. It can change its form and structure through self-reconfiguration to quickly adapt to various tasks and environments. This adaptability enables the robot to complete tasks more efficiently.

Secondly, our design considers the high efficiency and also saves the cost. The modules of the modular robot can run in parallel, to improve the operation efficiency of the robot. In addition, the modular design can make the robot easier to maintain and repair, only need to replace the damaged module can continue to work, reducing the cost of repair and maintenance, and the same module can be purchased to reduce the production cost.

Finally, our project also has high scalability. Modules of modular robots can be added or deleted at any time, which makes the functional scalability of robots very high.

5.2 Weaknesses

The main problem we met in our design is the power-driven system and connection mechanics. At the beginning, we wanted to use electromagnets, for power driven and connection. We did the mathematical analysis, and find that the magnetic force is so small when the magnets are not attached. Then we use servos and mechanic claws. After building the shell and mechanical entity, we find the connection part is small and delicate. We tried multiple methods like magnets, strings and gears, but they are complex and unreliable. For the aim of reliability concise shape, we remove the connection part, but it is still connectable and disassemble. Besides, the servos currently used can only determine the rotation Angle by controlling the rotation time, but this is unstable. We can solve this problem by using digital steering gear, but the price of digital steering gear is more expensive, so we did not apply it in the project.

5.3 Limitations

The current link mode of our modular robot cannot support free disassembly, which requires troublesome steps to rearrange the link order of modules, so the shapes that can be formed are relatively limited. In addition, as our driven system uses servos, it is difficult to reduce the volume of the module, which will have a certain impact on its mobility and stability.

6. Conclusion

6.1 Accomplishments

The computer control interface is clear and concise so that users can clearly operate the transformer. 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 $3375cm^3$($15cm$ * $15cm$ * $15cm$), and lighter than 1kg. The blocks are not affected by each other, which means we can control the blocks independently. The absence of one block does not affect the execution of the others. Combinations of blocks can be transformed into many different configurations. If a component in one block breaks, we can replace it with a component in another block. All in all, our modular robots have the characteristics of user-friendliness, independence, flexibility, and adaptability.

6.2 Uncertainties

There are still some problems in our project. The first one is the block connection problem. We tried a lot of different ways to connect blocks of modular robots. At first, we wanted to use the suction of the electromagnet to hold it in place, but we found that the electromagnet only produces enough suction when it is very close. The gap between our blocks exceeds this distance and the electromagnet is not able to generate enough suction to connect the blocks. Then, we tried magnets. But we found that when two blocks are connected and one block is suspended, the suspended block will slide off.In addition to this we also tried to use the hook claw, trying to retract the hook claw to hold the surface where the two blocks connect. However, we found that the connection in this way is not stable enough, and the hook claw may fall off and cause the connection to break. In addition, we find that the motor restricts the minimum size of the entire equipment, and prolonged use of the motor increases the risk of gear breakage. If the gear breaks, the motor torque will be insufficient to support some operations of the entire project.

6.3 Ethical considerations

6.3.1 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 micro-sized 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 [4]. 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.

6.3.2 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.

6.3.3 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 [4]. Further experiments need to be conducted if we would like to use micro-sized MSRR (such as medical robot) to be used in the medical operations.

6.4 Future work

For Future improving of our project, first we can use digital motor to solve the problem of rotate degree, the motor we use now is MG996R, and it’s controlled rotating speed is consistent, so we can only change the rotate degree by change the rotating time, but it’s not accurate, if we can use digital motor, we can make the rotate degree more accurate, and if we can use motor with higher motor torque, we can reduce the risk of gear damage and greatly prolong the service life of the motor. Also, if we can find a driving device that’s smaller and cheaper than motor, we can improve our design and our project will have a wider range of applications.

Also, our project is actually a basic model, in a sense, we can attach anything on our project, as long as we have the right connector. For example, we can install cameras and microphones on it, and through training on image and sound signals, it can respond to specific signals to fulfill personalized custom requirements. For low-gravity environments such as space and the lunar surface, magnetic force can be transmitted through magnetic fields in a vacuum environment without the need for a medium, so we can use electromagnetic coils instead of motors as driving devices, which can further reduce the volume and have higher combination degrees of freedom. With training on image signals, it can perform emergency repairs outside the cabin to effectively ensure the safety of astronauts' lives.

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Appendix A Requirement and Verification Table

Table 6 System Requirements and Verifications

Requirement	Verification	Verification status (Y or N)
The computer battery should 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.	Y
The Arduino software should be able to transfer the written code into the Arduino device	Write a test Arduino code(Example: let the lights flicker). Transfer the code into Arduino module. Power on, observe whether the lights flicker. If the lights flicker, then it meets our requirements.	Y
The send-transceiver module should 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	Use it to send out a sinusoidal signal 433MHz. Receive the signal and pass it into filter at 400MHz-450MHz filter interval. Obverse the frequency domain of the signal after passing through the filter. Also, obverse the frequency domain of the noise after passing through the filter. 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.	Y
The Serial Port Monitor must be able to 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.	Y
Li-ion battery must be able to 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	Y

	keep steadily at about 5V, then it meets our requirements.	
Battery Management System (BMS) must be able to 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.	Y
The Receive-Transceiver Module must be able to 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.	Y
The Microcontroller of the block must be able to 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. If the positive or negative of the resistor’ s voltage changes, then it meets our requirements.	Y

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