ECE 445 Design Document

Customizable Automatic Pottery Wheel-Throwing Machine

Team #22

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1 Introduction

1.1 Problem & Solution

As a traditional approach to manufacture the pottery product, the wheel-throwing method requires exquisite craftsmanship to achieve acceptable consistency in symmetry, shape, and wall thickness. To address these challenges, we aim to design a manipulator to assist the production of pottery, capable of implementing customized shapes with high accuracy and efficiency.

A complete pottery forming process consists of five steps, i.e., centering, opening, pulling up, shaping, and cutting off. We mainly focus on the clay shaping step as the most pivotal stage, where the final form of a clay piece is determined and basically prepared to be fired. This is also the most difficult step in manufacturing due to the requirement of high-precision center-of-gravity control.

Our goal is to develop an automatic manipulator system to implement the pulling-up and shaping steps with the customized target outline inputted by the user.

In our design scheme, the manipulator system consists of a SCARA-based manipulator, a programmable motor driver integrated on the PCB, a standalone pottery wheel, and a software controller. For the manipulator part, we attach a distance sensor to scan the height of the clay preform; and we design a special gripper with vertical planar parallel arms to drive the pose of the end-effector, avoiding the collision with the pottery wall. The software part, however, could be either embedded or distributed; the former one requires us to program firmware using Arduino and flash to ESP32 directly, and the latter one is to flash micro-ROS firmware only and run ROS 2 nodes on the PC side. We would try both and select the effective one.

Following the hollow cylinder formation in the opening step, the manipulator first scan the height of the preform using the distance sensor, and then insert the inner half of the gripper in a collision-free manner. Next, the manipulator will gradually adjust the inner diameter of the hole to the inputted bottom radius by pressing the wall from one side and pulling up for multiple times as an initial pose standardization. After this preparation, it can start the shaping step from bottom to top according to the input custom shape.

1.2 Visual Aid

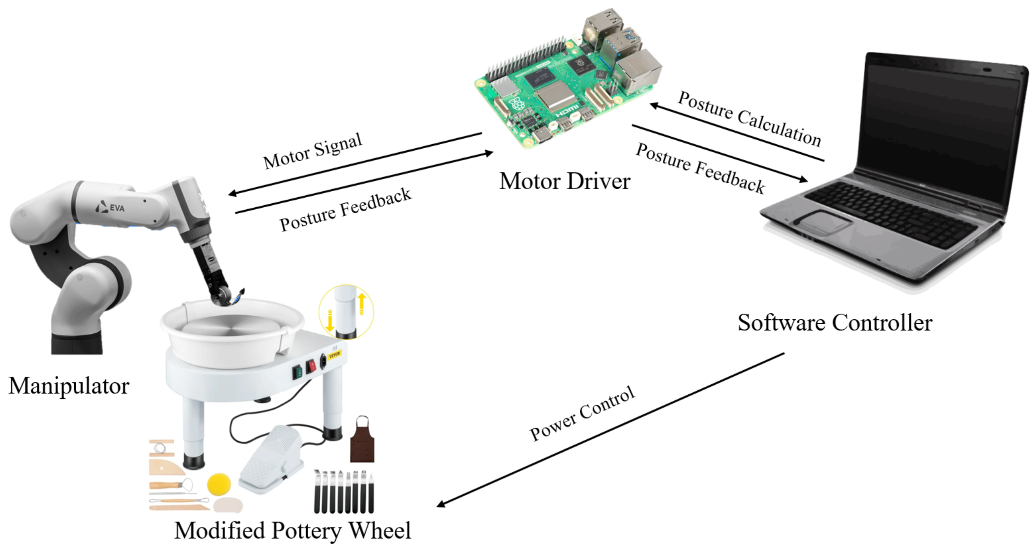

Figure 1: Visual Aid [3][4][5][6]

1.3 High-level Requirements

- Implement the automatic pulling-up and shaping steps of the pottery production. The process should be fully automated, given the opened cylinder produced by the first two steps.
- The shaping process must be controlled by a user-friendly program to enable users to adjust key parameters such as shape outline and wall thickness. The interface should be intuitive, requiring minimal training.
- Current design has 4 translational and rotational joints, where 3 of them are controlled by the open-loop stepper motors with 5% error at maximum. We need to introduce a method to suppress the accumulative error.

2 Design

2.1 Block Diagram

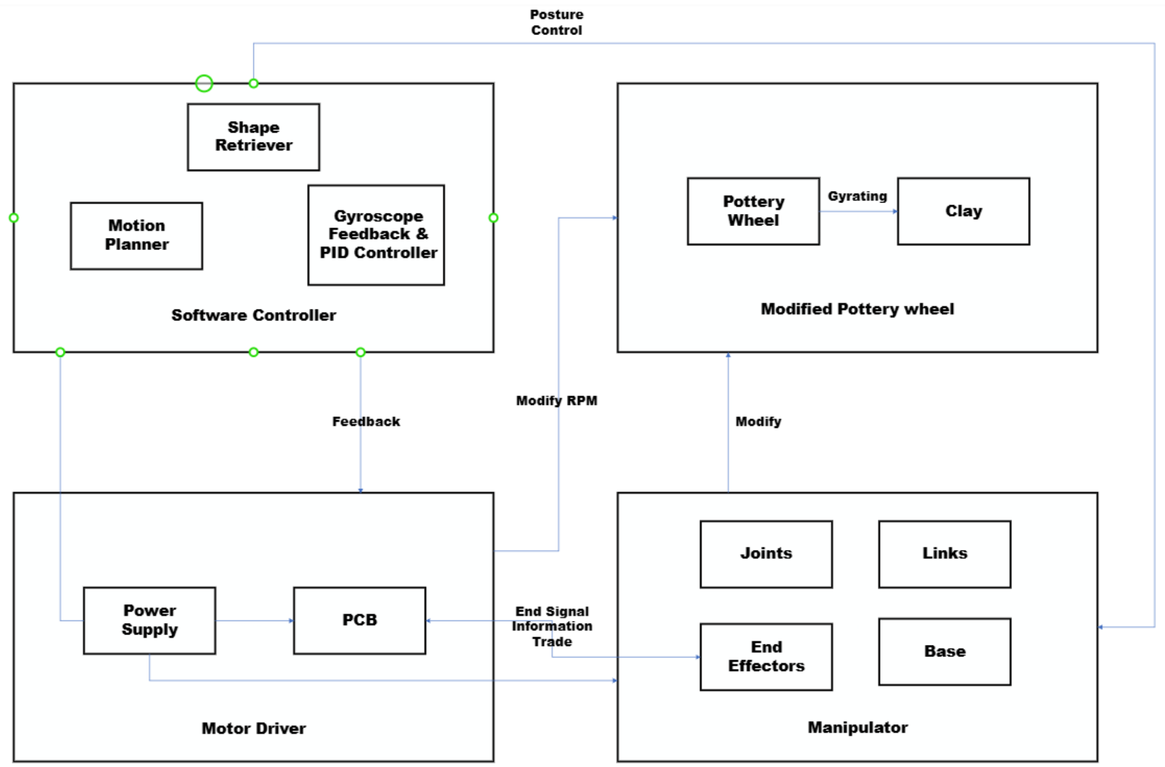

Figure 2: Block Diagram

2.2 Motor Driver

The Motor Driver includes two parts, the PCB and Power Supply.

2.2.1 Power Supply

Pottery Wheel is directly driven by 220V AC household power supply. For manipulator, stepper motors are controlled pulse signal generated by PCBs which requires power adaptor. As shown in the below figure, the adaptor, theoretically, can accept 100-240V AC and then convert it into 12V DC.

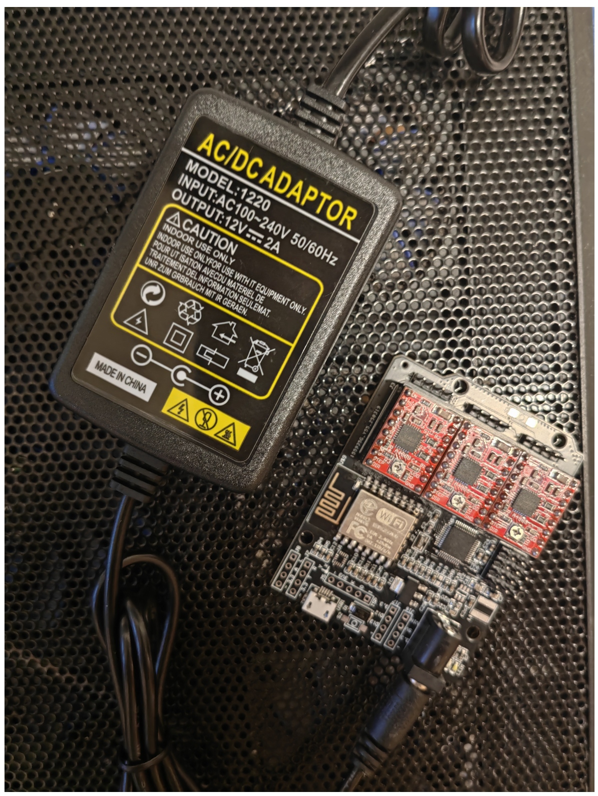

Figure 3: Power Supply

- Maximum current should exceed 2A to avoid the possible workload.
- The conversion efficiency must reach more than 90% to reduce energy waste and heat generation.
- The output voltage fluctuation should be less than ±5%, and the ripple noise should be less than 50mVpp to avoid interference with the circuit.

2.2.2 PCB

In this project, the PCB is not only responsible for controlling the motors, but also for information communication between hardware and software. PCBs will receive the signal from sensors and then generate pulse signal to drive stepper motors.

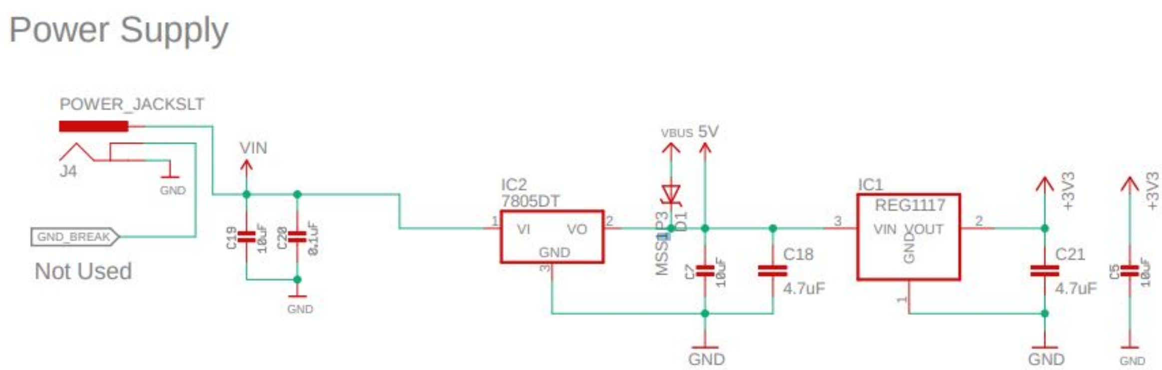

Figure 4: PCB Power Supply

Power Supply part transforms the 12V Vin into voltages of 5V and 3.3V to be used respectively by the microcontroller and all motors. The three-terminal regulator 7805DT outputs 5V, LDO regulator REG1117 outputs 3.3V. PRT-111543 is the power plug interface module, and we use a capacitance input/output voltage filtering.

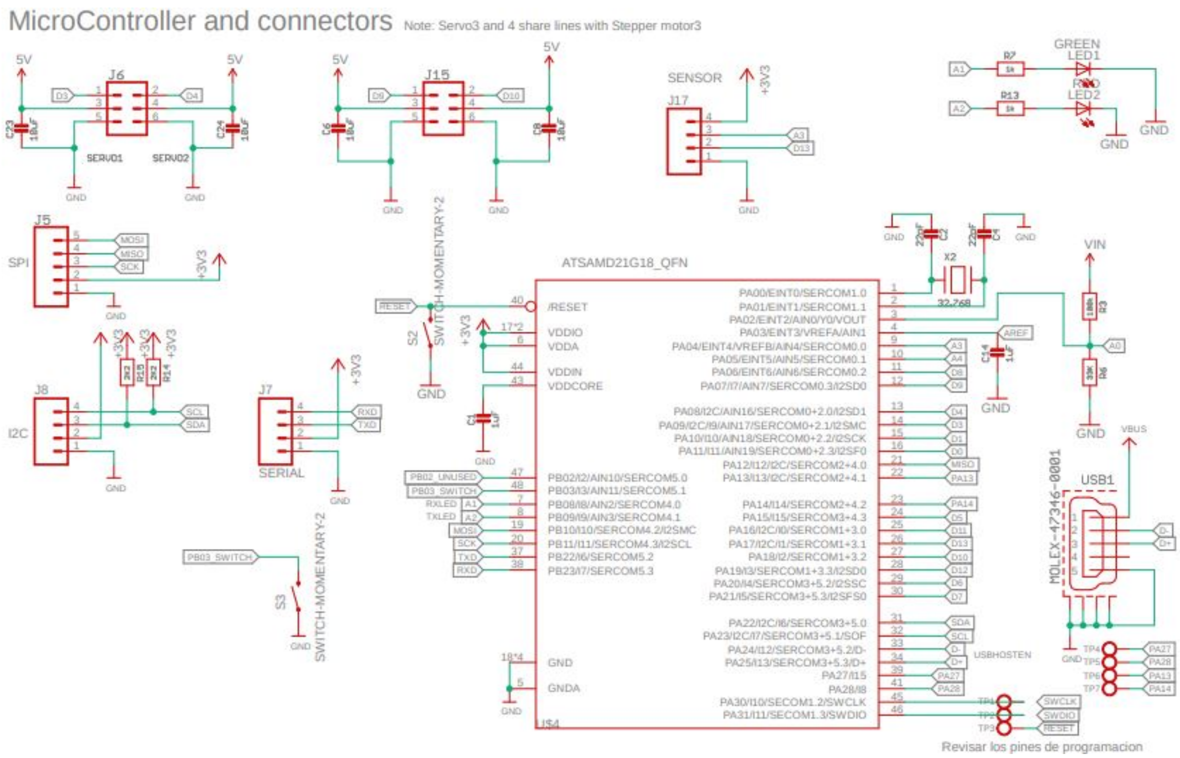

Figure 5: PCB MicroController and Connectors

Microcontroller and connectors use chip ATSAMD21, which is a 32-bit microcontroller with ARM Cortex-M0+ core. It support USB communication. Multiple PWMs are used to control three stepper motors and two servo motors. UART, I2C, SPI are used to communicate with ESP8266 and sensors.

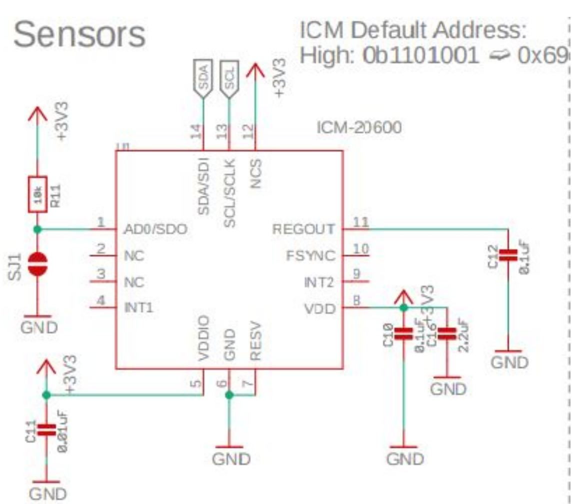

Figure 6: PCB Sensors

Sensors part uses ICM-20600 inertial measurement unit chip to give feedback control and adjust robot arm pose.

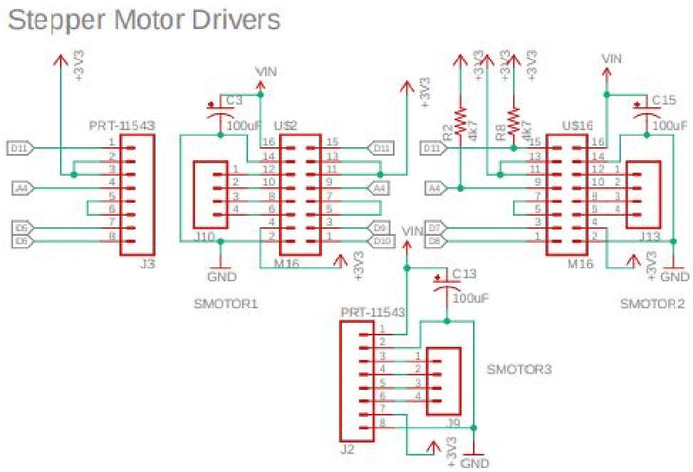

Figure 7: PCB Stepper Motor Drivers

Stepper Motor Drivers with three pin sets and three control board for stepper motors are mounted on these three SMOTOR1-3.

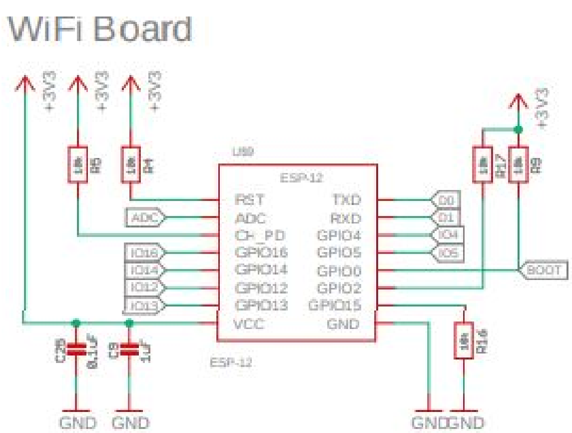

Figure 8: PCB WIFI Board

WIFI part are built in ESP8266MOD chip and we use the ESP-12 WIFI part inside to realize wifi communication to some extent if needed.

In this project, the PCB is not only responsible for controlling the motors, but also for information communication between hardware and software. PCBs will receive the signal from software codes in the board and then generate a pulse signal to drive stepper motors. PCBs receive data from the sensors on the manipulator and transmit it back to the board (software part).

2.2.3 Interaction with other subsystems

The Motor Driver receives control signal from the Software Controller. For the first stage, we will use Arduino to direct control the motor in order to test the performance of the manipulator. For the second stage, the feedback may be provided by both ROS or Arduino. (For more information, please refer "Software Control Section") Meanwhile, the Software Controller would receive the feedback from the motor driver. The Encoder would send the angle of motor back to the Software Controller

2.2.4 Subsystem Requirements

Table 1: Requirements and Verification of Motor Driver

Requirement	Verification
The adapter can output a stable voltag and whether the maximum current can reach 2A to drive the motor	Use laboratory instruments to measure whether the adapter can output stable voltage and current
12V voltage can be successfully transformed and motors can be driven to move the pose of robot arm	After power on the motors can move smoothly to drive the robot arm. The robot arm can reset and have enough precision to do repeatable works

2.3 Pottery Wheel

The pottery wheel is used to supply stable rotational force, which helps the manipulator better control the thickness and shape of the clay in the molding process. In the process of kneading, it can accurately adjust the speed and smooth the clay wall in the process of rotation, improving the fineness and consistency of the finished product.

Figure 9: Pottery Wheel

To verify if the pottery wheel is suitable for shaping clay, we tried to use this pottery wheel to hand-shape clay and it was successful. This shows that the rotation speed and weight of this pottery wheel are sufficient to complete the task

Figure 10: Testing of Pottery Wheel

2.3.1 Subsystem Requirements

Table 2: Requirements and Verification of Motor Driver

Requirement	Verification
Whether the rotation speed and load of the pottery wheel are sufficient to shape the clay	Simulate the process of shaping clay and test whether the pottery wheel is sufficient to complete the whole process
A lot of water is needed to soften the clay during the clay shaping process, so the pottery wheel needs to have high waterproof performance.	During the use of the pottery wheel, pour a certain amount of water on it and observe whether it can maintain normal operation for a long time.Verification

2.4 Manipulator

2.4.1 Base

The base of the manipulator refers to the stationary part where the rest of the robotic arm is mounted. It consists of a raised support to align the average working height introduced by the pottery wheel. The base is 3D-printed.

2.4.2 Links

The links are the skeleton that extend the end effectors to specific space positions. To simultaneously locate the working positions of the inner and outer end effectors, we propose a 5-link structure, where the last two links (and joints) of a 3R robotic arms are duplicated; so there is one shared link from the base (L_1), and two links each for inner and outer controls (L_2, L_3 for inner links, and L_2', L_3' for outer ones).

2.4.3 Joints

The joints are rotatable parts which connect the links together. Each joint consists of a motor and corresponding connectors. Taking the cost into account, we choose stepper motors MS42DDCR [8] instead of servo motors; and as a supplement, we plan to attach the gyroscopes to each link to provide posture feedback for the closed-loop control. Meanwhile, we have two steering servo motor to control the end effector.

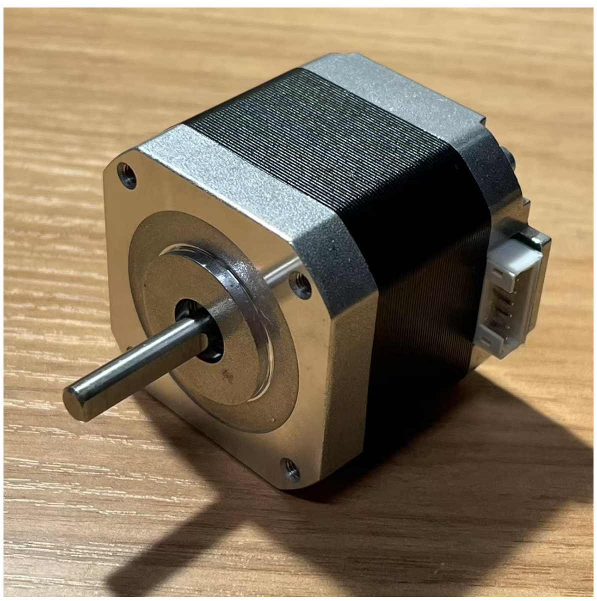

Figure 11: Stepper Motor

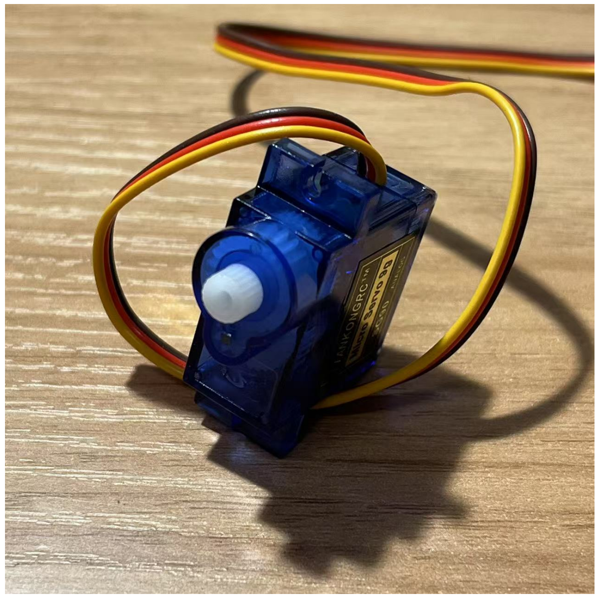

Figure 12: Steering Motor

2.4.4 End Effectors

The end effectors refer to the terminal modules which operate the shaping process. Due to the plasticity of clay, we will install a rolling tool to each terminal. This can not only exert sufficient pressure to shape the pottery walls, but protect the tools from rapid wear and tear by replacing the sliding friction with rolling friction. We have modeled a planar parallel arm to realize this function. This structure uses a wheel to shape the clay from both sides in parallel.

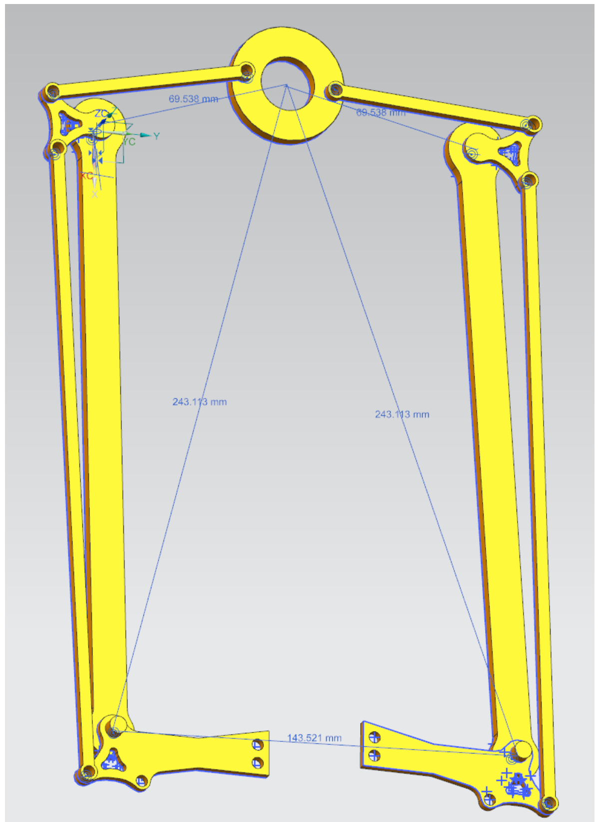

Figure 13: End Effector

2.4.5 Subsystem Requirements

Table 3: Requirements and Verification of Manipulator

Requirement	Verification
The base must suppress vibrations such that the peak vibration amplitude at the end-effector remains below 0.5 mm during operation. The fixture to the workbench must allow no more than 0.2 mm of relative motion under maximum load.	Vibration suppression can be verified by observing the system's stability and checking for undesired movement or noise during operation.
To prevent the inner links from colliding with the pottery wall, the link L3 should be sufficiently thin, relatively long and approximately vertical along the central axis of the pottery vessel.	This can be verified by manually testing the manipulator's range to ensure no collision with the pottery wall, and using a plumb line and goniometer to confirm that link L3 is vertical and aligned with the central axis of the vessel.
The kinematic structure of the manipulator must support full 2D planar reachability, allowing the end-effector to access any position within the defined workspace area (Estimating 200mm x 200mm).	This can be verified by performing a workspace coverage test, moving the end-effector throughout the defined area and confirming positional reachability in all directions within the plane.
The end-effector must be sufficiently long (50mm – 100mm) to reach into the pottery body for shaping operations, and must possess functionality analogous to a human hand to manipulate and form the clay.	This can be verified by physically testing the end-defector's insertion depth into the clay body and assessing its ability to perform shaping tasks comparable to those of a human hand.

2.5 Software Controller

Software Control is used to directly control the manipulator. This subsystem basically includes two parts.

2.5.1 Arduino

Arduino is an open-source electronics platform based on easy-to-use hardware and software, designed for building interactive devices and control systems. Here we use Arduino to directly distribute basic command on the manipulator, in order to do testing on simple tasks. In simple-structure and task-clear robotics, Arduino has a well performance. Using Arduino and C++, we could directly control the stepper motor and steering servo motor, in order to control the pose.

2.5.2 ROS 2

In the situation using Arduino cannot finish our work or satisfy the requirements, we will use ROS for more complicated commands. For foreseeable tasks including applying close-loop control and path planning. We are considering using ROS 2 to perform decision-making and navigation. ROS is a flexible, open-source framework for building robotic systems, primarily designed for Linux environments, both C++ and python are supported. It contains a large number of tool software, library code, and conventions to simplify the difficulty and complexity of creating complex and robust robot behaviors across robot platforms. The main feature of ROS is Distributed Node Architecture: Independent executable programs that perform specific functions are encapsulated into nodes. Nodes can transmit and receive information through topics.

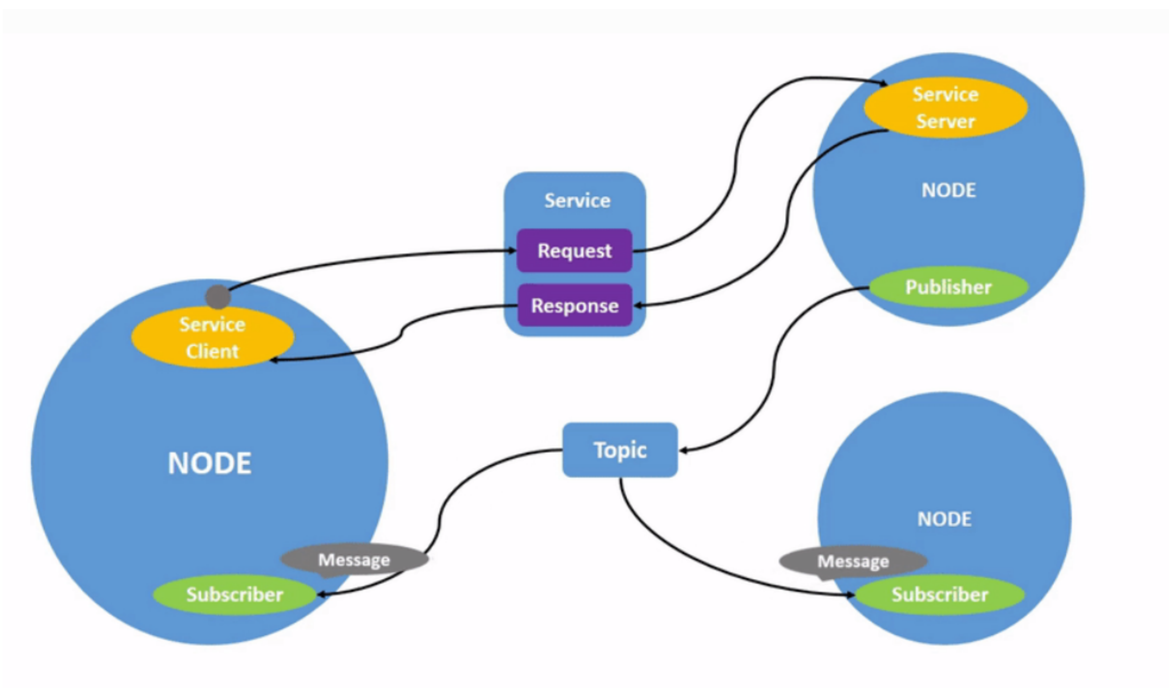

Figure 14: Frames of ROS2

2.5.3 Forward Kinematics

Forward kinematics calculates the end-effector pose according to the given joint status, while the inverse kinematics tries to solve the opposite task. In our design, the trajectory points are basically continuous, so we only need to utilize the probe method in the neighborhood to obtain the inverse kinematics from forward kinematics, which is definite and solvable.

```
function forward_kinematics($M \in \mathbb{R}^{4\times4}$, $S \in \mathbb{R}^{6\times n}$, $\Theta \in \mathbb{R}^{n}$):  // $n$ is # joints
    $T \leftarrow \mathbb{I}_{4\times4}$  // Initialize $T$ as identity matrix
    for $i \leftarrow 1$ to $n$ do
        $(\omega_x, \omega_y, \omega_z, v_x, v_y, v_z) \leftarrow S_{*,i}$
        $V \leftarrow \begin{bmatrix} 0 & -\omega_z & \omega_y & v_x \\ \omega_z & 0 & -\omega_x & v_y \\ -\omega_y & \omega_x & 0 & v_z \\ 0 & 0 & 0 & 0 \end{bmatrix} \in \mathrm{se}(3)$
        $T \leftarrow T e^{V \Theta_i}$
    end for
    return $TM$
end function
```

Listing 1: Forward Kinematics Algorithm

2.5.4 Subsystem Requirements

Table 4: Requirements and Verification of Manipulator

Requirement	Verification
The communication between ROS2 and Arduino must operate in real-time, ensuring that control commands are transmitted with a latency below 10 ms to maintain responsive arm movements.	This can be verified by measuring the round-trip latency using time-stamped messages and an oscilloscope or logging mechanism during operation.
The integration must implement robust error detection and recovery mechanisms in the ROS2-Arduino communication interface, ensuring that message loss or hardware faults trigger appropriate error-handling routines without causing system crashes.	This can be verified by simulating communication interruptions and hardware faults, then monitoring system logs and behavior to confirm that errors are correctly detected and handled.
The system must support synchronized multi-axis control for the robotic arm, ensuring that all joints move in coordination to achieve smooth and accurate motion profiles, with positional errors not exceeding 2% of the intended trajectory.	This can be verified by running predefined motion sequences and using high-resolution encoders or motion capture systems to measure the arm's positional accuracy and synchronization during operation.

3 Cost & Schedules

3.1 Cost

Table 5: Cost Table

Item	Description	Quantity	Price
Pottery Wheel	⌀12.5cm, rpm 0-240, 2.2kg	1	230
High-Whiteness Porcelain Clay	400g	24	54
PCB	ESP32, 30Pin	1	6.01
Jumper Wire	sg-220, 21cm	1	4.05
Type-C Wire	Blue, 0.3m	1	1.68
PCB	ESP32-WROOM-32	2	48.14
PCB	0.96 OLED IIC	1	9.17
3D Printed Component	SCARA Arm Kit	1	711

3.2 Schedule

Table 6: Schedule

Week	**Shihan Lin**	**Zixu Zhu**	**Mofei Li**	**Minhao Shi**
4.14 – 4.20	Design End Effector	Assemble Manipulator	Learn Arduino	3D print End Effector
4.21 – 4.27	Complete software architecture	Test and compare Arduino performance	Test and compare Arduino performance	Test and compare Arduino performance
4.28 – 5.04	Build Final overall system	Build Final overall system	Build Final overall system	Build Final overall system
5.05 – 5.11	Collect Data and visualization	Document Data and measure final debug	Final Debug	Final Debug
5.12 – 5.18	Prepare Final Presentation	Prepare Final Presentation	Prepare Final Presentation	Prepare Final Presentation
5.19 – 5.26	Complete Final Report	Complete Final Report	Complete Final Report	Complete Final Report

4 Ethics & Safety Risks

4.1 Ethical Risks

4.1.1 Unconscious Plagiarism

We refer to technology documents and modify some existing publicly available mechanical structures to meet our needs. We believe that all of our team members are honest and respect the intellectual property of others, but we must be careful about the risk of unintentional plagiarism. Therefore, we must confirm the similarity between our code and the references and assess whether the copyright of the mechanical structure can be used.
(AMC code of ethics: 1.5 Respect the work required to produce new ideas, inventions, creative works, and computing artifacts.)

4.1.2 Safety first

During any experiment and test, we promise that we will take safety as the most important principle. Any behavior that may put members or other people in danger will be completely ruled out.

4.1.3 Protect the environment and reduce waste

We promise not to use materials that are extremely harmful to the environment during the experiment. During the experiment, we will try to reuse the clay used for the experiment as much as possible and reduce the waste of electricity and water.

4.1.4 Honest

We will honestly admit our mistakes and sincerely accept the advice of others. At the same time, any cheating are not allowed. If we receive any guidance from previous works, we will indicate the source in the quotation.

4.1.5 Professional

During the work process, we will strive to achieve high quality of project design. During the project process, we should conduct a comprehensive and thorough assessment of the skills required for the project and only work within our capabilities. At the same time, we should strive to improve our professional skills and maintain high standards of professional ability.

4.1.6 Teamwork

During the project, we promise to respect everyone fairly and not discriminate against others based on the task. We will not participate in any form of harassment or insults, and everyone's ideas will be respected. In the process of group cooperation, while every members should do the work they are good at, each member should be given the space to exert their abilities.

4.2 Machinery Risks

We need to use mechanical structures to shape clay, so we have to consider whether these mechanical structures will cause harm to the environment and people. First, we will reduce the output of the motor to reduce possible harm to people. Second, we will try to add emergency stop and lock procedures to prevent collisions.
(OSHA 29 CFR 1910)

4.3 Soldering Risks

We need to use soldering technology to process hardware, and soldering has certain safety risks. In order to reduce this risk, on the one hand, we plan to reduce the steps required for soldering, so we use 3D printing to replace traditional metal structures. On the other hand, when soldering must be used (such as PCB connection and use), all members must fully wear personal protective equipment and abide by safety operating rules.
(OSHA 29 CFR 1910)

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