Four-Axis Vacuum Stage for Advanced Nano-Manufacturing

ECE 445 Design Document

Group 5

Songyuan Lyu

Yanjie Li

Xingjian Kang

Yanghonghui Chen

TA:

Boyang Shen

Supervisor:

Oleskiy Penkov

1 Introduction

1.1 Objective

Currently, the nanocoating method, magnetron sputtering, has been frequently applied in industry. However, most magnetron sputtering applications are used to perform nanocoating in a 2D frame (on a flat surface) specifically for a sample with regular shape. Although magnetron sputtering is also used to coat with irregular shape objects, it takes a long time to perform the operation, and the coating film has low uniformity. It is a critical disadvantage when magntron sputtering is used to perform nanocoating for some medical implants such as dental teeth [1].
Our objective is to design a structure to enable magnetron sputtering in a three-dimensional frame in a vacuum environment. After investigation, implementing a robotic arm in the nanocoating machine can realize movement in a 3 dimensional frame with different postures [2]. Thus, our aim is to integrate a robotic arm into the nanocoating machine, and the robotic arm should satisfy the requirement to operate in a vacuum and high-temperature environment.

1.2 Background

Nanocoating, as a critical technique in nanotechnology, can be used to control the morphology of a material and achieve enhanced or multifunctional properties of the material [3]. It promotes progress in many different fields, such as surface engineering, aero-engineering, and material science. The working principle of nanocoating is to form a membrane that has a shape similar to the initial template. The nanocoating film is defined to have a thickness smaller than 100 nm, or the second phase nanoparticle is spread to the first phase matrix [3].
In industry, there are many advantages of nanocoating. For example, it can enhance the mechanical properties of some materials. These materials can be used to manufacture some structural components. In addition, the coating film can also increase the corrosion resistance of some materials. The use of these materials can be used to produce some medical devices and increase the lifetime of these instruments [4] [5].
With the development of nanotechnology, there are many nanocoating techniques to produce nanocoating films. Some conventional nanocoating methods include spray coating and direct precipitation [6]. However, these coating methods may result in extra residual stresses and delamination. Thus, it will not retain strong mechanical stability. In comparison to these traditional nanocoating methods, the mainstream nanocoating technique is the physical vaporization deposition (PVD) method. One of the most popular PVD methods is magnetron sputtering. This method can realize better coverage and adhesion of the coating film [7]. During the operation of magnetron sputtering, firstly, inert gas like Argon will be input into a vacuum system, Then, a voltage will be applied to the electrodes, and the plasma will be formed. The inert gas will be ionized, and be accelerated to sputter onto the cathode, which is composed of the target material. The target material will become versatile and is transported to deposit on the substrate, as shown in Fig. 1.

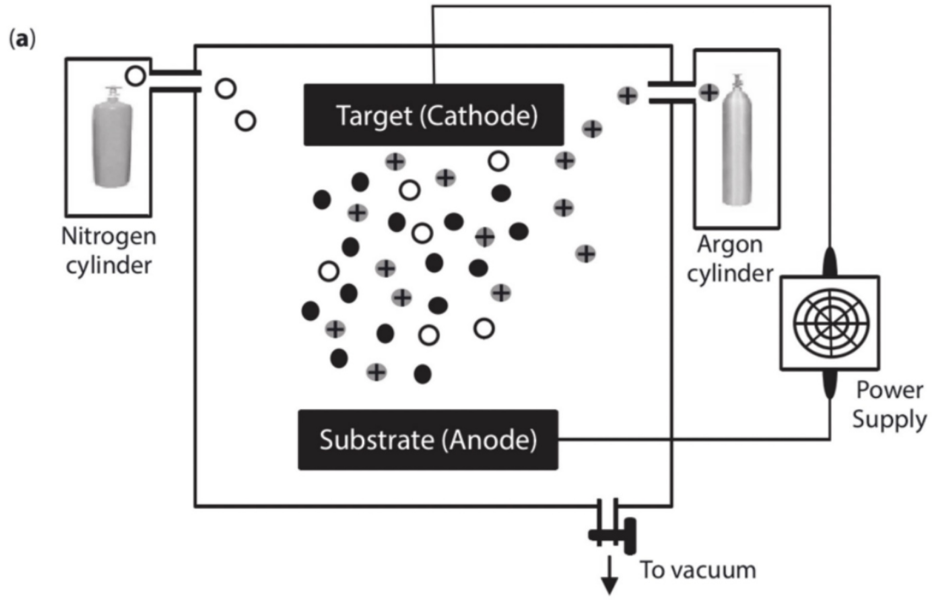


Figure 1: A schematic of magnetron sputtering process

The magnetron sputtering method allows the utilization of a small amount of materials to deposit the film. The film has high mechanical properties and uniformity.

Integrating a multi-axis stage into the magnetron sputtering process is an innovative attempt. The vacuum stage should be able to operate normally in high vacuum and high temperature environment, and it should not affect the operation of other steps during the coating process.

1.3 High-level Requirements

- The system must function in the magnetron sputtering machine without being jammed by strong electromagnetic fields.
- The robotic arm can correctly take the sample to be irradiated in different angles to get coating in high uniformity.

2 Design

The four-axis vacuum stage needs three sections for successful operation. In the control module, STM32F407 Microcontroller Unit (MCU) is connected to the four stepper motor controllers with RS485 protocol to amplify and transmit the signal. It is also connected to PC through USB port with insulation. Then it connects to TFT touch screen in the interface module through Serial TTL protocol. To connect step motor controllers and actuator module in the vacuum space, the electrical wires need to be connected with telfon insulated cables through CF63 conflat flange interface. In the actuator module, the telfon insulated cables are connected to the four step motors, and the electrical signal can be transmitted to actuate them.

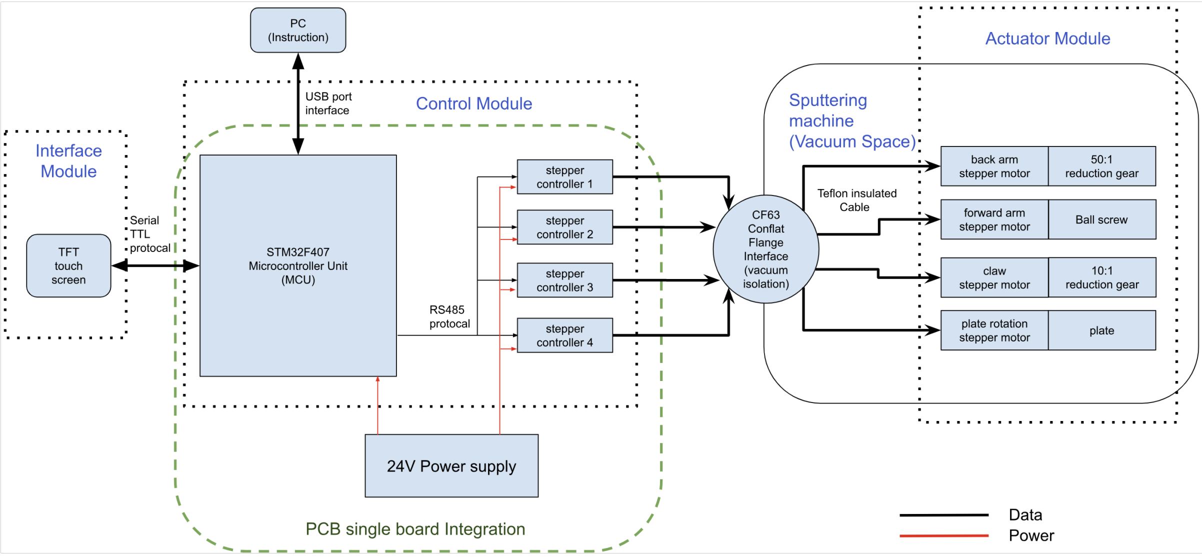
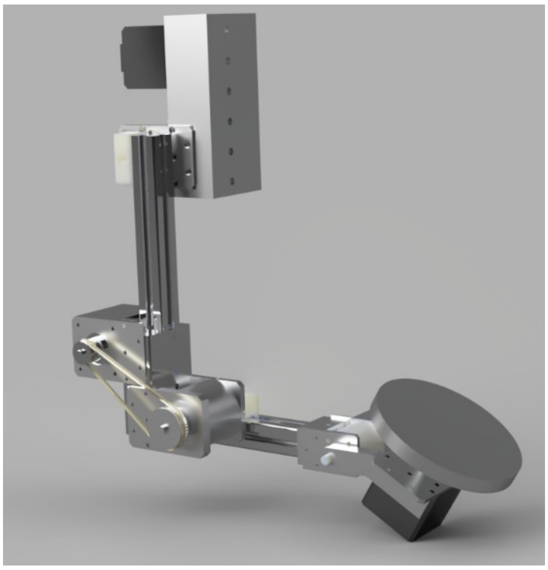
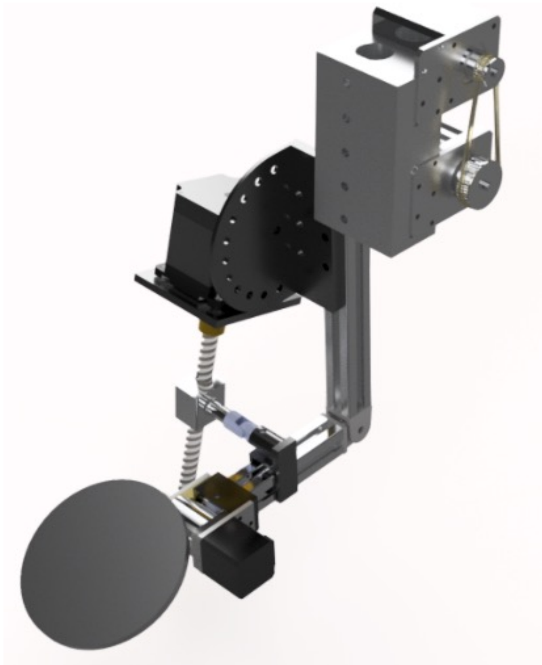


Figure 2: Block diagram of the system

The physical design of the two generations of the vacuum stage are shown below. The vacuum stage has 4 Degree of Freedom, and will be actuated by four motors. In the second generation, the step motor between the first and the second links is replaced by a jack screw. This is to increase the stability of the four-axis vacuum stage.



(a) The first generation of the robotic arm



(b) The second generation of the robotic arm

Figure 3: Physical Design of the robotic arm

2.1 Control Module

2.1.1 Microcontroller Unit (MCU)

Requirement	Verification
Can send RS-485 signals to stepper controller and drive a TFT touch screen	Run a set of test programs, check the functionality.

2.1.2 Stepper Motor Controller

Requirement	Verification
Receive RS-485 signals from the MCU and control motors correctly.	Install in the system and run test programs, the motor should be controlled to the velocity or the position we assigned.

2.2 Actuator Module

2.2.1 Stepper Motor

Requirement	Verification
Three 42 stepper motors and one screw motor are needed. They need to actuate the robotic arm stably (The torque should be able to bear the weight of the robotic arm)	A. Running the simulations in MATLAB and Fusion 360 to make sure that the torques of the stepper motors should be larger than the torques needed to bear the weight. B. Install the system and mark the start position, run a simple up and down program 100 times, the end position should be within 1mm tolerance.

2.2.2 Reduction Gear

Requirement	Verification
The reduction gear need to bear the weight of the robotic arm and exert enough torque to actuate the manipulator when combined working with the stepper motors.	Theoretical calculation based on iteration-1 as below. Install the reduction gears on the arm and test if the motor can move smoothly within the set range of motion

Component	Spec	Weight
42*48 stepper motor	0.6Nm	$\approx 350g$
28*30 stepper motor	0.07Nm	$\approx 100g$
42*40 reduction gear	10:1	$\approx 250g$
42*51 reduction gear	50:1	$\approx 350g$
28*33 reduction gear	10:1	$\approx 200g$
shaft - joint 1 connection		$\approx 570g$
joint 1 - 2 connection		$\approx 190g$
joint 2 - 3 connection		$\approx 45g$
plate	r=50mm	109g

Table 1: Component Weight

Joint-4: plate rotation:

To calculate the moment of inertia, the formula is shown below:

$$I_{plate} \approx \frac{1}{2} \times M \times r^2 \tag{1}$$

After calculation, the moment of inertia is $1.36 \times 10^{-4} [kg \cdot m^2]$

To calculate the angular acceleration, we have:

$$\alpha = \frac{\tau}{I} \approx \frac{0.07Nm}{1.36 \times 10^{-4}} = 513.76 [rad \cdot s^{-2}] \tag{2}$$

Joint-3: claw:

$$\tau_{claw-maxpower} = \tau_{stepper} \times GR \tag{3}$$

Where $\tau_{claw\_maxpower}$ is the maximum power that the claw can reach, $\tau_{stepper}$ is the applied torque of the step motor and GR is the reduced ratio of the claw reducer.

$$\tau_{claw\_maxpower} = 0.07Nm \times 10 = 0.7 [N \cdot m]$$

$$\tau_{claw} \approx (109g + 100g) \times 35mm \approx 0.0073 [N \cdot m] << \tau_{claw\_maxpower}$$

Joint-2: forward arm:

Using the same formula demonstrated in joint-3, we can calculate and compare the exerted and required torques

$$\tau_{farm\_maxpower} = 0.6N \cdot m \times 2 \times 10 = 12 [N \cdot m]$$

$$\tau_{farm} \approx (109g + 100g) \times 130mm + (45g + 100g + 200g) \times 100mm \approx 0.062 [N \cdot m]$$

After comparison, we can find that $\tau_{farm\_maxpower} >> \tau_{farm}$

Joint-1: back arm:

With the same method, we have:

$$\tau_{barm\_maxpower} = 0.6N \cdot m \times 2 \times 50 = 60 [N \cdot m]$$

$$\begin{gathered} \tau_{barm} \approx \\ (109g + 100g) \times 200mm + (45g + 100g + 200g) \times 170mm + (190g + 350g + 250g) \times 70mm \\ \approx 0.16 [Nm] << \tau_{barm\_maxpower} \end{gathered}$$

All joint torque load at a safe range.

2.3 Mechanical Arm Structure

Requirement	Verification
1. The jack screw mechanism should be compatible with the other three step motors. During the prismatic motion of connector along the slideway of the jack screw, the second link of the robotic arm should revolute smoothly around the first joint. 2. The weight of the robotic arm should be uniformly distributed. This is to decrease the required torque to actuate the manipulator and avoid fracture or cracks. 3. The length of each link of the robotic arm should be carefully considered. It should be guaranteed that there is no interference between the trajectory of the robotic arm and the working space.	1. A CAD model will be constructed in Fusion 360, and the compatibility of the steo motors and jack screw can be verified by conducting the actuation simulation of the whole robotic arm. 2. The weight distribution of the robotic arm and the resultant torques, followed by safety factor, concentrated stress can be guaranteed by finite element analysis(FEA) 3. The robotic arm will be modelled in Matlab Simulink. The trajectory of the robotic arm will be visualized using Simulink to see if there is interference with the working space

2.4 Interface Module

2.4.1 button

Requirement	Verification
1. Start Button: Pressing the button initiates the robotic arm's planned trajectory. 2. Stop Button: Pressing the button immediately halts all robotic arm motion. 3. Return Button: Pressing the button returns the robotic arm to its initial state.	1. Power on the system, press the start button and observe robotic arm motion. Robotic arm is expected to begin moving along the predefined trajectory if the start button is working properly. 2. Start the robotic arm, press the stop button during motion and observe robotic arm behavior. Robotic arm is expected to stop all motion immediately (no residual movement) if the stop button is working properly. 3. Start and then stop the arm in a non-initial position, press the return button, observe motion. Robotic arm is expected to move safely back to the predefined initial position and stop if the return button is working properly.

2.4.2 TFT touch screen

Requirement	Verification
1. Display Visibility 2. Communication Link Initialization and Data Transmission Integrity	1. Power on the TFT screen and display the GUI. All UI elements are clearly visible (no glare, pixel defects, or blurriness). 2. Start the program, monitor handshake signals (e.g., UART) to confirm protocol initialization. Then Send known data packets (e.g., fixed position values) and capture raw data received by the TFT and compare to transmitted values. Last, check system logs for errors. If it is working properly, protocol should be established (e.g., ACK received), received data matches transmitted data (no loss/corruption) and no errors in logs.

2.5 Connection

2.5.1 CF63 Conflat Flang Interface

Requirement	Verification
The 4*4 cables needed by 4 motors are connected through the interface, signaling well.	Connect cables through it, resistor should below $1\Omega foreverycable.$

2.5.2 Teflon Insulated Cable

Requirement	Verification
Carry signals and power from CF63 to motors safely, not being damaged by the sputtering or signal interfered.	A. The technical specs will be checked to match the nano coating machine before buy it. B. Install it in the sputtering machine, control the motor during the sputtering process. Check the cables after one coating progress to see if any damage on it.

2.6 Case

Requirement	Verification
1. Can be mounted in the server rack, occupies less than 2u of space. 2.The box needs to have a certain storage limit function	1. Install the case into the server rack in the lab, not interfering other cases on the rack. 2.The box will be used to store important components, and it is required that the components do not interfere or collide and fall off

2.7 Tolerance analysis

For the tolerance analysis, we will focus on the difference between input signal and output signal, which is also the difference between input angle and output angle for each joints. To determine the tolerance, we will conduct tests on each joint angle. We will set the test angle to be θ, conduct the test for 30 times, and let the robotic arm move back and forth. Then the final difference angle is determined to be ϕ, and the error between input angle and output angle can be expressed as:

$$e = \frac{\phi}{30} \tag{4}$$

Where e is the error, and ϕ is the total difference angle in the 30 tests.

3 Costs

Part	Price(RMB)	Quantities	Cost (RMB)
STM32F407ZGT6 Development Board	658.52	1	658.52
Half moon shaped cast aluminum base	7.45	1	7.45
”Emm42” stepper controller	60	4	240
42mm Stepper motor	38	2	76
42mm reduction gear (1:50)	120	1	120
28mm Stepper motor	45	2	90
28mm reduction gear (1:10)	145	1	145
screw motor	598	1	598
2020 aluminum profile	N/A	2	20
Customized aluminum parts	N/A	N/A	2591
24V power supply	118.9	1	118.9
CF63 connector	1200	1	1200

These are the costs of the prototype. When the system goes to mass production, the cost for customized parts will be lower.

4 Schedule

Week	Songyuan Lyu	Xingjian Kang
2/24/25	Define the basic dimensions and geometric structure of the robotic arm as a foundation for kinematic analysis.	Compare potential motor models and match them with suitable motor controllers.
3/3/25	Establish coordinate frames and kinematic equations for the robotic arm. Set up the initial MATLAB code structure.	Pick an MCU with sufficient performance to handle communication and control tasks.
3/10/25	Further refine the forward and inverse kinematics in MATLAB, and develop the trajectory planning code. Apply the Jacobian method to determine joint angles.	Develop the system schematic, detailing power distribution, signal lines, motor driver connections, and any required safety features.
3/17/25	Use MATLAB to plot joint angles and create animation of the iteration process. Verify the correctness and stability of the kinematic algorithms.	Install Keil IDE, set up the toolchain, and explore sample projects. Familiarize with STM32's hardware abstraction layer (HAL) or low-level (LL) libraries.
3/24/25	Calculate required torque and speed based on the expected load of CNC aluminum components. Finalize stepper motor specifications and determine an appropriate gear reduction ratio.	Conduct fundamental tests (LED blinking, reading sensor inputs). Make sure the development board work correctly.
3/31/25	Write control software to drive stepper motors and achieve precise joint control. Perform testing and fine-tuning to align hardware performance with MATLAB simulations.	Test RS485 from STM32F407 development board to "Emm42" stepper controller
4/7/25	Combine hardware, software, and control algorithms for a preliminary system test. Test movement range, joint actions, and error margins, recording data for further improvements.	Test TFT touchscreen functionality. Visualize control parameters.
4/14/25	Identify improvements based on the first-generation test results. Design and sketch the second-generation arm structure, focusing on enhanced stability using a jack mechanism.	Build a simple interface on the STM32 screen (or external display) showing motor positions, speeds, errors, etc.
4/21/25	Develop kinematic and dynamic models for the revised structure. Assess load, inertia, and coupling between joints.	Build a set of actions for arm motion. Assign functions to physical buttons and touchscreen virtual buttons.
4/28/25	Visualize the new arm's trajectory in a simulation environment, validating joint angles, velocities, and accelerations. Refine control strategies to minimize vibration and impact.	Optimize motion profiles and timing to ensure smooth, consistent coating.

Week	Songyuan Lyu	Xingjian Kang
5/5/25	Verify component specifications and machining tolerances. Begin assembling the second-generation robotic arm.	Verify that all four motors can start, stop, and coordinate movements in unison.
5/12/25	Complete the mechanical, electronic, and control system integration. Test motion performance and communication latency in a real hardware environment.	Use the kinematic algorithms to command precise motion of all four motors.
5/19/25	Establish communication with the host computer or other devices to enable real-time monitoring and control. Optimize the protocol and data handling to reduce transmission delays.	Adjust the system based on test feedback (reduce vibrations, enhance control accuracy).
5/26/25	Conduct comprehensive performance evaluations, including accuracy, speed, and stability. Collect data and make any last-minute refinements to the algorithms or hardware design. Prepare the final presentation.Prepare the final presentation.	Thoroughly test simultaneous multi-motor motion, communication stability, and user interface.Prepare the final presentation.

Week	Yanjie Li	Yanghonghui Chen
2/24/25	Continue creating initial component models (e.g., motors, linkages). Verify dimensional feasibility and alignment within the overall design.	Confirm voltage/current needs and RS485 communication requirements for each motor controller.Identify required safety features (e.g., overvoltage protection, filtering).
3/3/25	Use FEA to determine the required arm length for achieving coating objectives. Evaluate stresses and deformations under expected loads.	Finalize the plan to place four RS485 module boards on a single PCB.Determine the physical arrangement and spacing to minimize interference.
3/10/25	Finalize 3D models for motors, linkage components, aluminum profiles, and coating environment. Check assembly compatibility in Fusion 360.	Plan a regulated 24V input shared by four independent power branches. Include filtering (bypass capacitors, ferrite beads) and protection (TVS diodes) for each branch.
3/17/25	Fabricate the initial robotic arm parts using 3D printing. Prepare for mechanical assembly by ensuring print quality and dimensional accuracy.	Lay out all connections (24V, GND, RS485 lines) in a schematic tool. Specify components (connectors, diodes, capacitors, etc.) and create a bill of materials.
3/24/25	Assemble the printed mechanical components. Work with the electronics team to integrate motor control hardware and ensure compatibility.	Position the four RS485 modules to minimize thermal and signal interference. Ensure proper trace width and spacing for high-current paths and differential signals.

Week	Yanjie Li	Yanghonghui Chen
3/31/25	Run basic functional tests (e.g., motion range, joint stability) outside the coating machine. Assess load-bearing performance to confirm it meets initial design parameters.	Link the eight A/B lines (four pairs) in parallel on the PCB. Implement termination and biasing resistors as needed for the single differential bus.
4/7/25	Move the prototype into the coating machine for preliminary, careful testing. Verify that the arm can operate safely and reach necessary positions for coating.	Send the finalized design files to a PCB manufacturer. Assemble the board, mount the RS485 modules, connectors, and essential components.
4/14/25	Collect feedback from in-chamber tests. Adjust arm geometry, material choices, or fastening methods to improve reliability.	Verify each branch's voltage output, current handling, and protection features. Confirm continuity and proper routing of RS485 signals.
4/21/25	Order aluminum profiles and any additional custom parts for the revised design. Confirm delivery timelines for final assembly.	Connect the PCB's A/B outputs to the STM32's RS485 transceiver. Test basic data transmission to a single motor controller to confirm signal integrity.
4/28/25	Replace or enhance 3D-printed parts with machined or aluminum-profile components as needed. Validate the assembled structure for final shape, strength, and functionality.	Power all four motor controllers simultaneously. Validate reliable half-duplex data exchange with all four boards using the STM32's DE/RE pins.
5/5/25	Conduct formal coating trials in the actual production environment. Gather data on coating uniformity, repeatability, and throughput.	Check for signal interference or crosstalk among the four modules. Introduce additional protection (ferrite beads, improved grounding, etc.) if needed.
5/12/25	Refine control strategies, motion profiles, and mechanical alignments based on test results. Make any small design tweaks for improved performance or ease of maintenance.	Combine the PCB with the robotic arm's mechanical and control systems. Test synchronized motor movement across all four axes, ensuring precise and stable motion.
5/19/25	Run the arm for longer durations to confirm long-term stability. Identify potential failure points and address them before final demonstration.	Adjust any resistor values or PCB design factors if voltage drops or noise occur under load. Validate the overall reliability and stability during extended operation.
5/26/25	Showcase the finished robotic arm performing coating tasks under real operating conditions. Present documentation of the design process, test data, and outcomes (e.g., FEA, load tests). Prepare the final presentation.	Compile final PCB documentation, including schematics, layout files, and component details. Transition to full deployment and conduct long-duration stress tests to verify the system's robustness.Prepare the final presentation.

5 Ethics and Safety

As a research team in the engineering and science fields, we have always regarded ethical responsibility and safety norms as the core criteria for technology development. In the nano-coating process optimization project, we are committed to strictly adhering to the IEEE Code of Ethics and ensuring that the technology development process complies with the fundamental requirements of public safety, environmental protection and social responsibility through systematic management measures and team practices.[8]

During the design phase of the project, the team prioritizes the potential impacts of technology applications on public health and the ecological environment. All technical solutions are required to go through a safety risk assessment process, focusing on analyzing possible mechanical, electrical or chemical risk factors in equipment operation. For key aspects of the vacuum coating process, we will develop standard operating procedures that clearly label the safe operating range and prohibitions of the equipment. For processes involving material handling, such as magnetron sputtering, we strictly follow laboratory chemical management practices to ensure that the storage, use and disposal of hazardous substances comply with environmental standards. Team members receive regular safety training and case studies to strengthen their awareness of risk prevention, and treat every technical decision with a scientific attitude.

Technical transparency is a fundamental principle that we adhere to. In the course of the project, any technical improvements or process adjustments will be documented through a standardized documentation system. For the technical limitations or potential risks of the equipment, we promise to explain to the partners in a professional and objective way to avoid misjudgment due to incomplete information. The team establishes open communication channels and encourages internal members and external experts to give constructive comments on technical solutions. If design defects or operational hazards are found during testing, the correction process will be immediately initiated and improvement measures will be communicated to the relevant parties in the form of a technical memorandum.

At the team management level, we strictly implement a conflict of interest review mechanism. All procurement decisions are subject to tripartite price comparison and compliance review to ensure that the supplier selection process is open and transparent. The technical qualifications and business reputation of partner organizations will be taken as important assessment indicators to eliminate any form of improper exchange of benefits. Team members regularly sign a professional ethics commitment, explicitly prohibiting the use of their positions for personal gain. For external factors that may affect technical judgment, relevant personnel are required to proactively declare and avoid relevant decisions.

The laboratory safety system is constructed to cover the entire life cycle of the equipment. The design of the electrical system adopts the safety protection standards common in the industry, all high-voltage components are equipped with insulation protection and overload protection devices, and the key circuits are equipped with emergency power-off switches. The mechanical structure is designed with full consideration of ergonomics, with physical isolation devices and eye-catching markings around the moving parts to avoid accidental contact during operation. A two-person collaboration system will be strictly implemented during the prototype testing phase of the equipment to ensure timely response to abnormal situations. For operators of special processes, in addition to standard protective equipment, special protective measures will be configured according to specific risks.

User safety protection program throughout the product design. Equipment terminals will be equipped with simple and easy-to-understand operating guidelines and risk tips, and key functions will be set up for hierarchical management of permissions. Before delivery, we will provide a complete training program to ensure that operators are proficient in the characteristics of the equipment and emergency response methods. The establishment of regular maintenance and inspection system and remote technical support system will effectively reduce the potential risks in the long-term operation of the equipment. All safety warning messages are in multi-language versions combining graphics and text, taking into full consideration the adaptability of different usage scenarios.

Team building focuses on creating an equal and inclusive working environment. The recruitment and assessment process follows the principle of competence orientation and eliminates any discrimination based on gender, race or belief. We continue to raise team members' awareness of their responsibilities through regularly organized technical ethics workshops. We have set up an anonymous feedback channel to protect members who raise reasonable questions from being criticized, and any violation of professional ethics will be subject to an independent investigation process. In cross-cultural cooperation, we respect the business practices and cultural traditions of our partners and handle technical disagreements in a professional manner.

Responsibility for environmental protection is implemented in every technical detail. The selection of materials gives priority to renewable and recyclable properties, and process optimization focuses on reducing energy consumption and waste generation. Chemical reagents are purchased and used in accordance with the principles of green chemistry, and waste disposal solutions are certified by professional organizations. The energy efficiency management of equipment adopts the industry's common optimization strategy to minimize carbon emissions while ensuring performance.

We understand that the value of technological innovation lies not only in performance breakthroughs, but also in the assumption of social responsibility. Through the establishment of a standardized safety management system and ethical practice mechanism, the team is committed to finding a balance between technical feasibility and social acceptance. In the future, we will continue to improve the monitoring and evaluation system, and actively accept the supervision of industry organizations and the public, so as to fulfill our commitment to responsible innovation with practical actions.

6 Reference

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