Four-Axis Vacuum Stage for Advanced Nano-Manufacturing

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1 Introduction

1.1 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 [1]. 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 [1].

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 [2] [3].

As the development of the nanotechnology, there are many nanocoating techniques to produce nanocoating films. Some conventional nanocoating methods include spray coating and direct precipitation [4]. However, these coating methods may result in extra residual stresses and delamination. Thus, it will not retain strong mechanical stability. Compared to these traditional nanocoating methods, the mainstream nanocoating technique is 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 [5]. 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.

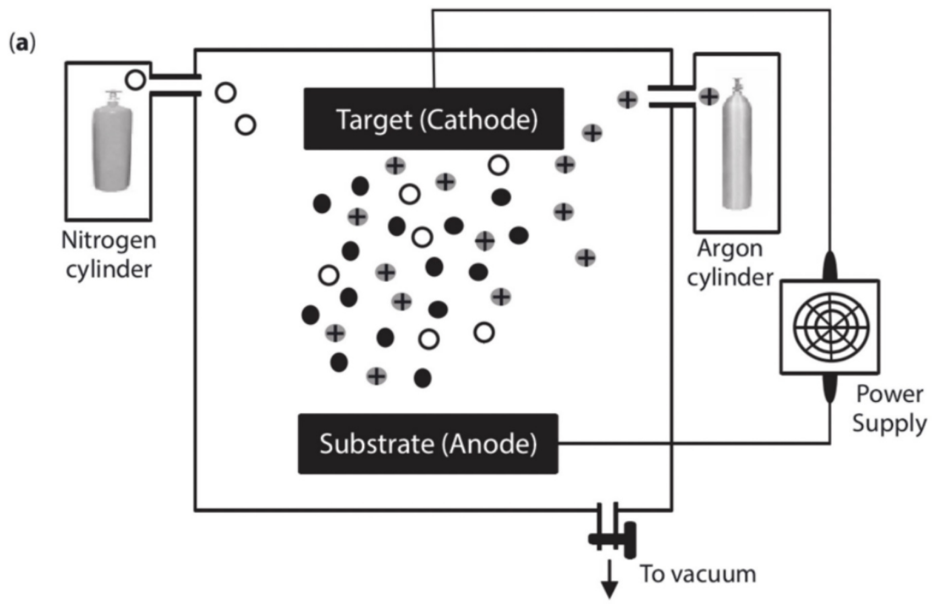

Figure 1: A schematic of magnetron sputtering process

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

1.2 Motivation and Objective

Currently, the nanocoating method - magnetron sputtering has frequently applied in industry. However, most of the magnetron sputtering 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 costs a long time perform the operation, and the coating film has a low uniformity. It is a critical disadvantage when magntron sputtering is used to perform nanocoating for some medical implants like dental teeth [6].
Our objective is to design a structure to enable magnetron sputtering in three dimensional frame in a vacuum environment. After investigation, Implement a robotic arm into the nanocoating machine can realize movement in 3 dimensional frame with different postures [7]. Thus, our aim is to integrate a robotic arm into the nanocoating machine, and the robotic arm should satisfy the requirement to stay in a vacuum and high-temperature environment.

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

2.1 Block Diagram

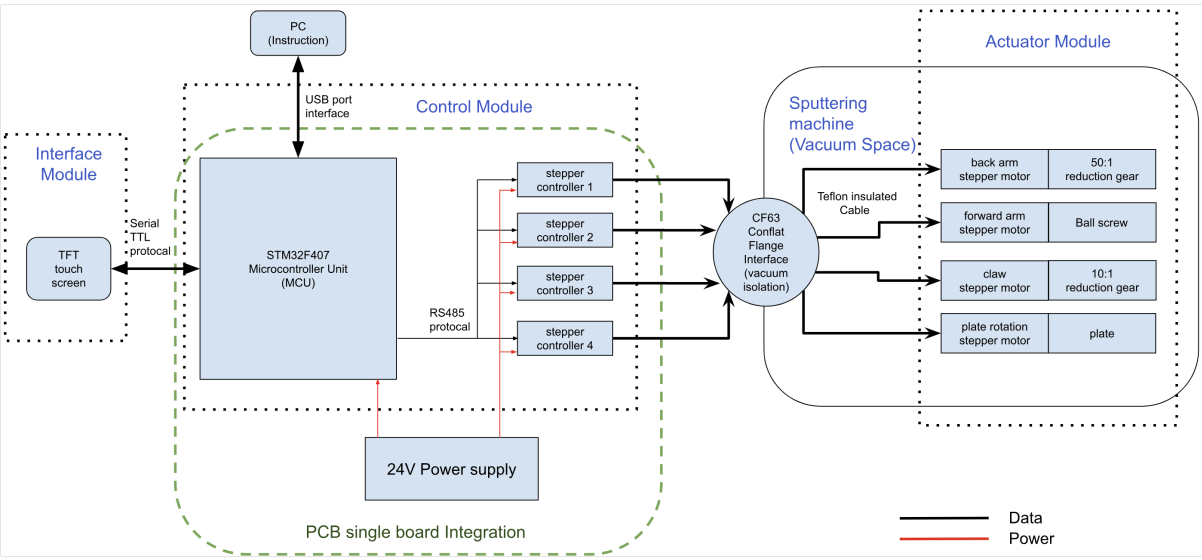

Figure 2: Figure 2: Block diagram of the system

2.2 Block Descriptions – Functionality and Requirements of each component

2.2.1 Summary of the System

- The 4-DOF robotic arm integrates Interface, Control, and Actuator modules to enable precise 3D manipulation of specimens in a magnetron sputtering vacuum environment. The system ensures uniform nanocoatings by dynamically adjusting specimen orientation via stepper motors, reduction gears, and vacuum-compatible interfaces.

2.2.2 Function and requirement of each block and component

- Interface Module:

  1. PC (Instruction):

  Functionality: Hosts user-defined coating programs (e.g., rotation sequences, tilt angles) and sends commands to the MCU.

  Connection: Linked to the STM32F407 MCU via USB or serial TTL.

  Requirements: Support Windows/Linux-based control software. Transmit commands with 10 ms latency.

  2. 7-inch TFT Touch Screen:

  Functionality: Local user interface for real-time monitoring (e.g., motor positions, coating progress) and manual input.

  Connection: Communicates with the MCU via Serial TTL protocol (adjustablt, 57600 baud).

  Requirements: 800x480 resolution with 30 Hz refresh rate.

  3. USB Port:

  Functionality: Enables firmware updates and direct PC-MCU communication.

  Requirements: USB 2.0 compliant; isolated to prevent EMI interference.

- Control Module:

  1. STM32F407 Microcontroller Unit (MCU):

  Functionality: Executes motion planning algorithms (e.g., inverse kinematics), coordinates stepper motors, and processes user inputs.

  Connection: Receives commands from PC/TFT screen via USB/TTL. Sends control signals to stepper motors via RS485 protocol.

  Requirements: 168 MHz clock speed for real-time computation. Operate in -40°C to +85°C range (vacuum-compatible).

  2. RS485 Protocol:

  Functionality: Robust communication between MCU and stepper motor drivers in high-EMI environments.

  Requirements: above 115.2 kbps data rate with CRC-16 error detection. Support up to 4 nodes (one per motor).

3. 24V Power Supply:

Functionality: Powers stepper motors and MCU.

Requirements: $\leq 3\%$ voltage ripple under 8 A peak load

Short-circuit and overcurrent protection.

4. PCB Single Board Integration:

Functionality: Consolidates MCU, motor drivers, and power circuitry into a compact board.

Requirements: FR4 substrate with conformal coating for humidity resistance.

- Actuator Module:

1. Sputtering Machine (Vacuum Space):

Functionality: High-vacuum environment for magnetron sputtering deposition.

Connection: Hosts the robotic arm via CF63 Conflat Flange Interface.

Requirements: Maintain vacuum integrity during arm motion.

2. CF63 Conflat Flange Interface:

Functionality: Vacuum-sealed mechanical interface between the robotic arm and sputtering chamber.

Requirements:

Use copper gaskets for leak rates 1x10 mbar·L/s.

3. Teflon Cable:

Functionality: Transmits power/data between vacuum and atmospheric environments.

Requirements:

Withstand 200°C and 10^3 mbar vacuum.

4. Stepper Motors:

4.1 Back Arm Forward Arm Stepper Motors:

Functionality: Control radial movement of the robotic arms. The backward arm stepper motor is connected with a 50:1 reduction gear, which increases torque output while reducing speed. The reduction gear can provide high torque for lifting or moving heavier loads. The forward arm stepper motor is connected with a ball screw, which converts the rotational motion of the motor into precise linear motion, enabling smooth and accurate movement of the forward arm.

Requirements:

1:50 reduction gear for at least 70 N·m output.

4.2 Claw Stepper Motor:

Functionality: Adjusts specimen grip force.

Requirements: 0.7 N·m torque with 1:10 gear reduction.

4.3 Plate Rotation Stepper Motor:

Functionality: Rotates specimen plate for omnidirectional coating.

Requirements: Can hold the plate stably and rotate it smoothly.

5. 10:1 Reduction Gears:

Functionality: Amplify torque for precise motion control.

Requirements: Backlash 0.02°; lifetime 10,000 hours in vacuum.

6. Data/Power Lines:

Functionality: Deliver power and sensor feedback between components.

Requirements: Shielded cables to mitigate EMI from magnetron.

2.3 Mechanical Design

To build the four-axis vacuum stage, a four-degree-of-freedom robotic manipulator will be implemented into the nanocoating machine.

2.3.1 CAD Modeling

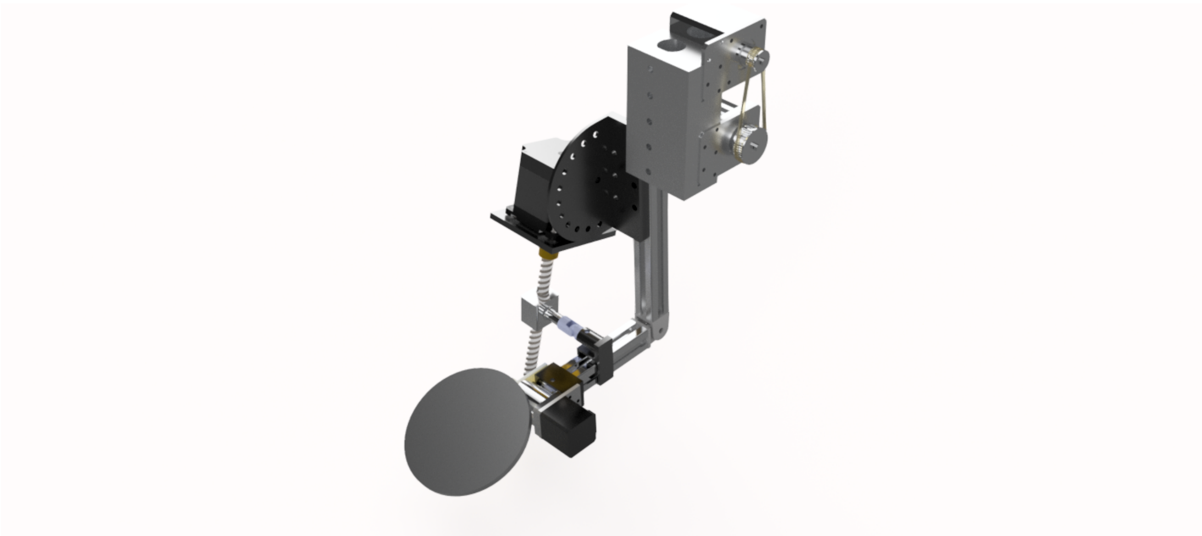

Figure 3: CAD Modeling of the 4 DOF robotic arm

2.3.2 Stability and Flexibility

The screw motor is fixed on the backward arm using a angular adjuster. This enables the screw motor to change the angle between it and the backward arm, giving flexibility of the mechanical structure. The flexible structure makes it convenient to perform a kinematic analysis and lower the risk of failure. The screw motor is fixed on the backward arm, and the rotation of the forward arm will align with the movement of the block along the screw rod. This makes the operation of the robotic arm more stable and precise.

3 Ethics

As members of the engineering and scientific community, we recognize the importance of adhering to the IEEE Code of Ethics in the design, development, and implementation of our project.

3.1 Upholding Integrity, Responsibility, and Ethical Conduct

1. Safety, Health, and Welfare of the Public

   The primary aim of this project is to enhance the quality of nano-coating processes, which have wide-ranging industrial and societal applications. By improving coating uniformity and mechanical properties, the project contributes to the development of safer and more reliable nanotechnology-based products. We will ensure that our design complies with ethical engineering practices and sustainable development principles to minimize waste and environmental impact.

2. Transparency in Risks and Limitations

   We will disclose any limitations or potential risks associated with the vacuum stage, such as mechanical failures or environmental hazards from the magnetron sputtering process. These disclosures will help stakeholders make informed decisions about the deployment of the technology.

3. Avoiding Conflicts of Interest

   We will avoid any real or perceived conflicts of interest in our professional activities. If such conflicts arise, we will disclose them to the relevant parties to ensure transparency and maintain trust.

4. Rejection of Unlawful Conduct and Bribery

   Throughout the project, we commit to adhering to all legal and ethical standards. We reject any form of bribery or unethical practices in procurement, manufacturing, or collaboration processes.

5. Acknowledgment and Correction of Errors

   We will seek and accept honest criticism of our work, acknowledging and correcting any errors identified during the design, testing, or implementation phases. Proper credit will be given to all contributors, including team members and external collaborators, for their intellectual and technical contributions.

6. Competence and Qualification

   We commit to undertaking tasks for which we are qualified through training and experience. If limitations in our expertise arise, we will seek additional guidance, training, or collaboration to ensure the project's success.

3.2 Treating All Persons Fairly and Respectfully

Our team is committed to treating all members, collaborators, and stakeholders with fairness and respect. We will not engage in discrimination based on race, religion, gender, disability, age, national origin, sexual orientation, gender identity, or gender expression. We will foster a respectful and inclusive working environment, ensuring that no individual is subjected to harassment, bullying, or any form of inappropriate behavior. The design of the robotic arm will prioritize the safety of operators and users. We will avoid false or malicious actions that could harm others' property, reputation, or employment. All safety measures will be thoroughly tested and documented to prevent injury or damage during operation.

3.3 Ensuring Ethical Conduct Among Colleagues

We will actively encourage our team members and collaborators to adhere to the IEEE Code of Ethics. Through regular meetings and discussions, we will ensure that ethical considerations are integrated into every stage of the project. We will report and address any ethical violations that may arise during the project. Retaliation against individuals who report violations will not be tolerated.[8]

4 Safety Concerns and Guidelines

4.1 Electrical Safety

- **Risks:** Electric shock, short circuits, overheating, or high-voltage hazards.
- **Mitigation:** Complete mandatory safety training, insulate electrical components, use circuit breakers, and follow high-voltage safety protocols if required.
- Work will always involve two team members present, as per *ECE 445 Safety Guidelines*.

4.2 Mechanical Safety

- **Risks:** Pinching, crushing, or collisions from moving parts.
- **Mitigation:** Add emergency stop buttons, enclose moving parts, mark safe zones, and conduct regular maintenance.

4.3 Lab Safety

- **Risks:** General lab hazards and potential exposure to hazardous materials during magnetron sputtering.
- **Mitigation:** Always work in pairs, wear PPE, follow hazardous material handling protocols, and create a **Lab Safety Manual** if necessary.

4.4 End-User Safety

- **Risks:** Electrical shocks, mechanical hazards, or misuse.
- **Mitigation:** Include safety enclosures, provide user manuals, and conduct testing to verify reliability under all conditions.

4.5 Safety Plan

- Complete all mandatory safety training and submit certificates on Blackboard.
- Conduct weekly safety audits and ensure emergency procedures are reviewed and practiced.

5 Reference

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