ECE445

SENIOR DESIGN LABORATORY

DESIGN DOCUMENT

Latte Art Coffee Machine

Team #10

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1 Introduction

The automation of food preparation has become an important research direction in modern robotics and intelligent manufacturing. Coffee preparation, especially latte art, requires precise control of fluid flow, motion trajectory, and timing. Traditionally, high-quality latte art depends heavily on the experience and skills of a barista. However, achieving consistent artistic patterns manually is difficult and time-consuming. Inspired by the motion control mechanisms used in X–Y plotters and 3D printers, this project proposes an autonomous latte art machine capable of generating customized patterns from user-provided images.

1.1 Problem Statement

Latte art creation requires coordinated control of the milk pouring position, velocity, and path. Human baristas can achieve this through practice and intuition, but replicating the same pattern repeatedly with high accuracy is challenging. In addition, existing coffee machines typically focus on brewing automation rather than artistic customization.

The main problem addressed in this project is how to design a system that can:

- Prepare coffee inside a container with a predefined size.
- Interpret user-submitted images and convert them into executable motion paths.
- Precisely control the movement of a pouring mechanism to create latte art patterns.
- Ensure repeatability and consistency in the produced designs.

Therefore, the challenge lies in integrating image processing, motion control, and fluid dispensing into a single automated system.

1.2 Solution Overview & Visual Aid

The proposed system is an autonomous latte art machine inspired by the kinematic structure of an X–Y plotter and the layered motion strategy used in 3D printers. The system converts a user-provided image into a path trajectory, which is then executed by a two-axis motion platform controlling the position of the milk dispensing nozzle above the coffee surface.

The overall workflow of the system includes:

1. User uploads a desired latte art image.
2. Image processing module extracts contours and generates a motion path.
3. Motion planning module converts the path into control commands.
4. X–Y positioning system moves the dispensing mechanism.
5. Controlled milk flow creates the final latte art pattern.

This architecture allows the machine to produce customized latte art patterns with high precision and repeatability while maintaining flexibility in design.

User Image Input → Image Processing → Path Generation
↓
Motion Controller → X–Y Motion Platform → Latte Art Output

Figure 1: Conceptual workflow of the autonomous latte art machine.

1.3 High-Level Requirement List

To achieve the project objectives, the system must satisfy several high-level functional and technical requirements:

- **Container Compatibility:** The system must operate within a predefined cup size and maintain accurate positioning relative to the coffee surface.
- **Image-to-Path Conversion:** The machine should be able to process user-uploaded images and convert them into motion trajectories.
- **Precision Motion Control:** The X–Y movement system must achieve sufficient spatial resolution to produce recognizable latte art patterns.
- **Stable Fluid Dispensing:** The milk dispensing mechanism must maintain a consistent flow rate to ensure pattern clarity.
- **Repeatability:** The system should reproduce the same latte art pattern reliably across multiple operations.
- **User Interface:** A simple interface should allow users to upload images and initiate the coffee-making process.
- **System Safety and Reliability:** The machine must operate safely with hot liquids and maintain stable operation during repeated use.

The combination of motion control, image processing, and automated beverage preparation forms the foundation of the proposed intelligent latte art system.

2 Design

2.1 Block Diagram

This block diagram illustrates the overall workflow of the latte art coffee machine system. The process begins with the user uploading an image or scanning a QR code, which is then transmitted to the controller. The system performs image processing to recognize and analyze the input image, followed by outline and pixel extraction to obtain the essential features of the pattern. Based on this information, a path planning module generates motion commands that define how the pattern will be drawn. These commands are sent to two actuators: the plunger motor and the X–Y motion motor. The plunger motor is responsible for dispensing coffee into the cup, while the X–Y motion motor controls the movement of the nozzle across the surface. By coordinating these two actions, the system executes the latte art drawing process and produces the final coffee pattern.

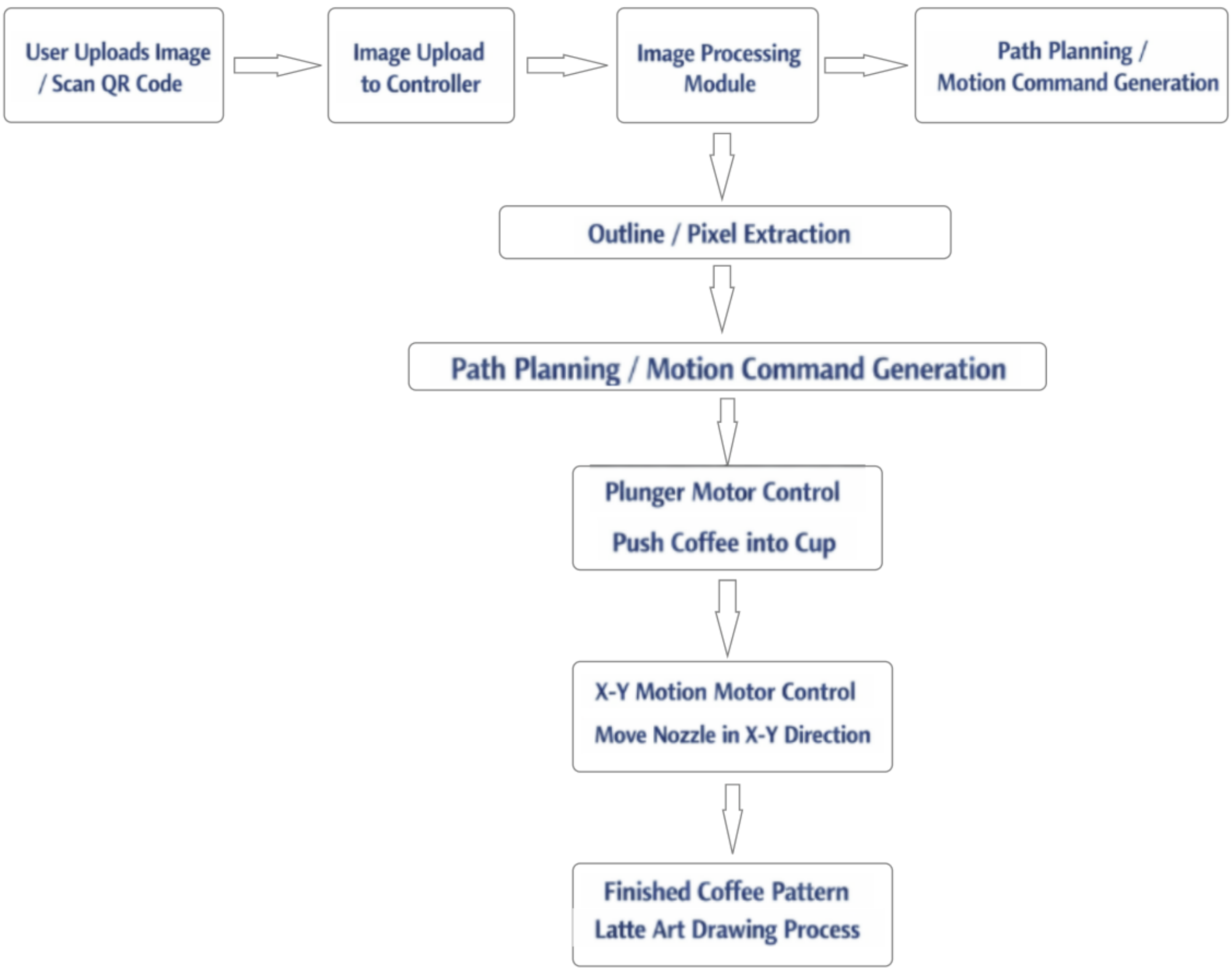

Figure 2: Block Diagram

2.2 Subsystems Description

2.2.1 X-Y Platform

The mechanical structure of the automatic latte art machine is based on a planar motion platform. Since the printing process only requires the nozzle to move above the surface of the coffee foam, a two-dimensional X-Y mechanism is sufficient to achieve the desired pattern generation. Compared with a multi-joint robotic arm, an X-Y platform provides a simpler structure, lower manufacturing cost, and easier motion control, which makes it suitable for a compact prototype system.

The X-Y platform is designed to move the dispensing head precisely to predefined coordinates above the cup. The motion in the horizontal plane is separated into two independent orthogonal directions. One axis controls the left-right movement of the dispensing head, while the other controls the forward-backward movement. By combining these two motions, the nozzle can reach any target point within the printable area. This coordinate-based movement method provides good repeatability and allows digital image data to be translated directly into physical motion commands.

In the proposed design, the cup remains fixed during operation and the dispensing head performs the planar motion. This arrangement reduces the disturbance of the liquid surface and improves printing stability. The X-Y platform therefore serves as the core motion unit of the machine, providing the positional accuracy required for pattern formation on the foam surface.

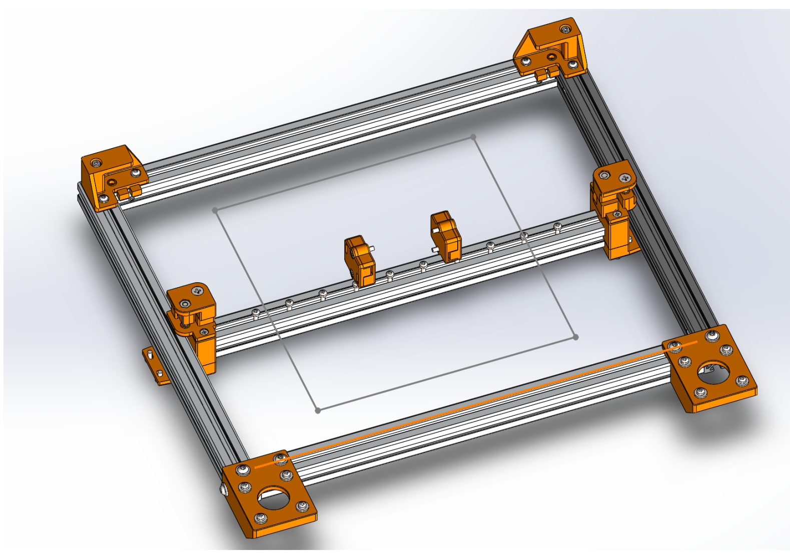

Figure 3: X-Y Platform Design

2.2.2 Dispensing Mechanism

The dispensing mechanism is responsible for depositing a controlled amount of liquid onto the foam surface in order to generate visible patterns. Its function is to convert electrical control signals into physical droplets or short pulses of liquid output. During printing, the dispenser is activated only when the nozzle reaches a target position that must be marked according to the processed image.

A point-by-point dispensing strategy is adopted in this design. For each target coordinate, the nozzle stops briefly and releases a small quantity of liquid onto the coffee surface. This method simplifies the control logic because the system only needs to determine whether each point should be printed or skipped. It also reduces the difficulty of flow regulation compared with continuous line printing. Therefore, pulsed dispensing is well suited for a prototype machine intended for stable and repeatable operation.

To ensure printing quality, the dispensing mechanism should satisfy several requirements. First, it must respond quickly to control signals so that the amount of liquid released at each point remains consistent. Second, the structure should be lightweight to minimize the load on the X-Y platform. Third, the nozzle should be easy to clean and maintain, since liquid residue may affect subsequent printing performance. Based on these considerations, the dispensing mechanism is treated as the terminal execution unit of the whole system.

2.2.3 Control System

The control system coordinates image processing, motion execution, and liquid dispensing. Its main function is to transform an input pattern into a sequence of motion and dispensing commands. In the proposed design, the input image is first preprocessed and converted into a binary representation. Dark regions correspond to positions that need to be printed, while blank regions are ignored. In this way, the image is transformed into machine-readable data.

After image preprocessing, the controller generates the corresponding coordinate sequence for printing. The X-Y platform is then driven to each target position in order, and the dispensing mechanism is activated when necessary. The entire printing process can therefore be divided into three stages: pattern generation, motion planning, and real-time actuation. This workflow establishes a clear relationship between digital image data and physical printing behavior.

The control system also determines the overall performance of the machine. A well-designed controller can reduce unnecessary motion, improve printing efficiency, and enhance the consistency of the final pattern. In addition, the system should provide basic functions such as initialization, homing, manual adjustment, and printing control. Through the cooperation of the X-Y platform and the dispensing mechanism, the control system enables the machine to automatically reproduce user-defined latte art patterns with stable operation and acceptable accuracy.

2.2.4 User Interface

This module allows the user to upload an image, send it to the system, and initiate the image processing procedure.

2.3 Subsystem Requirements

2.3.1 X-Y Platform Requirements

The X-Y platform shall provide precise and repeatable planar motion for the dispensing head above the coffee surface. In order to ensure that recognizable latte art patterns can be produced, the subsystem must satisfy the following requirements:

- The X-Y platform shall provide a minimum printable area of 120 mm $\times$ 120 mm to cover the target cup opening and allow full-pattern generation.
- The positioning accuracy of the dispensing head shall be within ± 1.0 mm in both the X and Y directions over the entire printable area.
- The repeatability of the X-Y platform shall be within ± 0.5 mm for repeated motion to the same coordinate.
- The commanded resolution of motion shall be no greater than 0.5 mm per step in both axes.
- The maximum steady-state travel speed of the dispensing head shall be at least 40 mm/s, while maintaining the positioning accuracy requirement.
- The overshoot after a commanded stop shall not exceed 1.0 mm in either axis.
- The platform shall reach any target coordinate within the printable area in no more than 3 s.
- During operation, vibration-induced displacement at the dispensing head shall remain below ± 0.5 mm under nominal motion conditions.
- The cup shall remain fixed relative to the platform, and the alignment error between the platform coordinate origin and the cup center shall be less than ± 1.0 mm after calibration.

2.3.2 Dispensing Mechanism Requirements

The dispensing mechanism shall deposit controlled amounts of liquid onto the foam surface in a repeatable and localized manner. Since the design uses point-by-point dispensing, the subsystem must satisfy the following requirements:

- The dispensing mechanism shall release individual droplets or pulses with a volume variation of no more than $\pm 10\%$ from the nominal dispensed amount.
- The mechanism shall achieve an actuation response time of no more than 0.2 s for both start and stop commands.
- The liquid flow shall stop completely within 0.3 s after a stop command is issued.
- The diameter of a deposited dot on the foam surface shall be between 2 mm and 5 mm under nominal operating conditions.
- The positional offset between the nozzle center and the actual deposited liquid point shall not exceed ± 1.0 mm.

- The nozzle-to-liquid-surface distance shall be maintained at 10 ± 3 mm during operation.
- The dispensing mechanism shall operate continuously for at least 50 dispensing cycles without clogging or performance degradation.
- Residual dripping after a stop command shall not exceed one unintended droplet per dispensing event.
- The dispensing head mass mounted on the X-Y platform shall not exceed 500 g in order to limit motion instability and vibration.

2.3.3 Control System Requirements

The control system shall convert an uploaded image into executable motion and dispensing commands for the latte art machine. It must coordinate image processing, motion planning, and actuator control with sufficient accuracy and speed.

- The control system shall accept a user image and convert it into a binary or equivalent printable pattern within 10 s.
- The control system shall generate coordinate-based motion commands that cover at least 95% of the intended printable pattern area.
- The controller shall synchronize X-Y motion and dispensing commands such that the timing error between motion arrival and dispensing actuation does not exceed ± 0.1 s.
- The controller shall not miss more than 1% of intended dispensing points in a complete print job.
- The controller shall provide a homing function that establishes the reference origin with a repeatability of ± 0.5 mm.
- The control system shall support manual start, stop, and reset commands from the user interface.
- The system shall complete the execution of one standard latte art pattern within 120 s after printing begins.
- In the event of an abnormal condition, the controller shall stop motion and dispensing within 1 s of detecting the fault.

2.3.4 User Interface Requirements

The user interface shall allow the user to upload an image, initiate the printing process, and monitor basic system status.

- The user interface shall accept at least one common image format, such as PNG or JPG.
- The image upload process shall complete successfully for at least 95% of valid input files smaller than 10 MB.
- The user shall be able to initiate image processing and printing in no more than three interaction steps after uploading the image.

- The interface shall display system states including idle, processing, printing, and error.
- The interface shall provide a user notification within 2 s if an invalid file format or upload failure is detected.
- The interface shall provide a manual stop or cancel function that sends a stop command to the control system within 1 s.

2.4 Subsystem Verifications

2.4.1 X-Y Platform

This subsystem is required to accurately control the motion of the nozzle in the X and Y directions without introducing excessive error. In addition, the vibration generated during operation should remain within an acceptable range. This subsystem can be tested after the platform is constructed, or verified after the entire project is completed.

2.4.2 Dispensing Mechanism

This subsystem is required to precisely control the liquid flow rate, including rapid start and stop of the dispensing process. The nozzle position should also maintain an appropriate distance from the liquid surface so that excessive splashing error can be avoided. This subsystem can be tested independently by using a syringe and a linear motor.

2.4.3 Control System

This subsystem is required to correctly process the image uploaded by the user, perform edge detection, and generate the drawing pattern. It should also optimize the pattern according to the characteristics of the image and design a reasonable drawing path to improve efficiency. This subsystem can be tested after the X-Y platform is completed.

2.4.4 User Interface

This subsystem is required to correctly receive the image uploaded by the user and transfer it to the Control System. The verification of this subsystem is relatively simple, since it only requires the file to be uploaded successfully.

2.5 Tolerance Analysis

Two major sources of error exist in this project.

2.5.1 Distance Between the Nozzle and the Liquid Surface

Since the proposed system adopts an X-Y motion platform, the nozzle position along the Z-axis is fixed. A certain vertical clearance must therefore be reserved to ensure safe motion above the liquid surface. However, this clearance introduces a lateral deposition error because the droplet travels through air before reaching the foam surface.

To reduce this error, the cup height is fixed by the holder and the nozzle is aligned vertically during calibration. These measures keep the nozzle-to-surface distance stable and suppress the horizontal velocity component, thereby ensuring acceptable printing accuracy.

2.5.2 Motor Motion Accuracy Error

The motors used in the X-Y platform and the nozzle control mechanism may both introduce motion errors. These errors can lead to two main problems. Errors in the X-Y platform may reduce the drawing accuracy and cause the printed pattern to deviate from the intended shape. Errors in the nozzle control motor may prevent the liquid injection from stopping at the correct time, which may result in connected strokes or blurred pattern details.

To reduce these problems, different improvement methods can be applied to the two subsystems. For the X-Y platform, a gear reduction mechanism can be used to improve motion accuracy. By reducing the output speed of the motor, the platform can achieve more stable and precise movement. For the nozzle control motor, a combination of gears and a worm drive can be adopted to further reduce speed and improve control precision, so that the dispensing process can start and stop more reliably.

At the software level, additional image processing methods can also be introduced. The target pattern can be slightly modified in advance to reduce the number of sharp turns and large-angle direction changes of the nozzle. In this way, the motion path becomes smoother, which helps reduce the influence of motor error during operation and improves the overall printing quality.

2.5.3 Error Caused by Liquid Surface Disturbance Due to Vibration

For relatively complex patterns, the repeated back-and-forth motion of the nozzle may cause vibration and disturb the liquid surface. As a result, the printed pattern may deviate from the intended shape.

To reduce this error, a software-based solution is planned to minimize vibration. For example, smoother velocity profiles can be applied during the acceleration and deceleration of the nozzle. In addition, the maximum movement speed of the nozzle can be limited to a certain extent in order to reduce vibration. These measures help improve the stability of the liquid surface and reduce the influence of vibration on printing accuracy.

2.6 Supporting Material

Supporting Material	**Purpose**
System Block Diagram	Shows the relationship among image input, control system, motion platform, and dispensing mechanism.
X-Y Platform Figure	Explains the planar motion structure and the nozzle positioning method.
Dimensional Layout Drawing	Specifies printable area, cup placement, and nozzle travel range.
Control Flowchart	Describes the sequence of image processing, motion planning, dispensing, and completion.
Design Parameter Table	Summarizes quantitative targets such as accuracy, repeatability, and response time.
Tolerance Analysis Summary	Explains major sources of error and their expected influence on print quality.

Table 1: Supporting materials used to communicate the technical details of the design.

3 Cost

In order to build the autonomous latte art machine prototype, several mechanical and actuation components need to be purchased. These components mainly support the motion system, the fluid dispensing mechanism, and the structural framework of the machine. The estimated cost list is shown in Table 2.

Item	**Price (RMB)**
Syringe (2 units)	20
Electric Motor (4 units)	600
Structural Steel for Frame and Connections (3D Print Material)	306
Aluminum Rod	50
Development Board	150

Table 2: Estimated component cost for the autonomous latte art machine.

The listed components represent the essential hardware required to construct the prototype system. Additional minor costs such as fasteners, wiring, and electronic control components may be included during the later development stage.

4 Schedule

Week	**Tianheng Wu**	**Yukang Lin**	**Jingyang Cao**	**Yuhao Shen**
2/24	Select components	Research fluid control	Setup software env	Order parts
3/3	CAD design	Design pump	Edge detection	Motor driver
3/10	Build frame	Assemble pump	Contour extraction	Single-axis control
3/17	Mount motors	Flow test	Path generation	Dual-axis control
3/24	Optimize rigidity	Mount pump	UI development	Homing/limits
3/31	Hardware integration	Fluid timing	Software integration	Safety wiring
4/7	Repeatability test	Milk test	Complex images	Reliability test
4/14	Cup positioning	Nozzle adjustment	Safety limits	Software stability
4/21	Motion tuning	Final fluid settings	Image optimization	Final hardware
4/28	Final calibration	Documentation	Presentation materials	Demo setup
5/5	Rehearsal	Rehearse talk	Rehearse software	Backup test
5/12	Final presentation and report			

5 Ethics and Safety

The development of an autonomous latte art machine involves not only technical considerations but also ethical responsibilities and safety requirements. Since the system interacts with users, processes user-provided images, and operates with hot beverages and moving mechanical components, it is important to ensure that the design follows responsible engineering practices.

5.1 Ethics

Ethical considerations in this project mainly relate to responsible system design, user privacy, and proper use of technology. The machine accepts images uploaded by users and converts them into latte art patterns. Therefore, the system should ensure that user data is handled appropriately and not stored or misused without permission.

In addition, the system should be designed to avoid generating inappropriate or offensive images. A basic filtering mechanism or user guidelines may be implemented to prevent misuse of the system. Since this project is inspired by existing technologies such as X–Y plotters and 3D printers, it is also important to respect intellectual property and properly acknowledge relevant prior work.

Another ethical aspect involves transparency and reliability. The machine should clearly communicate its capabilities and limitations, ensuring users understand that the generated latte art may vary depending on system precision and fluid dynamics. Engineers involved in the project must prioritize honesty, responsible design, and user trust throughout development.

5.2 Safety

Safety is a critical aspect of the autonomous latte art machine because the system involves mechanical motion, electrical components, and hot liquids. Several safety measures must be considered during the design and operation of the machine.

First, the motion system, including motors and the X–Y positioning platform, should be enclosed or shielded to prevent accidental contact with moving parts. This reduces the risk of injury during operation.

Second, the system must safely handle hot coffee and heated milk. The container holding the beverage should remain stable, and the dispensing mechanism should operate within a controlled range to avoid spills or splashing.

Third, electrical safety is essential. Proper insulation, secure wiring, and stable power supply should be ensured to prevent short circuits or overheating of components such as motors and controllers.

Finally, the structural frame made from steel connections should be firmly assembled to maintain mechanical stability during operation. A well-designed structure will prevent vibration, misalignment, or unexpected movement of the machine, ensuring safe and reliable performance.

By integrating these ethical and safety considerations into the design process, the project can achieve a responsible and practical engineering solution.