Automatic cake decorator
ECE 445 Senior Design

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Team 47

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1 Introduction

1.1 Problem

The current challenge lies in manual cream decoration on cakes, prompting the need for an automated solution. Traditional methods often result in variations in cream thickness, coverage, and overall quality due to the nature of manual application. This not only demands skilled and creative workers but also leads to increased production costs and the potential for human errors. Moreover, labor costs can be a significant factor in the overall production costs.

1.2 Solution

We decided to make an automatic cake decorator machine, which puts creams with fancy shapes and curves on the top surface of the cake. The automation is not only presented in the "putting cream on the cake" process, but also the design: it could adapt the decoration according to the size and shape of the cake, eliminating the need to design or modify manually. And it provides different styles to choose from according to user preference.

The mechanical structure of the machine resembles that of a cartesian robot, or a 3D printer, which is two perpendicular sliding rails (powered by linear motors) connected to each other, able to move its tips to arbitrary x-y positions. A large syringe with cream inside is mounted at the tip, leaving a trail of cream when pushed by a motor. A sonar may be installed to detect the height of the cake, and another DOF on the z axis of the machine can be added so that the syringe tip can be adjusted up and down automatically to near the surface of the cake. The user connects to and operates the control flow of the machine on a laptop.
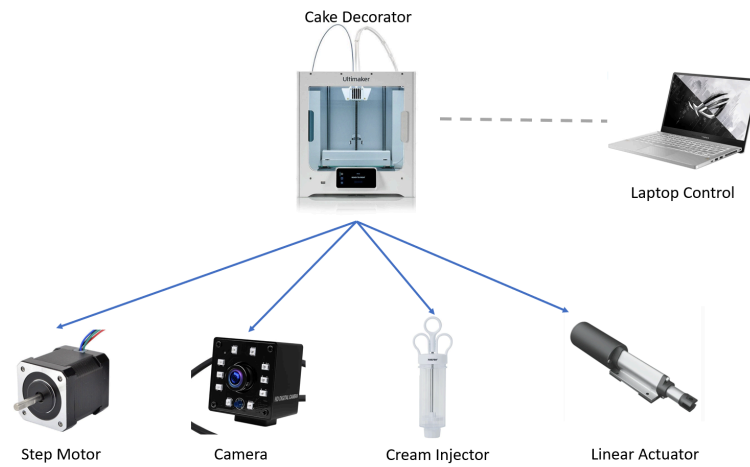
1.3 Visual Aid

Fig. 1 Visual Aid

1.4 High Level Requirements

- Cake shape and edge is detected successfully for more than 90% of the trails, within 10 pixels of range from the edge in the camera view, and not distracted by any other objects, or confused by patterns already presented on the cake.
- In the user program, at least four decoration line shapes or styles for the user to choose from.
- The movement of the motors are accurate enough to navigate the cream injector, with a maximum of 1 cm of deviation from the designed trajectory.
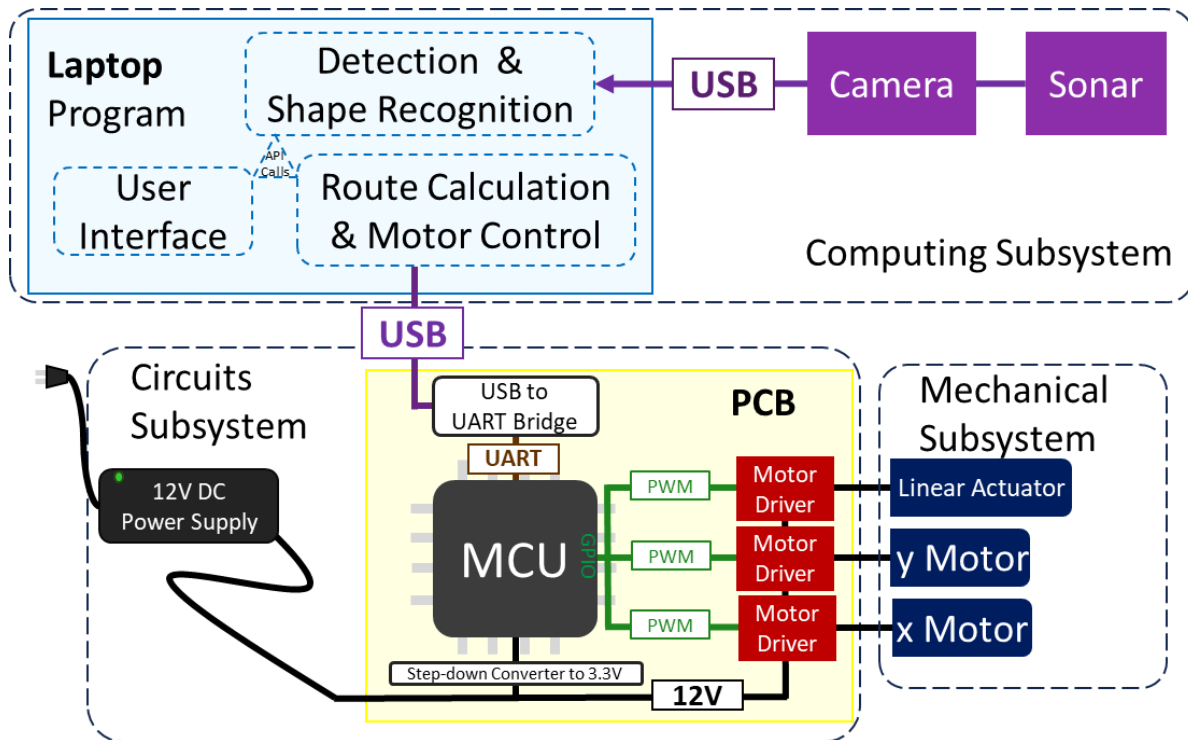
2 Design

2.1 Block Diagram

Fig. 2 Block Diagram

2.2 Block Description

2.2.1 Computing Subsystem
1x Adjustable Metal Stand
1x 1080p USB Camera
1x Laptop

This subsystem includes a HD webcam holded by a metal stand looking down to the top surface of the cake, connected to the laptop via USB. Our program is running in the laptop, and divided into several modules:

1. Computer vision part detect the position, shape and outline of the cake from the camera capture
2. The route calculation and motor control, as the name suggests, decide and give the signals for the motor to move. It's not directly connected to the motors, but to the MCU on the circuit's subsystem via USB. Once a key is pressed, it would send out the calculated target motors speeds calculated as described above to the MCU, allowing it to drive the mechanical parts.

3. The UI module handles the interaction between the modules above and users. It makes the cake detection result transparent to the user, and allows the user to choose the decoration style, or let it re-detect if the result is incorrect. This means the decoration may not necessarily be a simple line along the edge, but some zig-zag curves, with connected and unconnected parts, resulting in some fancy shapes and textures. Then it shows some operation buttons for the start and termination of the motor moving and decoration process.

All these modules will be written in C++, compiled and linked as a single program, so communication between them is standard C++ function call.

2.2.2 Circuit Subsystem

1x ATmega328P MCU
3x A4988 stepper motor driver board
1x self designed PCB with other electrical components
1x 12V DC power supply

The core of this part is the ATmega328P MCU, along with its peripheral soldered on our self-designed MCU: step-down converter for powering it, USB to UART bridge chip handles its communication with laptop, A4988 drivers connecting it with the motor. The control from the laptop to the motor gets through this datapath.

The subsystem also includes a separate 12V DC power supply powering all these electrical components, as well as the motor in the next subsystem.

2.2.3 Mechanical Subsystem

1x Manual height adjustable stand
1x Large cake pan
2x Linear slide rail
3x 42 stepper motor 1.5A 1.8 Degrees
1x linear actuator
1x Metal frames and parts
1x Extra Large Dessert Decorating Syringe Set
1x Rubber hose

The structure of the machine resembles that of a cartesian robot, or a 3D printer, which is two perpendicular sliding rails (powered by motors) connected to each other, able to move its tips to arbitrary x-y positions. A large syringe with cream inside is mounted at the tip, extruding the cream uniformly when pushed by a motor.

2.3 Subsystems Requirements

2.3.1 Computing Subsystem

For the camera, for the system to meet the third high level requirements of 1cm of accuracy, the real-world resolution should be 0.5cm, allowing it to have an error of half a centimeter to the left and right. Say we the camera covers an area area of 2m * 1.125m, the theoretical resolution should be around at least 400*225 pixels. Actual camera digital resolution on the datasheet should definitely be higher, as there are optical resolution limitations and noise.

For our program, it should recognize the edge of the camera with DNN based semantic segmentation algorithms. It could identify the position of the cake, and fit the edge into a set of waypoints for the cream extruder to follow. This is essential for the first high level requirement. The segmentation algorithm should be within the range of 10 pixels and success rate of more than 90%.

Although this subsystem is not connected to the actuators (motors in the mechanical subsystem) directly, the computation done in it is essential for a accurate decoration as the user previewed, and contribute to meet the third high-level requirement of accuracy of 1cm. There are two aspects:
1. Uptill now, the trajectory is calculated with respect to the pixel coordinates, and needs to be mapped into x-y coordinates on the decorating machine. The algorithm should be able to do unprojection from camera view to physical coordinates. It also needs automatic recalibration if the relative position of the camera and the machine is changed, by referring to two marks put at the boundaries of the machine. After the calibration, the mapping should not shift for more than 1 cm.
2. The program calculates the velocity movement of the motors necessary to push out the cream uniformly and move seamlessly along the designed trajectory. The trajectory must be projected onto the x and y axis, representing the positions of motors controlling the two axis. As the speed to move along the trajectory may not be constant, a dummy variable of s would be introduced. The position (expressed as P) is a 2x1 vector, with the two components x and y positions:
$$P = \begin{bmatrix} x(s) \\ y(s) \end{bmatrix}$$
and s is a function of time t *s(t)*. Then the derivative of P wrt t:
$$\frac{dP}{dt} = \frac{dP}{ds} \cdot \frac{ds}{dt} = \begin{bmatrix} \frac{dx}{ds} \\ \frac{dy}{ds} \end{bmatrix} \cdot \frac{ds}{dt}$$
This is the time-varying speed the two motors should target when decorating the cake. Therefore, the sample rate of the route should be at least 60Hz, allowing us to have an accurate calculation of the derivative, that makes sure the speed does not have an error greater than 1 mm/s.

2.3.2 Circuit Subsystem

The ATmega328P operates at a voltage between 2.7V to 5.5V. Its standard bundled step-down converter could easily handle this range, dropping the voltage from 9-15V to 3.3 ± 0.1 V.

The motors are rated at 1A maximum current, which is impossible to drive by the GPIO of the MCU which just has 18mA max current. That's why we need the A4988 motor driver to receive only control signals from the MCU and give power outputs to the motors.
The A4988 motor driver requires two power supplies:
   - One for its logic circuit, requiring a voltage range of 3-5.5V. This can be powered by sharing with the MCU's step-down converter.
   - Another for powering the motor where the current is transmitted through it. This requires a range of 8-35V, which can be drawn from our 12V DC power supply directly.

The total power of the electrical components used is listed as follows:
   - The motors operates at max 12V and 1.2A, resulting in a maximum power of 15W, and there are three of them
   - The elements on the PCB: MCU, motor drivers, and the peripherals including resistors and capacitors are all designed for low-power computing applications by the manufacturer, and would not exceed a total power of 15W.
Therefore, the external DC power supply at least 15W*3 + 15W = 60W, and should supply a stable voltage within the range of 9-12V.

2.3.3 Mechanical Subsystem

Before decorating, the injector should move to the corner of the machine to avoid blocking the camera. Based on the detection of CV, the motor can adjust speed on the x and y axis to make it move along the right track. If the linear motor reaches the bottom of the syringe, it will stop pushing.

According to observation on human decoration on cakes, the speed of moving the syringe is around 0.1 - 1 m/s. If too fast, cream would be thrown away and would not stick to the cream; if too slow, the cream would stack up on the cake causing ugly patterns. So our motor should be able to drive the system within this speed range.

Mechanical systems should be reliable enough. It needs to finish the decoration of the cake in more than 95% of the trials, without errors such as syringe getting stuck in by the cream, or motors and mechanical slides stuck somewhere in the middle.

2.4 Risk Analysis

In our design, we plan to incorporate a camera positioned atop the machine to accurately detect the potion and edges of the cake. However, due to inherent properties of the camera, distortion may occur at its periphery, leading to potential inaccuracies in detection. It is very critical to find the right balance – placing the camera too far from the cake may compromise accuracy, while positioning it too close may amplify distortion effects. To address this challenge, we aim to identify an optimal camera placement that minimizes both sources of error, ensuring precise and reliable detection.

2.5 Risk Tolerance

In our project, we will use a voltage regulator that can convert 12v to 3.3v to guarantee voltage supply is constant and voltage supply can satisfy each different component. For the regulator, we will plan to use LM317 3-Terminal Adjustable Regulator. The LM317 component is a regulator with adjustable positive voltage, capable of delivering over 1.5 A within an output voltage span from 1.25 V to 37 V. To mitigate risks, we prioritize operational stability, demanding the regulator to maintain a steady 3.3V output. It's imperative that the regulator maintains precise voltage accuracy to adhere to component specifications.

$$\text{Vin-Vout} > \text{Vdropout}$$
$$5-3.3 > \text{Vdropout}$$

We use 5 for the input voltage to account for maximum expected ripple. This tells us to choose a dropout voltage less than 1.7 V.

If too much power is dissipated inside the regulator, it will overheat. In this case, we must determine the power dissipated in the device, P_D.

$$P_D = i_{out} * V_{ce}$$
$$P_D = i_{out} * (V_{in} - V_{out})$$

According to the parameters given by the device and the Vin and Vout we want to achieve, we can calculate the junction temperature, T_j. If the junction temperature exceeds the maximum T_j, there will be thermal problems in the circuit.

$$T_j = i_{out} * (v_{in} - v_{out}) * (\theta_{jc} + \theta_{ca}) + T_a$$

3. Safety and Ethics

3.1 Food sanitation safety concerns

According to IEEE Code of Ethics I.1 *[3]*, The health of the users is essential. Our product is designed to deal with food, creating potential hazards for food safety, and we are well aware of that. In the machine, the syringe holding the cream and the food tray holding the cake are components that have direct contact with the food. They are parts bought by us instead of made by us, which are manufactured for food use, adhere to FDA regulations for Packaging & Food Contact Substances (FCS). *[4]* Other mechanical parts such as the sliding rails, and motors, though no physical contact with our food, can potentially put dust on the cake. So we make sure to clean them with food level wipes to make sure they are clean and won't pollute the cake.

3.2 Ethical considerations for food waste

The best way to set-up, test and showcase the functionality of our machine to simulate real-life circumstances is to use real ingredients: cream and cake. So some food will inevitably be wasted. We should reduce the amount as much as possible this includes:
- Except for the final demonstration, we will be replacing real cake with fake ones made from cupboards. And we will try to give the cake to everyone after the demonstration.
- In the experiment, since we are not eating them, we would try to recycle the cream by getting them off from the fake cake and put back into the syringe. And we might be able to find some out-of-date cake for the experiments.

4. References

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