VM4670J Latte Art Processor

Team Members:

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Introduction/Related Work/Problem Definition

We want to design a program for latte art process to reduce the workload and stress on café employees.

Currently, most latte art techniques still rely on manual execution, which can be an exhausting task for employees in high-volume coffee shops. Taking our school's Manner café as an example, a single employee may need to create latte art for nearly 100 cups of coffee a day. If these tasks could be handled by robotic arms, it would significantly improve working efficiency.

Modeling the physical process of coffee latte art can be complex, involving complex calculations of fluid mechanics and real-time feedback that may require computer vision assistance. At the same time, in the simulation, the rendering of the liquid surface and the disturbance of the cup when it is moved also require precise design.

https://experthubrobotics.com/robots/robotic-cafe/coffee-robot-with-latte-art

This link is a complete coffee robot, which is a product that is already in commercial use. This gives us a big idea about how to start from scratch.

https://blog.csdn.net/liuyunduo/article/details/84098884

This article is about how to modify fluids by huge amount of particles.

Method/Algorithm

There are mainly three parts for the implementation of our latte art processor. They are recognition part, placement part and latte art part.

Recognition:

The Sobel algorithm is a widely used edge detection technique in image processing and computer vision. It helps to identify the boundaries of objects within an image by emphasizing regions of high spatial frequency, which correspond to edges.The Sobel operator computes the gradient of the image intensity function. It uses two 3x3 convolution kernels, one for detecting horizontal edges and one for detecting vertical edges.

After applying the kernels, the gradient magnitude and direction can be calculated using:

$$\text{Magnitude: } G = \sqrt{Gx^2 + Gy^2}$$

$$\text{Direction: } \theta = \arctan(\frac{G_y}{G_x})$$

The effectiveness of Sobel edge detection for coffee cup identification stems from the distinct intensity transitions that typically occur at cup boundaries. When you have a coffee cup on a surface, there's usually a sharp contrast between the cup's edges and the background, creating strong gradients that Sobel easily detects. The algorithm combines the horizontal and vertical gradients using the mathematical principle of gradient magnitude - essentially calculating the strength of the edge regardless of its direction. This makes it particularly good at finding the complete outline of circular objects like coffee cups, where edges occur in multiple directions.

Placement:

After recognizing the cup edge, we can model it as a circle or a square, then we calculate the direction vector from the arm's endpoint to the shape's center and moves the endpoint of the arm to the shape in that direction by a defined speed. The movement is controlled by the sign of the direction vector.

The simulation begins by randomly generating either a circle or square shape at a random position, then creates a valid placement region around a fixed point. During each iteration, the algorithm calculates the direction vector from the arm endpoint to the shape's center and moves both the arm and the shape along this vector at a constant speed. The simulation continues until either the shape reaches the valid placement region or the maximum number of iterations is reached.

Latte Art:

The SPH (Smoothed Particle Hydrodynamics) algorithm is a computational method used for simulating fluid dynamics. For the study of fluids, there are two completely different perspectives, namely Euler perspective and Lagrange perspective. The coordinate system of the Euler perspective is fixed, just like observing the flow of the river from the side of a river. The analysis of the fluid from this perspective requires the establishment of grid units, while the Lagrange perspective regards the fluid as the flow unit.SPH algorithm is a typical Lagrangian perspective, its basic principle is to simulate the motion law of fluid through particles, and then convert it into a grid for fluid rendering. SPH represents fluids using discrete particles that move through space, each carrying properties like mass and velocity.

The simulation consists of three main components: particle initialization in the detected cup region, SPH dynamics simulation for realistic fluid behavior, and visualization of the milk flow. Each particle carries properties including position, velocity, density, and intensity, which are updated based on the Wendland smoothing kernel function. The milk pouring process follows a sinusoidal path with added randomness for natural appearance, while particle interactions create realistic fluid spreading effects through density computations and velocity updates. The visualization combines these elements with Gaussian smoothing to create smooth, continuous animations of the latte art formation. The entire process is designed to mimic the physical behavior of milk being poured into coffee, creating artistic patterns through fluid dynamics simulation.

As for the edge detection part, we choose to use Sobel algorithm. While Sobel works well for basic edge detection, it can be sensitive to noise and might detect unwanted edges from shadows or reflections on the cup's surface. For a robust latte art system, we might need to consider preprocessing the image with techniques like Gaussian smoothing to reduce noise, or post-processing steps to focus specifically on the edges that define the cup's rim and the coffee surface. The key advantage of Sobel for coffee-cup application is its computational efficiency and ability to provide clear edge information that can help guide the robot's understanding of where to create the latte art patterns.

The Shape Pushing Simulation focuses on robotic manipulation, implementing a straightforward pushing strategy with simplified physics. Its strength lies in its clear goal-directed approach, where the mechanical arm follows a direct path to push objects toward a target. The algorithm uses basic vector calculations for movement and doesn't account for complex physical interactions. While this simplicity makes it computationally efficient and easy to implement, it might not accurately represent real-world physics where factors like friction, object rotation, and momentum would play important roles.

The Latte Art Simulation, on the other hand, takes a more sophisticated approach using Smoothed Particle Hydrodynamics (SPH) to model fluid dynamics. This algorithm shows greater complexity in its physics simulation, accounting for particle density, fluid spread, and interactions between particles. The use of the Wendland kernel function for density calculations and the incorporation of Gaussian smoothing creates more realistic fluid behavior. However, this increased realism comes at the cost of higher computational complexity, requiring calculations for thousands of particles and their interactions.

Implementation and Experimental Results

https://github.com/BBuf/Image-processing-algorithm-Speed

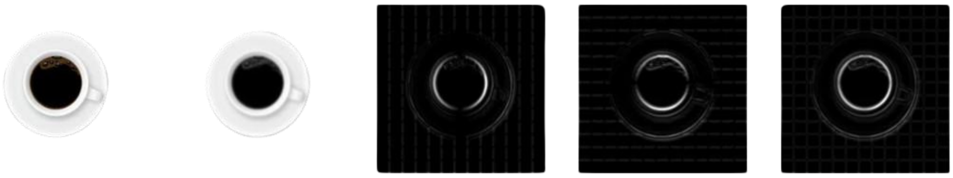
This repository contains different strategies for image processing algorithm which is useful for the design for our latte art processor. We refer to the example code for Sobel algorithm here. We mainly refer to the mathematical ideas of sobel algorithm and write targeted functions according to the actual needs of our project.

https://github.com/leonardo-montes/Unity-ECS-Job-System-SPH

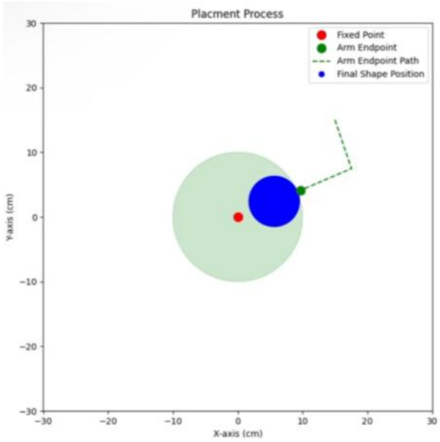
This repository contains code examples of SPH algorithm, which is commonly used to modifying motion of fluids. We mainly refer to the mathematical idea of SPH algorithm and python implementation, combined with the physical process of coffee latte we need to make appropriate modifications.

As for the placement part, it’s totally original, based on modeling of physical processes. While there have been commercial attempts at coffee latte robots, there is no published literature on design algorithms, so for us it was a self-made endeavor. From the analysis of the physical process, the selection of the appropriate algorithm implementation is basically based on our analysis of the demand and the effect of the trade-off.

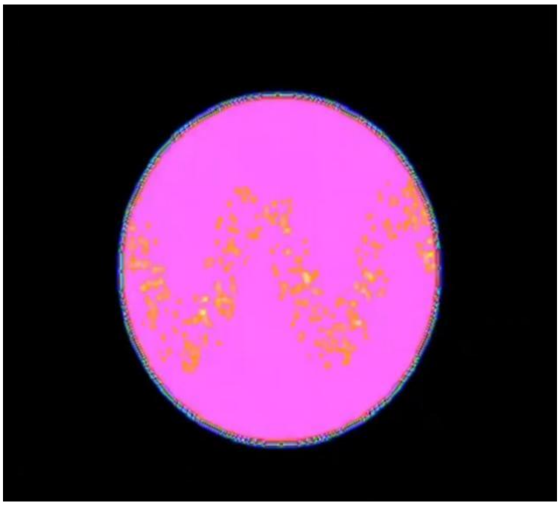
None of the materials we refer to are used directly in our project, as they are only used to show how the mathematical methods we refer to should be translated into code.



This is a picture of the recognition of coffee cups that we achieved using the sobel algorithm. As you can see, when the dark coffee and the light cup provide enough contrast, our algorithm can identify the coffee cup mouth very well and determine the object of the subsequent operation.



After obtaining the cup shape, our program will equate it to a circle, as shown in the blue circle in the image. The green point represents the end of the mechanical arm. By calculating and calibrating the displacement vector in the center of the target area (red point), the end of the mechanical arm is controlled to push the cup to the working area of the drawing machine, as shown in the green valid region.



In the process of latte art, we used SPH algorithm to simulate the situation of coffee liquid level after adding milk, and the diffusion effect of milk can be seen in the figure. This is a simple simulation of the drawing process. Because the physical process of coffee and milk diffusion is more complex in the actual process of latte art, we do not have the ability to fully understand the physical relationship in a limited time.

The proposed latte art processor has several limitations and drawbacks that can impact its overall effectiveness. First, in the recognition phase, the Sobel edge detection algorithm is sensitive to lighting conditions. Variations in light can create shadows or reflections on the coffee cup, leading to false edges and misidentification. Additionally, in cluttered environments, the algorithm may mistakenly detect edges from surrounding objects, further complicating the accurate recognition of the cup. The approach of approximating the cup's shape as a circle or square can also fall short, particularly for uniquely designed cups or those with handles, which may affect the precision of the placement process.

In the placement phase, the dynamic movement of the arm is constrained by a fixed speed and direction. This rigidity may not accommodate real-time adjustments necessary for navigating around obstacles or adapting to slight movements of the cup. Furthermore, the defined placement region may not be flexible enough to accommodate different cup sizes or positions, potentially resulting in inaccuracies when positioning the latte art.

When it comes to the latte art generation using the Smoothed Particle Hydrodynamics (SPH) algorithm, computational complexity poses a significant challenge. The SPH method can be resource-intensive, especially when simulating a high number of particles, which may lead to performance issues on less powerful hardware. This can manifest as lag or reduced frame rates in real-time applications. While introducing randomness to the fluid simulation can enhance realism, it may also yield unpredictable patterns that do not align with user expectations for specific latte art designs. Moreover, the simplifications employed in the SPH model might not fully capture the complexities of fluid dynamics, resulting in less realistic simulations under certain conditions.

To quantify these limitations, we could conduct experiments to evaluate recognition accuracy and performance metrics. For instance, recognition accuracy might vary significantly under different lighting conditions, with ideal lighting yielding around 95% accuracy, while dim lighting drops to about 70%, and cluttered backgrounds may result in only 60% accuracy. Performance metrics could demonstrate that as the number of particles in the simulation increases, the time taken for the simulation rises sharply, with 100 particles requiring approximately 20 milliseconds, while 1000 particles could take around 400 milliseconds.

Summary and Relevance

In this project,we have realized basic functions for the latte art processor to work properly, based on the knowledge we learn from dynamics, kinematics, path planning and the sensor part from this course. We were not able to apply our programming to an actual robot to test the effect, but I think we have demonstrated the potential of this coffee latte robot at the code level.

As for future expectations, I think we may be able to adopt more advanced detection methods than sobel algorithm when image recognition is carried out. sobel algorithm is highly sensitive to the noise in the image, and it may be difficult to deal with some blurred cases where the edge and background color are close.

In the design of using the end of the mechanical arm to push the object, we currently adopt a relatively simple physical process modeling, only need to consider the displacement and velocity vectors, but in actual motion, the round cup may rotate with the push of the mechanical arm, which brings trouble. We do not currently consider this occurrence due to time constraints, but if it is possible perhaps A learning model using A* algorithm or with the help of diffusion strategies can self-correct behavior even when perturbations occur.

For the simulation of the drawing process, it is obvious that only a very simple simulation can be carried out at present, but it is also very time-consuming because of the addition of SPH algorithm. Perhaps this part can be done in the future by other, more lightweight and aesthetically pleasing methods.