2025 IEEE/SICE International Symposium on System Integration (SII)
January 21-24, 2025, Munich, Germany

Robotic Cooking: Adaptive and Precise Cutting System Based on Food Outer Shape and Internal Flexibility

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Abstract— **The universal task of cutting requires the extensive use of knives and other cutting tools in our daily lives. When cutting soft and hard objects such as meat, fish, and fruit, humans can perform efficient cuts without causing damage by adapting their movements to the characteristics of the food. The effective manipulation of a knife by a robot is imperative for automating such tasks. This research aims to develop a cutting motion system capable of handling various food materials and automating cooking operations in restaurants and food manufacturing plants by studying human sensory knife manipulation and its impact on the reaction force while cutting food materials. In order to automate the cooking process for various types of food ingredients, it is necessary to recognize the shape of the targets and determine the position and angle of the knife accordingly. In this study, we developed a method that takes into account the shape and flexibility of the food to minimize deformation during cutting. By measuring the reaction forces encountered when cutting various food materials, we devised a pull cut motion system capable of generating trajectories suited to the specific shape of the food material. This paper describes the cutting system and the results of a demonstration experiment.**

I. INTRODUCTION

Automation of the cooking process is necessary to improve work efficiency in everyday life and in restaurants. The cooking process involves multiple technologies, such as manipulation and processing of ingredients, and pouring and transporting of seasonings and beverages [1], [2]. Appropriate task planning is necessary to efficiently automate these processes [3]. Furthermore, planning includes a variety of cooking conditions and processes, making it more complex depending on the task.

In the cutting process, when cutting soft foods such as meat, fish, and fruit, the quality of the product will be reduced if the reaction forces and shape changes from the food material are not carefully handled [4], [5]. Robots are required to generate motion that adapt to the widely different properties of each food material. Humans perform these motions with skills learned from everyday experience, and the quality of cooking depends greatly on the time and experience spent cultivating the skills. For automation by robots, it is necessary to design a knife motion control system that takes into account the characteristics of food ingredients. Design of knife motion includes learning-based motion planning through simulation [6] and research focusing on the effect of the blade angle on the food material [7]. Appropriate design of knife motion enables cutting without damaging the food. For those dealing with physical parameters, there are methods to suppress deformation mainly by using force control [8]-[10]. By incorporating the reaction force from the food into the motion design, it is possible to realize human sensory work and improve the quality of cooking.

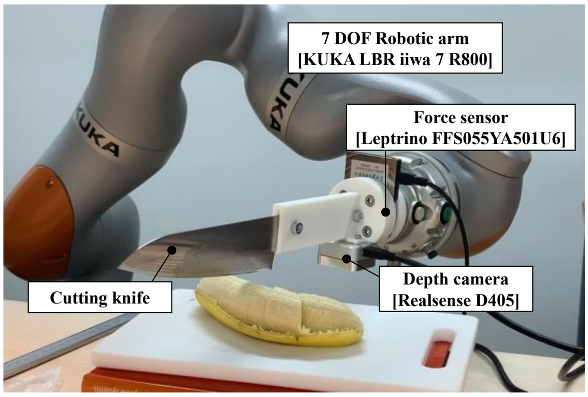

Figure 1. Robotic cutting system.

However, most previous methods analyze and design the cutting motion and perform motion planning under the assumption that the position and shape of the target food material are known. In order to automate the cooking process in the restaurant and food manufacturing industries, where various types of ingredients are handled, it is necessary to integrate different methods such as ingredient shape recognition and cutting motion planning. In this study, we propose a knife operation method based on the shape of food ingredients and develop a cutting motion system that takes shape changes into account by controlling the reaction force during cutting, aiming to achieve integrated automation of the cooking process. We propose a method for appropriately cutting irregularly shaped food materials and achieving automation with a wider range of applicability than before.

II. OVERVIEW OF ROBOTIC CUTTING SYSTEM

The robotic cutting system is illustrated in Fig. 1. A depth camera (Intel Realsense D405) and a 6-axis force sensor (Leptrino FFS055YA501U6) are mounted on the tip of a 7-axis robot arm (KUKA LBR iiwa 7 R800). The depth camera recognizes the shape of the food and determines the starting position for cutting. The force sensor measures the processing reaction force at the contact point of the knife and generates cutting motions in real time in response to this force. Due to the robot arm's redundant degrees of freedom, multiple arm postures can be adopted for a specific knife position and orientation. Thus, even in a confined environment with many

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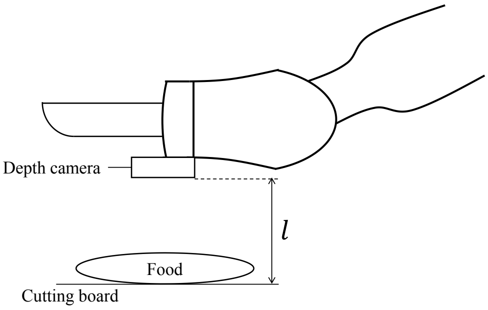
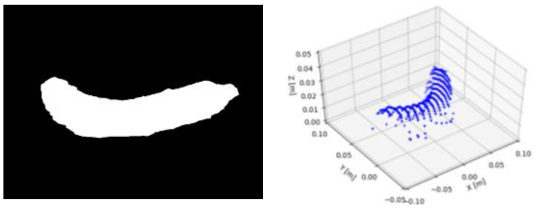


Figure 2. Food detection strategy.



(a) Binarized image (b) Measured shape

Figure 3. Detected shape by depth camera.

objects, such as a kitchen, the desired cooking motion can be achieved.

The system communicates through ROS (Robot Operating System). The force sensors acquire data at 1.2 kHz, and the robot arm sends control commands from ROS to KUKA's proprietary software, Sunrise Workbench, at 100 Hz. The aim of this study is to propose a method for knife operation in cutting, and the priority for fast cutting, which requires high responsiveness, is not high. Therefore, control is performed at 100Hz, which is a sufficient control rate for the cutting time.

III. CUTTING APPROACH

A depth camera is used to measure the object to perform a cutting operation according to the shape of the food. The slicing method is used in this study because it requires determining the cutting position based on the shape of the food. Based on the measurement results, the position and orientation of the knife for cutting are determined. To cut unknown shapes, which is the objective of this research, food materials with irregular shapes, varying sizes, curvatures, and a wide range of hardness are targeted. Bananas with different curvatures are sliced evenly without being mashed. Only the pulp is sliced, and the effect of the peel's hardness is not considered.

A. *Shape Measurement*

The methods for estimating the shape of food material using 2D images can obtain the curvature and thickness of cucumbers [11], [12]. In this research, position coordinates are required to design the knife's motion. Therefore, a depth camera is used to recognize the shape of the food. Since the position of the cutting board is known and the depth camera is attached to the tip of the arm, the positional relationship between the camera and the cutting board can always be calculated if the arm's posture is known. As shown in Fig. 2, the camera is moved directly above the cutting board to measure the position and shape of the food. When the distance from the camera to the cutting board is l, the entire image of the food can be obtained by binarizing the depth image using l as the threshold value. Fig. 3(a) shows the binarized images acquired by the RGB camera and the depth camera, demonstrating that the binarized image recognizes only the banana on the cutting board. By acquiring the distance information from the area of the food in the binarized image, the approximate shape of the food can be obtained, as shown in Fig. 3(b). Since the depth camera measures from above the cutting board, only the upper half of the banana's shape is captured.

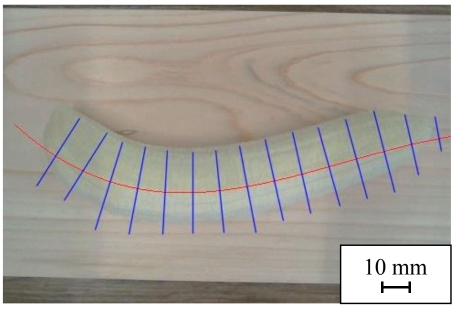


Figure 4. Cutting surface. Red line represents the centerline of the food, blue lines represent the cutting surface.

B. *Cutting Surface Detection*

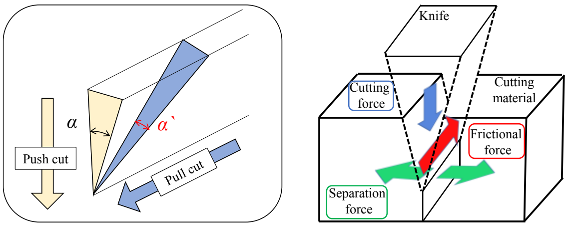
To determine the cutting plane, the centerline is calculated from the binarized image of the food. Curve fitting using the least-squares method is performed on the detected food area. This allows the centerline to be calculated even for bananas with individual differences in curvature. In the curve obtained by the least-squares method, a perpendicular intersecting line with a certain width is determined. This line represents the cutting plane for slicing bananas with individual differences into slices of equal width. Figure 4 shows the results of curve fitting and the determination of the cutting plane for the detection area shown in Fig. 3(a). The red line represents the centerline, and the blue line represents the cutting plane.

IV. MOTION AND FORCE CONTROL FOR FLEXIBLE FOOD

Cutting soft foods with minimal deformation is essential for improving quality. To achieve this, we propose a pull cutting motion that reduces the force required for cutting. We also propose a method to prevent food deformation by continuously measuring the reaction force and controlling it so that it does not exceed a threshold. In this study, cutting food thinly is defined as “slice cut”, and cutting while pulling the knife is defined as “pull cut”.

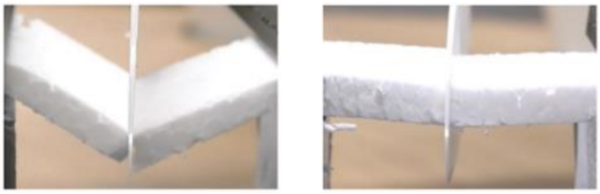
A. *Effect of Slice-cut*

Previous research by our group has clarified the mechanism of the pull cut motion [13], [14]. As shown in Fig. 5 (a), the cutting edge angle changes from α to an apparent α' as the knife descends in a pulling motion. The stress state during this process is shown in Fig. 5 (b). There is compressive stress caused by the pressing of the cutting edge and frictional stress caused by the pulling motion. When this frictional stress exceeds the tensile strength, the material separates. In other words, while the pushing action applies stress across the entire



(a) Pull cut mechanism. (b) Cutting principal.

Figure 5. Pull cut principal.



(a) Push Cut. (b) Pull Cut.

Figure 6. State of breakage after cutting styrofoam.

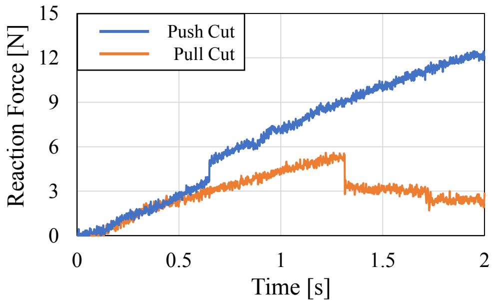


Figure 7. Reaction force comparing push cut and pull cut.

material, the pulling action concentrates stress at the cutting edge. To verify the effect of the pulling motion, a comparison of cutting methods using styrofoam foam was performed. Figure 6 (a) shows the behavior of styrofoam foam during cutting with only a pushing motion. Figure 6 (b) shows the behavior when a pulling motion is applied, demonstrating that the cut surface is smoother. Figure 7 shows the reaction force. The maximum reaction force when cutting with a pulling motion is one-third of that with a pushing motion alone. This result indicates that the pulling motion can cut with a smaller force and is suitable for reducing deformation of the food material.

B. Motion Control for Flexible Food

Flexible food materials can deform due to stress during cutting. The pulling motion reduces the vertical reaction force against the knife, thereby minimizing the deformation of the object. However, when cutting circular or irregularly shaped food materials, such as the banana used in this research, the frictional force generated by the pulling motion can cause the food material to move and rotate. In the past, some machines have fixed the food material or flattened the cutting board surface to prevent movement, but for automating the cooking process, it is desirable to cut the food material in its unprocessed state. Therefore, the initial cutting angle of the knife is determined based on the measured shape. If the cutting surface is circular and the knife is horizontal, the food material may rotate due to the frictional force generated by the pulling motion.

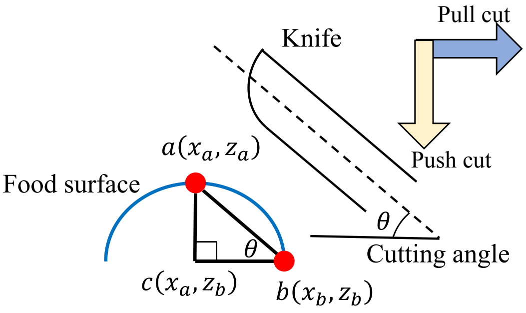


Figure 8. Cutting angle determined by measured shape.

If the cutting surface is circular and the knife is horizontal, the food material may rotate due to the frictional force generated by the pulling motion. Therefore, the cutting process begins with the knife tilted and is controlled to become horizontal by the end. Figure 8 illustrates the method used to determine the cutting angle. The two vertices of the cutting plane are determined from the measured shape of the food and the calculated centerline, assuming a right triangle in the plane. The angle θ at the vertex of this triangle represents the knife angle. This angle is calculated using the following equation.

$$\theta = \tan^{-1}\frac{|z_a - z_b|}{|x_a - x_b|} \tag{1}$$

The direction of the force can be decomposed into the force generated by the pushing motion and the frictional force generated by the pulling motion. However, accurately determining the frictional force is challenging because it depends on the velocity ratio between the pushing and pulling motions (push-pull ratio $\gamma = \frac{v_{pull}}{v_{push}}$) and the characteristics of the food material, such as viscosity. In this study, the push-pull ratio is set to 1.0, and the initial angle of the knife is adjusted so that the direction of the force is near the contact point between the banana and the cutting board.

C. Cutting Force Control

To enhance cooking quality, the cutting reaction force is controlled to prevent deformation of the food. The pulling motion reduces the reaction force required for the pushing motion, enabling processing without compressing the object. However, as shown in Fig. 7, even with the pulling motion, the reaction force increases with the amount of pushing. Therefore, the push force is controlled by setting a target reaction force during machining and adjusting the movement speed based on the measured reaction force.

To regulate speed based on the reaction force during cutting, a cutting force control system utilizing PID control is implemented. Using PID control, the system not only ensures that the reaction force does not exceed the target value but also brings the initial reaction force closer to the target for efficient cutting. Fig. 9 shows an overview of the system. A force sensor attached to the end-effector measures the reaction force in real-time and determines the feed speed. The speed refers to the

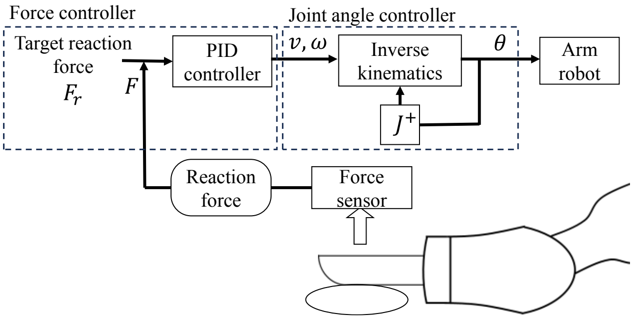


Figure 9. PID control system diagram to reaction force.

velocity of the end-effector, but the cutting motion also includes the knife's rotation. Since the robot arm is controlled using joint angles as command values, the hand tip's translation and rotation are converted into joint-specific changes, as shown in Fig. 9. The control cycle is set to 100 Hz, and inverse kinematics calculations are processed in parallel with feed rate calculations because each calculation loop must be completed within 10 ms. This approach enables real-time control of the cutting force. Because mathematically modeling the reaction force response is challenging, the PID parameters and target reaction force are determined through trial and error in this study.

V. CUTTING EXPERIMENTS

To verify the effectiveness of the proposed method, cutting experiments were conducted on bananas. The target cutting reaction force F_r was set to 1.0 N, and a randomly selected banana (unknown shape) was cut. In this study, experiments are conducted on bananas without peels. Experiments are conducted under conditions of varying hardness and shape to discuss the validity and robustness of the method. The conditions are as follows: A: normal banana; B: unripe (still green) banana; and C: ripe banana. To evaluate the performance of cutting force feedback control, we compare "push cut" which involves moving the knife vertically, with the proposed method of "pull cut". Both push cut and pull cut are applied to the same banana to avoid errors due to individual differences.

Finally, in Section D, the results under each condition are compared, and the accuracy of the proposed method for ingredients with different hardness and shapes is discussed.

A. *Normal Banana*

Figure 10, 11 show the cutting experiment and state of the banana after cutting. Table 1 shows the thickness of each slice, with both end slices excluded. Figure 11 and Table 1 show that all slices are approximately 10 mm thick, indicating uniform spacing. This indicates that the recognition of the unknown shape and the determination of the cutting plane were accurate. Figure 12 shows the reaction force response. By using cutting force feedback control, the reaction force followed the target value F_r, and cutting was performed with about half the force compared to push cut. In both cutting methods, there is a point where the reaction force temporarily decreases and then increases. This can be attributed to the center part of the cutting surface becoming softer, resulting in a momentary reduction in the force required for cutting as the knife passes through the center.

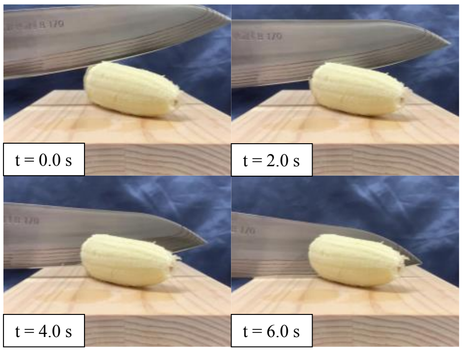


Figure 10. Cutting experiment.

Figure 11. State of banana after cutting.

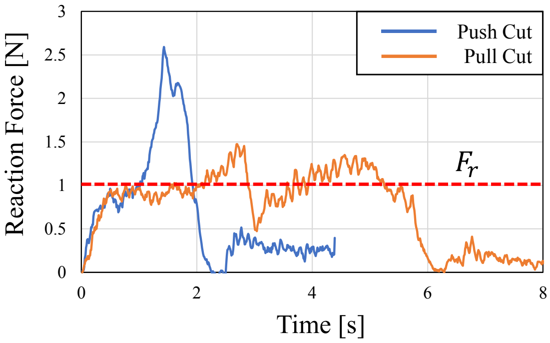


Figure 12. Reaction force of normal banana.

TABLE I. THICKNESS OF SLICES OF NORMAL BANANA

Thickness [mm]			
Avg.	Max.	Min.	SD
9.6	11.7	8.9	0.8

B. *Unripe Banana*

Figure 13 shows the reaction force response when cutting an unripe banana. Since it is unripe, condition B is harder compared to condition A, and the reaction force of the push cut is higher. However, the proposed method is able to maintain the cutting force near the target value, indicating that feedback control is being appropriately executed. Additionally, the temporary decrease of the reaction force response observed in Figure 12 is not present in Figure 13, suggesting that there was not much change in the internal hardness. Table 2 shows the thickness of each slice. Similar to Table 1, the thickness is on

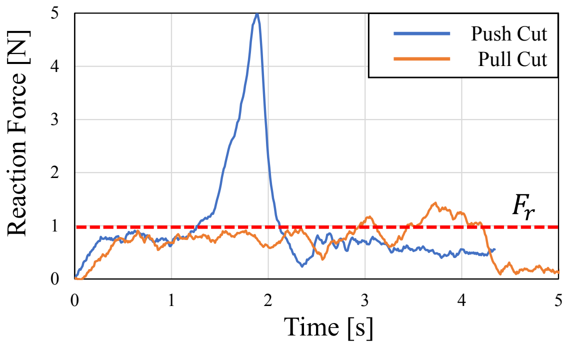


Figure 13. Reaction force of unripe banana.

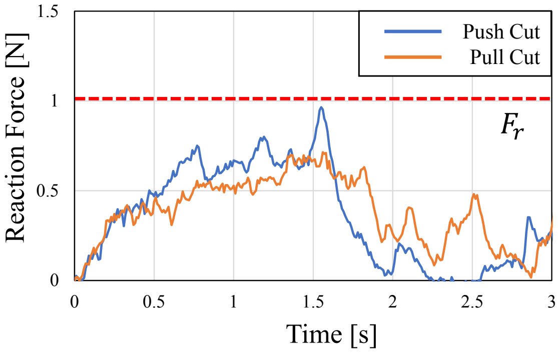


Figure 14. Reaction force of ripe banana.

TABLE II. THICKNESS OF SLICES OF UNRIPE BANANA

Thickness [mm]			
Avg.	Max.	Min.	SD
10.3	19.9	9.1	2.5

TABLE III. THICKNESS OF SLICES OF RIPE BANANA

Thickness [mm]			
Avg.	Max.	Min.	SD
10.4	12.5	9.0	1.2

average close to 10 mm, but the maximum value and SD (standard deviation) are larger. This accuracy will be discussed in Section D.

C. Ripe Banana

Figure 14 shows the reaction force response when cutting a ripe banana. Under this condition, the banana is soft, so even in the case of push and pull cut, the maximum reaction force is less than 1.0 N. Therefore, the reaction force response was almost unchanged compared to when using the proposed method. To achieve cutting that suppresses the deformation of the ingredient, it is necessary to determine the target cutting reaction force considering the state of the target, even for the same ingredient. Table 3 shows the thickness of each slice. As with other conditions, each piece is approximately 10 mm thick, indicating that the slices are evenly spaced.

D. Validity and Robustness

Figure 15 presents a comparison of the cutting surfaces under various conditions. It indicates that there is almost no difference in shape between push cuts and pull cuts, suggesting that no deformation occurred. The experimental results show that the force required to cut a banana depends on its hardness, but harder bananas do not deform, resulting in minimal deformation in this study. This suggests that the proposed method is effective for foods requiring significant cutting force but are soft and easily deformable internally. Examples include fruits with hard peels and meats or fish with high viscoelasticity that are difficult to cut. As observed in conditions B and C, the proposed method's effectiveness improves by appropriately determining the target cutting reaction force based on the food's condition.

Tables 1-3 show that most pieces are approximately 10 mm thick, indicating that the proposed method adapts well to shapes and demonstrates high robustness. In this study, curve fitting was performed on bananas, but with appropriately selected models adapted to the food, high-accuracy detection is achievable even for entirely different shapes.

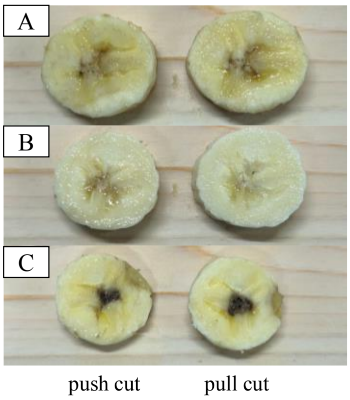


Figure 15. Comparison of cutting surface. In each condition, the left is push cut, the right is pull cut.

VI. CONCLUSION

In this study, we proposed a method to automate the cooking process by generating cutting motions based on the shape of the food while minimizing shape deformation. The method mathematically demonstrated skills acquired by humans through experience, enabling a high-quality cooking process. By combining force control with a pull cut motion, cutting was performed with minimal force, indicating the capability for food materials of various hardness. Our findings demonstrated that knife motion influences the shape deformation of the food material, highlighting the importance of considering the material's shape when generating cutting motions. However, this study primarily focused on the shape of the food material, and it is considered that incorporating additional characteristics such as viscosity and elasticity could lead to the development of more optimal motions. Moreover, since the hardness of food materials can vary depending on temperature and freshness during cooking, future research may need to consider factors beyond just shape.

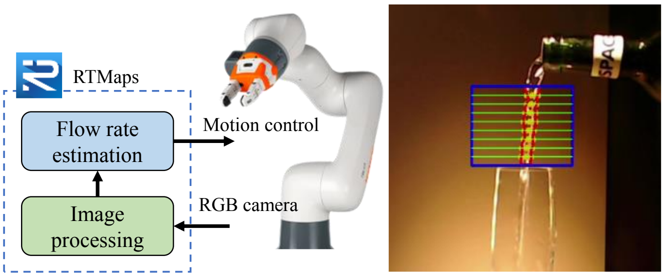
Lastly, while this study primarily focused on the cutting process, automating the cooking process requires integrating automation systems into other cooking and food-serving processes as well. By exploring methods of acquiring and utilizing information about food materials, we plan to extend our approach to optimize these additional processes. In the next section, we present a developed application that illustrates the potential advancements facilitated by this research.

VII. NEAR FUTURE WORKS

The final goal of this research is to fully automate the cooking process. We developed an application to measure the flow rate of pouring liquids, aiming to integrate fundamental technologies for automation. The pouring operation manages condiments and drinks, both crucial factors in food quality. Thus, accurate liquid dispensing is necessary for automation. Consequently, beyond the cutting methods proposed in this study, integrating key technologies such as servo control of the robot arm and process control of the pouring operation is essential for a robotic kitchen. Fig. 16 shows the concept of a robotic kitchen. A robot arm transfers wine glass and another robot pours water. Automating the preparation and providing achieves human operator less cooking system.

However, installing sensors on all the various liquid containers and cooking utensils in a kitchen is challenging. In this study, a non-contact flow measurement method [15] is employed to estimate the flow rate. The flow rate is estimated based on the width and velocity of the falling liquid, as measured by a camera. The estimated flow rate serves as feedback to control the pouring motion, ensuring high-quality cooking.

Figure 16. Concept of robotic kitchen.



(a) Flow rate control system. (b) Flow rate measurement.

Figure 17. Flow rate control application.

This method requires real-time flow measurement, making efficient image processing and flow estimation highly desirable. In this study, real-time measurement is achieved using RTMaps software developed by Intempora, which enables parallel operations. The pouring motion is controlled by a 6-axis robot arm, KUKA LBR iisy 3 R760, based on the measured flow rate. Flow rate control system and the measurement process are shown in Fig. 17.

ACKNOWLEDGMENT

We would like to thank Leptrino Co., Ltd. and YMG Company, Limited for providing the necessary resources for this study.

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