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Trajectory Planning for Meal Assist Robot Considering Spilling Avoidance

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Abstract— **In the near future, there will be a significant problem obtaining workers in the fields of welfare and nursing care because of a labor shortage. To solve this problem, many welfare robots, such as an upper extremity motion assistance robot and a meal assistance robot, have been studied. The purpose of this paper is to avoid spilling of the liquid when the spoon is transferred. In order to avoid spilling of the liquid, a spilling model was evaluated by using a CFD simulator. Thus, it was not necessary to build an exact model of the spilling model mechanism. The effectiveness of the proposed control is shown by CFD simulations and experiments.**

I. INTRODUCTION

The problem of a labor shortage caused by a lower birth rate will occur in the near future in many countries. In the service sector or welfare and nursing care fields, this labor shortage will be a major problem. In order to solve these problems, increases in the practical application of robotic and control technology have been seen in the medical and the welfare fields. Robots have been studied which are designed to assist disabled and elderly persons who require support in the upper extremities or hands and arms during mealtimes because caregivers become very busy for meal assist [1][2][3].

To satisfy this need, the meal assistance robots HANDY-1 [4], NeaterEater, WinsfordFeeder, and My Spoon [5] have been developed and put to practical use in the past studies. It has been shown that an assistance robot not only reduces the caregiver's burden but also allows the disabled person a degree of independence and satisfaction in being able to do perform a basic function for one's self.

However, many problems remain regarding the practical application of meal assistance robots. Liquid transfer control is a challenge in robot design for meal assistance robots. Persons usually drink soup or beverages at meals, but meal assistance robots with liquid transfer control have not yet been developed. Spilling can occur during carrying itself, burning patients and causing more labor to be required in the form of cleaning. Patients who have difficulty swallowing or weak sucking ability require a liquid diet, and there is thus a strong need for the development of a meal assist robot that can avoid spilling.

Liquid container transfer systems have been developed to replace pipelines in the chemical and food industries. In practical industries such as these, it is essential to avoid spilling caused by sloshing. Therefore, many studies have been published which analyze sloshing in a container or container transfer with sloshing suppression[6][7][8]. However, when the container is full of water, or a spoon is used as the container, sloshing-suppression control by itself cannot prevent the spilling of the liquid.

The purpose of this study, therefore, was to design a transfer control system for meal assist robots that incorporates spilling avoidance. In order to avoid spilling of the liquid, a spilling model was analyzed by using a CFD(Computational Fluid Dynamics) simulator. Thus, it was not necessary to build an exact model of the spilling model mechanism. The effectiveness of the proposed control is shown by CFD simulation and an experiment.

Fig. 1. Experimental Apparatus

II. EXPERIMENTAL APPARATUS

Fig.1 shows the robot transferring the spoon. The specifications of the manipulator are shown in Table I. A manipulator with six degrees of freedom was used. In this study, a general industrial robot was used to evaluate our proposed method. However, new meal assist robot which can work in actual hospitals is also currently being designed in our group. A spoon was fixed to the manipulator's end-effector, where the size of the spoon is shown in Fig.2.

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TABLE I

THE MAXIMUM ANGULAR VELOCITY OF THE MOTORS

	Maximum angular velocity [deg/s]
1st motor	$\pm$ 200
2nd motor	$\pm$ 128
3rd motor	$\pm$ 190
4th motor	$\pm$ 210
5th motor	$\pm$ 210
6th motor	$\pm$ 340

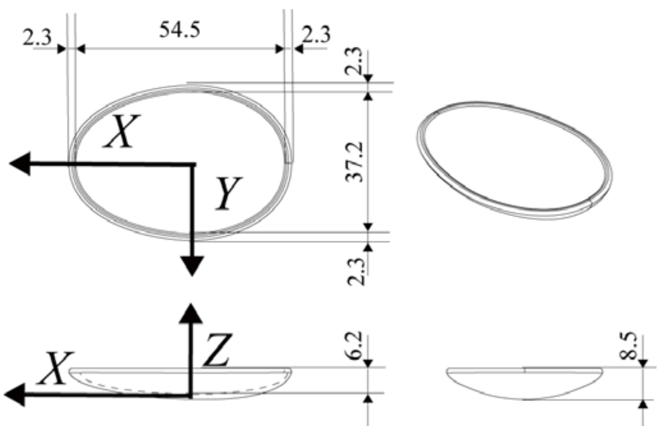

Fig. 2. Measure of spoon

III. SIMULATION ANALYSIS

In this study, the fluid analysis software, *FLOW-3D* from *FlowScience inc.*, is used. This simulator is a fluid calculation software that analyzes the three-dimensional transient flows of compressible/incompressible viscous fluid, and can treat free surfaces. The free surface calculation is performed based on the Volume of Fluid (VOF) method [9]. The Fractional Area Volume Obstacle Representation (FAVOR) method [10] is used for the shape matching of complicated obstacle.

The validity of this simulator has been demonstrated in many studies [11]. In order to identify the behavior of the liquid, the contact angle in the CFD simulation conditions is set to fit the experimental results by comparing the simulation and experiment, where the object liquid in the experiment is water in this study. Because the spilling of the liquid is affected by the contact angle. The object liquid in the experiment is water and the fluid volume is 0.0047×10^{-3}[m^3]. Table II shows the physicality of water.

A schematic diagram of the mesh setting is shown in Table III and Fig.3. x_s was 6.0×10^{-2}[m], y_s was 4.2×10^{-2}[m], z_s

TABLE II

FLUID PARAMETERS OF WATER

Fluid parameters	Water
Density	1000 [kg/m^2]
Viscosity	100×10^{-5} [Pa·s]
Temperature of the Fluid	293.2 [K]
Surface Tension	0.073 [N/m]
Surface Roughness	0.0025 [m]
Contact angle	75.0 [deg]
Gravity	-9.81 [m/s^2]

TABLE III

SETTING MESH PARAMETERS OF SPOON

	X direction	Y direction	Z direction
Min position	-0.030[m]	-0.021[m]	0.000[m]
Max position	0.030[m]	0.021[m]	0.015[m]
Total cells	100	70	25
Cell width	0.0006[m]	0.0006[m]	0.0006[m]

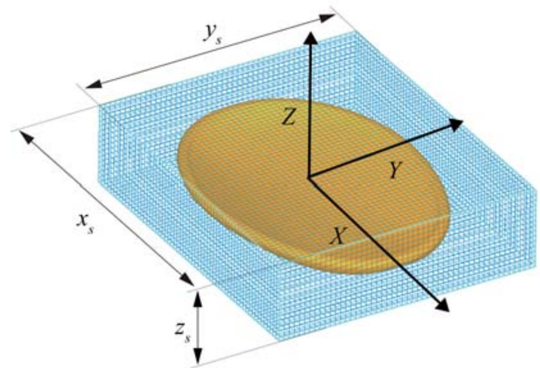

Fig. 3. Setting mesh of spoon

was 1.5×10^{-2}[m], and these mesh width was 6.0×10^{-4}[m]. The spoon containing the liquid is transferred on the Y-axis. Fig.4 shows the trajectory path with proportional control. The reference trajectory of the path was separately determined by integrating the velocity and acceleration. Here, the velocity and acceleration are 1.0 [m/s] and 5.0 [m/s^2] respectively. The proportional gains were set to K_p = 4.4, and the settling time was 1.49[s].

Fig.5 and Fig.6 shows the simulation results and experimental results of the proportional control. It can be said that the behavior of the liquid in the simulation was well identified to be same as experiment result. Furthermore, at time = 0.400 [s] and 0.530 [s], the simulation results express the phenomenon of the spilling of the liquid.

IV. SPILLING AVOIDANCE CONTROL

Fig.7 shows the flow chart of the control design approach with the CFD simulator. In this study, transfer control with spilling avoidance was solved by a genetic algorithm(GA) with a CFD simulator.

We discuss the spilling avoidance control for liquid meal assistance. The meal assist robot actions consist of dipping a spoon into a liquid meal and automatically carrying the spoon to the mouth. Therefore, the Y-axis of the spoon in Fig.2 was rotated to make its orientation parallel to the trajectory direction in Fig.8 during the movement to the dipping position. While it is dipping, the spoon containing liquid was carried. The 3-D transfer path can be independently designed on the Y and Z directions because the phenomenon of spilling is influenced by the planar path, and the movement on the Z direction does not cause spilling to occur. Thus, the trajectory path of the spoon had to be designed in a planar direction. As the trajectory of carrying, the starting point

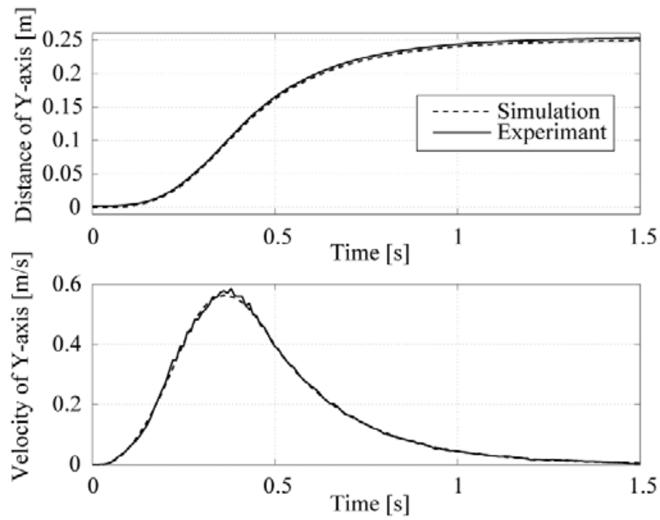

Fig. 4. Input and output data of the Y-axis path using proportional control

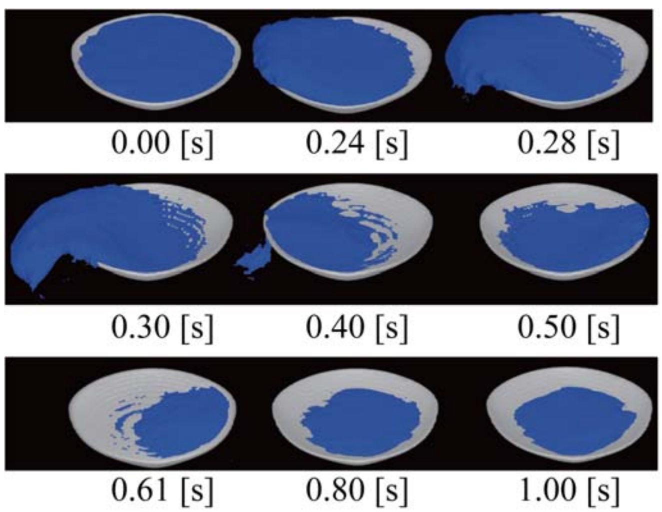

Fig. 5. Flow of liquid by simulation results

was set to (x, y, z)=(0.45, 0.00, 0.30)[m] and the point of the mouth was set to (x, y, z)=(0.45, 0.25, 0.30)[m] in this paper.

A. The equation of velocity curve

In this study, the transfer path was obtained by integrating the velocity curve, which is shown in Fig.9. This velocity curve is split in three parts, an acceleration part, a constant velocity part and a deceleration part. The acceleration part and deceleration part are set by (1)∼(3), where t is the time and, $a_i (i = 0 \sim 7)$ are the constants.

$$f\left(t\right) = \sum_{i=0}^{n} a_i t^i \tag{1}$$

$$f^{'}\left(t\right) = \sum_{i=0}^{n-1} (a_{i+1} t^i)(i+1) \tag{2}$$

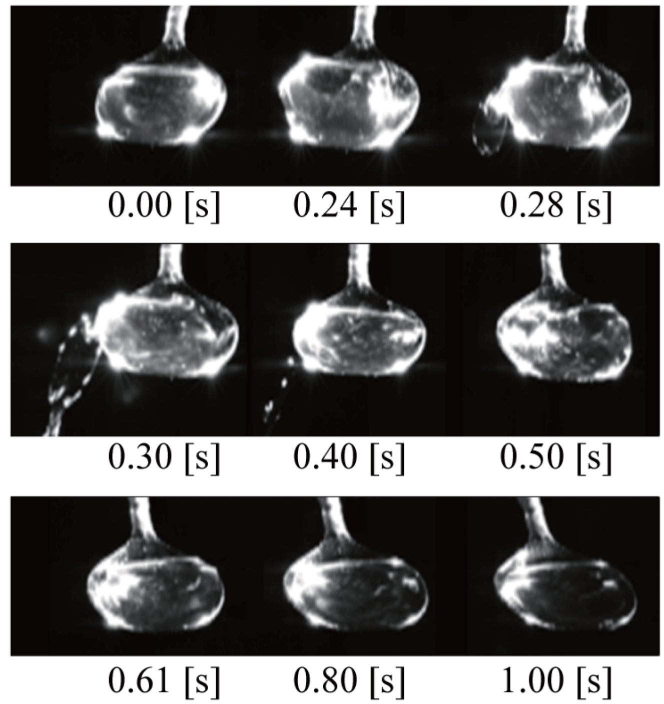

Fig. 6. Flow of liquid by experimental results

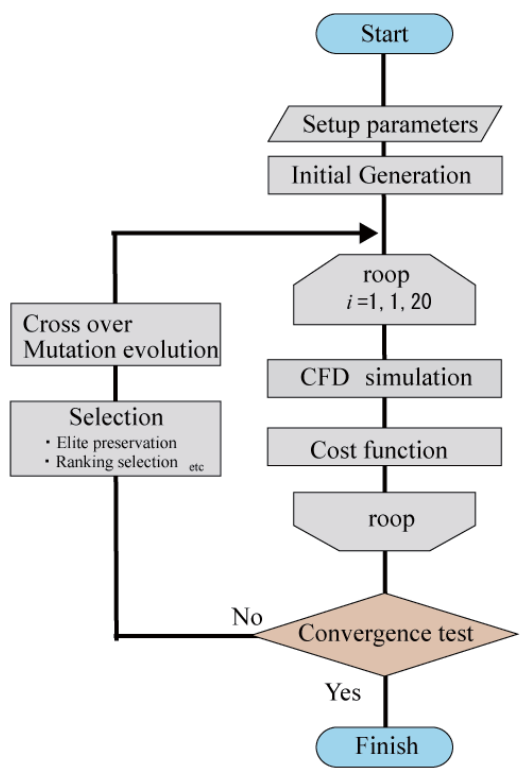

Fig. 7. Flow chart of new approach

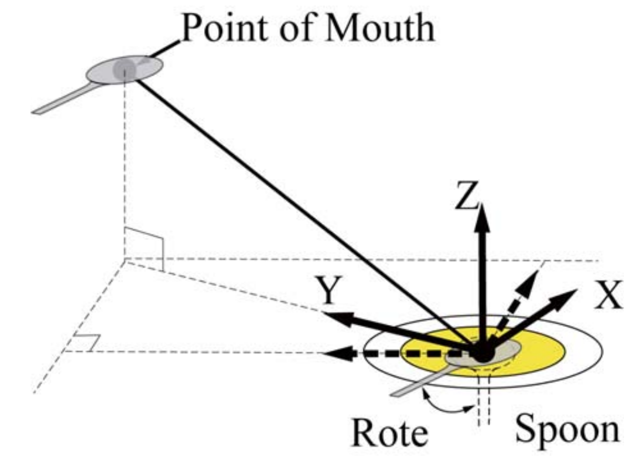

Fig. 8. The trajectory of carrying for meal assistance

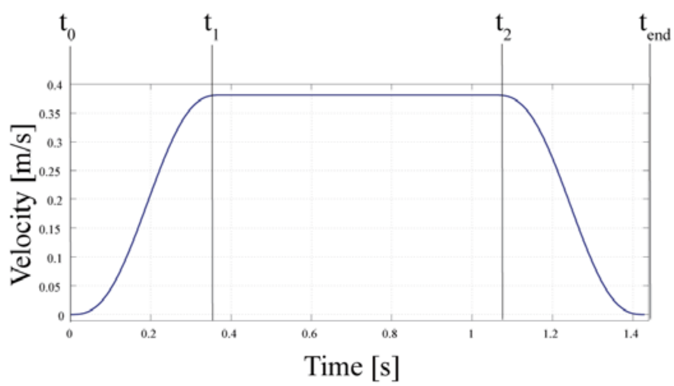

Fig. 9. Splitting the velocity carve in three points

$$f^{''}(t) = \sum_{i=0}^{n-2} (a_{i+2}t^i)(i^2 + 3i + 2) \tag{3}$$

The initial conditions are $f(0)$=0.0[m/s], $f^{'}(0)$=0.0[m/s^2], $f^{''}(0)$=0.0[m/s^3], the conditions at t=t_1 are $f(t_1)$=V_{target}[m/s], $f^{'}(t_1)$=0.0[m/s^2], $f^{''}(t_1)$=0.0[m/s^3] Therefore, (4) is solved by substituting the initial conditions into (1) $\sim$ (3).

$$a_0 = a_1 = a_2 = 0 \tag{4}$$

From the conditions at t=t_1, (5)$\sim$(7) are also given as

$$a_5 = \frac{6V_{target} - 6a_7{t_1}^7 - 3a_6{t_1}^6}{{t_1}^5} \tag{5}$$

$$a_4 = \frac{-15V_{target} + 8a_7{t_1}^7 + 3a_6{t_1}^6}{{t_1}^4} \tag{6}$$

$$a_3 = \frac{10V_{target} - 3a_7{t_1}^7 - a_6{t_1}^6}{{t_1}^3} \tag{7}$$

where the $t_1, V_{target}, a_7, a_6$ are unknown parameters solved by optimization problem using GA.

B. Formulation of design specifications

The specification of the velocity curve are formulated by making use of penalty functions, and then $t_1, V_{target}, a_7, a_6$ are simultaneously calculated to satisfy the specifications. In this design, Specs.(I)-(III) shown below were given.

Spec.(I): The maximum velocity is more than 0[m/s], in order to decrease the step back. Penalties are given if the following relation is not satisfied.

$$\min(V_t) < 0 \text{ [m/s]} \tag{8}$$

Spec.(II): The angular velocity of each motor do not exceed the manipulator constraint. Penalties are given if the following relation is not satisfied.

$$\max|\dot{\theta}_{\mathrm{j}}| > \dot{\theta}_{\mathrm{j}max} \text{ [rad/s] (j} = 1 \sim 6) \tag{9}$$

Spec.(III): The spilling liquid Q_{spill} [m^3] is more than 0 [m^3], where this spec is evaluated by using CFD simulator. Penalties are given if the following relation is not satisfied.

$$Q_{spill} > 0 \text{ [m}^3\text{]} \tag{10}$$

Parameters of velocity curve are obtained by minimizing the cost function expressed as

$$J_s = T_s + J_p \tag{11}$$

In (11). T_s is the settling time of the transfer expressed as follows:

$$T_s = \min\{t|\ |P_f - P(t+\sigma)| < P_e, \sigma \geq 0\} \tag{12}$$

where P is the position of the end-effecter at time t and P_f is the target point. T_s is the settling time for the target point. P_e is the admissible error for the target position which is set to 10^{-3}, and J_p is the penalty term expressed as

$$J_p = \omega_1 + \omega_2 + \omega_3 + \cdots \tag{13}$$

where ωi is the penalty. Each time the penalty conditions hold, the penalty $\omega_{\mathrm{k}} = 10^8(\mathrm{k} = 1, 2, \cdots)$, which is big enough to avoid the penalty conditions, will be added to satisfy the specifications. In order to obtain the velocity curve, the optimization problem with the constraints is formulated with: the target function (the settling time of the transfer T_s $\longrightarrow$ minimum) and the constraints (8) $\sim$ (10). In the (5)$\sim$(7), t_1, V_{target}, a_7 and a_6 are unknown parameters. The unknown parameters are computed by solving the optimization problem with the constraints expressed in (11).

To optimize the cost function, the GA is applied to the present problem because there are four unknown parameters in this case. Table IV shows the genetic algorithm parameters.

TABLE IV
PARAMETERS FOR GENETIC ALGORITHMS

Number of initial population	20
Number of population	20
Number of elite preservation	2
Crossover fraction	80[%]
Mutation evolution	5[%]

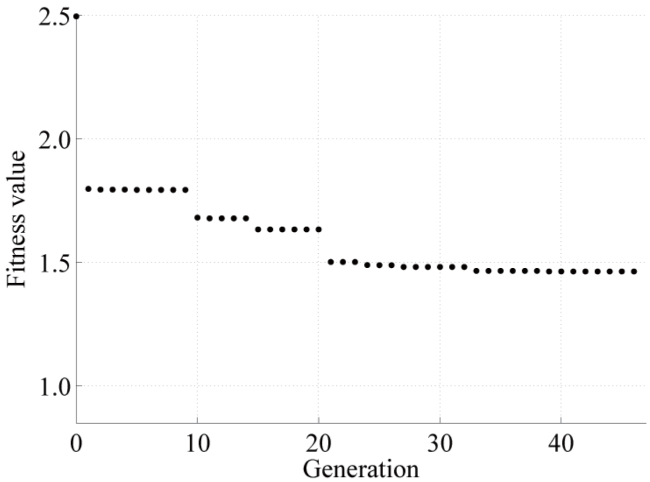

Fig. 10. Cost function for test model using velocity 7 dimensional function by new approach

C. Computation of velocity carve

Finally, each parameter is solved. In Fig.10, the results of the optimization of the cost function are shown. The computation time was about 100 hours. In Fig.10, the number of iterations of the convergence is around 33, and the settling time is converged at 1.49[s]. As a result of the computations, each parameter is V_1=2.25[m/s], t_1=0.255[s], a_7=-352.7, a_6=168.9, a_5=-42.1, a_4=8.7, a_3=5.6. Fig.11 shows the velocity curve by using the parameter. It can be said that the curve of both velocity and acceleration is smooth, and that the curve satisfied spec(I). And then, the velocity curve of spilling avoidance is constructed by combining the obtained velocity shown in Fig.11 and the constant velocity of 2.25[m/s], where the deceleration part was obtained to invert the obtained velocity, and the transfer lenght was able to adjust by adjusting the constant velocity length. Fig.12 shows the angular velocity of each motor in simulation which satisfies the desired specifications of 6DOF manipulator. Fig.13 shows the behavior of the liquid inside the spoon by using a CFD simulation. From the figure, it can be seen that the liquid was not spilled.

V. EXPERIMENTAL RESULTS

The experimental results are shown in Fig.14. The solid line is the experimental result and the dotted line is the simulation result. Fig.15 shows the behavior of the liquid inside the spoon during the transfer. As seen from the figure, the experimental result preselected by the simulation result

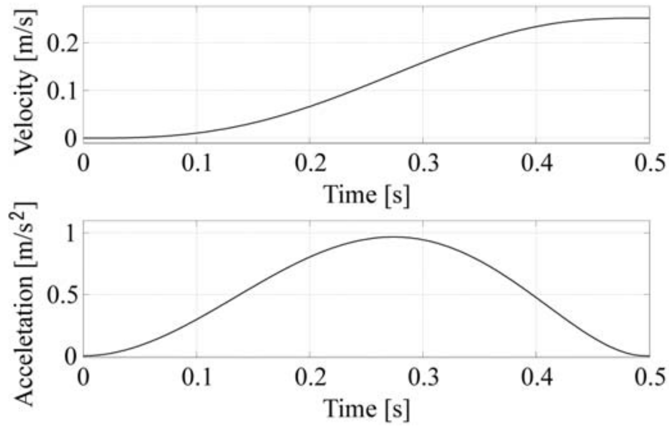

Fig. 11. Velocity and acceleration using velocity 7 dimensional function by new approach

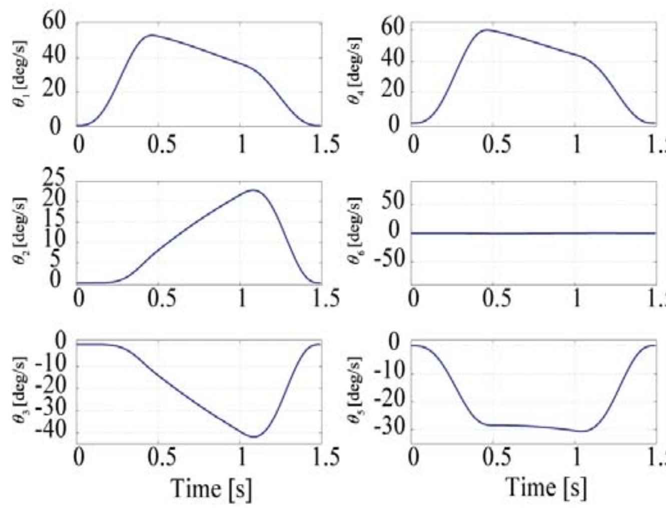

Fig. 12. The angular velocity of 6DOF manipulator

shown in Fig.13 was obtained. As a result, spilling avoidance control was realized. Compared with the proportional control shown in Fig.5 and Fig.6, the proposed control system could avoid spilling even with the same transfer time.

VI. CONCLUSIONS

The purpose of this study was to design transfer control with spilling avoidance for a meal assist robot. As a result, the study was successful in realizing transfer control with spilling avoidance. The effectiveness of the proposed transfer control was shown through simulations and experiments. Through various experimental results, it was demonstrated that the proposed transfer control satisfied the present requirements well.

The future works are to developed the meal assistance robot, and design the control assistance system considering spilling avoidance.

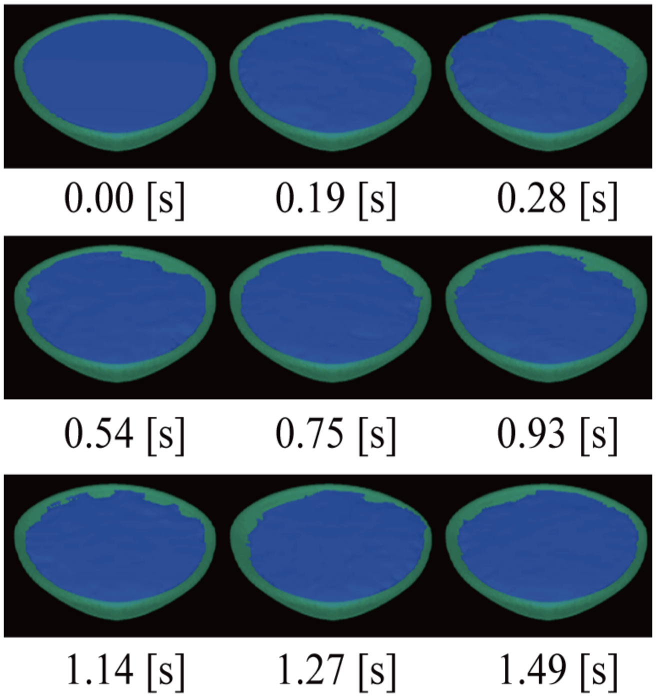

Fig. 13. Pictures of the behavior of the liquid inside the spoon by using CFD simulation

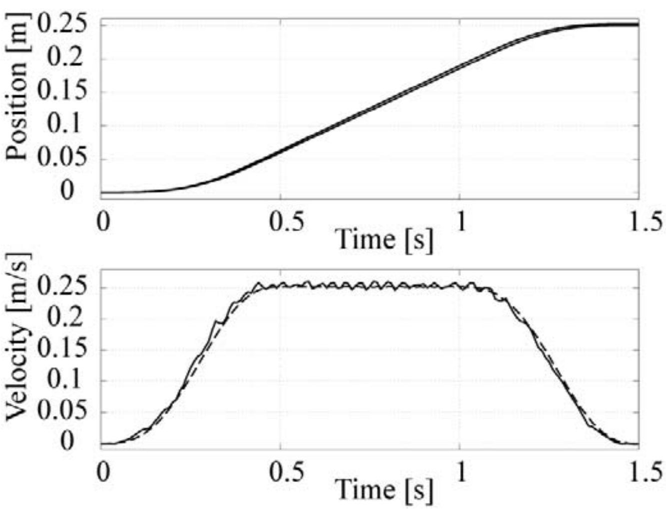

Fig. 14. Experimental result of the path

VII. ACKNOWLEDGMENTS

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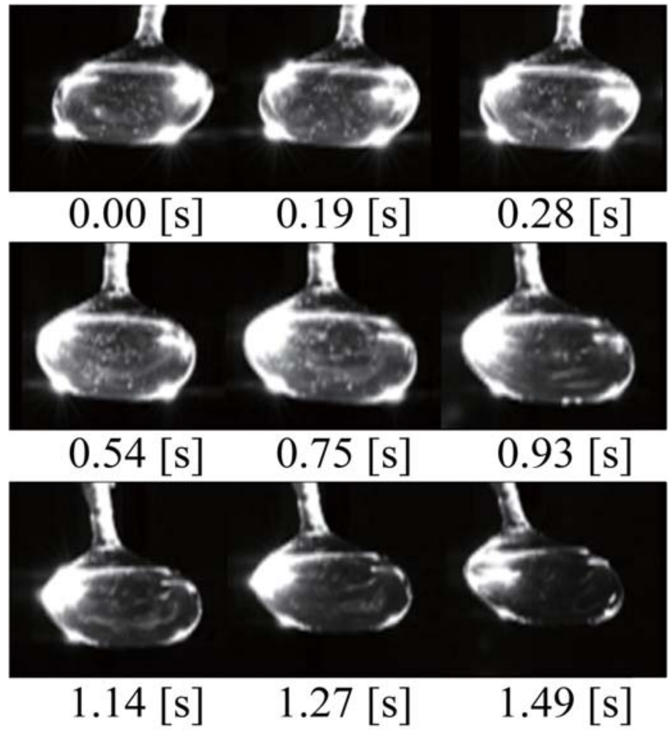

Fig. 15. Pictures of the behavior of the liquid inside the spoon by using 6DOF manipulator

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