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Assisting Upper Extremity Motion Through the Use of the Potential Method

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Abstract: In the near future, a labor shortage with constitute a significant problem in the fields of welfare and nursing care. 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 develop an upper extremity motion assistance control system which will be able to avoid collisions with the user's face and other objects. Collision information is transmitted to an operator by haptic control. In order to avoid collision, a potential field was derived by a diffusion equation in order to construct an algorithm of velocity restriction for haptic feedback. The effectiveness of the proposed system is shown by simulations and experiments.

1. INTRODUCTION

In October 2005, the number of elderly Japanese aged 65 or over was about 25 million, which is the highest recorded in Japan, for the first time exceeding 20% of the total population. The elderly population will continue to rapidly increase until the year 2020. The proportion of the aged in the general population will be 26.0% by 2015 and will reach 35.7% by 2050. It is expected that in the future one out of every three people in Japan will be over 65 years old. In light of this, we are facing a serious problem regarding the labor shortage due to a dwindling number of children. It is necessary to solve the problem of a shortage of caregivers that is expected to become more serious in the future. The burden on caregivers is increaseing every year, and will become more serious in a super-aging society.

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 (Hammel et al.(1989), (Loureiro et al.(2003), (Takahashi et al.(2001).

To satisfy this need, the meal assistance robots HANDY-1 (Whittaker(1992), NeaterEater, WinsfordFeeder, and My Spoon (Ishii et al.(2004) 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. For instance, the meal assistance robots developed in the past were mostly fully-automatic, employing a joystick, with food carried to the mouth automatically. It is hoped that in order to provide the body stimulation, the disabled individual will be able to move the body as much as possible and to stimulate the brain as in the case of Parkinson's disease patients who have the use of both arms. Thus, the development of a system that can assist the patient in eating using the hands is hoped for. However, an eating utensil cannot be grasped effectively by a weak or trembling hand, and problem arise as well regarding fatigue in the arms of the disabled person. It is therefore necessary to solve the problem of operability in the meal assistance device without causing discomfort to the user and to ensure safe operation in which collisions between the eating utensil and the user as well as other objects are avoided.

Therefore, in this study, a human-machine interface is developed in which user's intention is accurately transmitted to the robot in the form of a obstacle information as a potential field and force signals based on the force exerted by the user's hand. Thus, the end effector of the manipulator is smoothly decelerated in the regions of the mouth and dish. This device can assist in hand movement even when weak force is exerted on the eating utensil. The goal of this system is to assist a disabled person in eating and thus to allow the individual a further degree of independence, as well as to provide a rehabilitation effect.

The potential method (Tilove(1990) that uses a diffusion equation is applied in order to have better operational feeling. As a result, safety is maintained by decreasing the velocity in the area of the obstacle, and the device is operated by a control system driven based on the

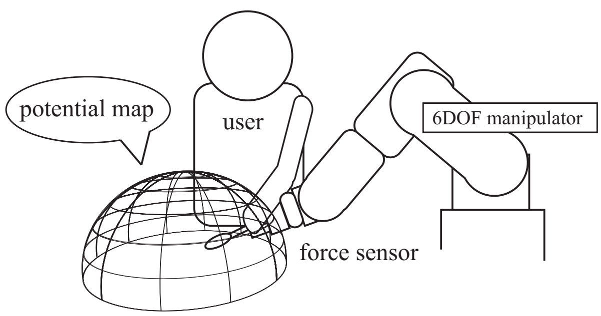

Fig. 1. Basic concept of this study

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operator's intention in a free space. The effectiveness of the proposed system is shown by experiments.

2. UPPER EXTREMITY ASSIST ROBOT

Figure 2 shows the upper extremity assistance robot used in this study. A manipulator with six degrees of freedom is used. A spoon was fixed to the manipulator's end effector. To obtain the operator's force information, a six-axis sense of force/torque sensor is attached to the end effector. RTLinux considered in real time was used as the operating system. The transfer function from the

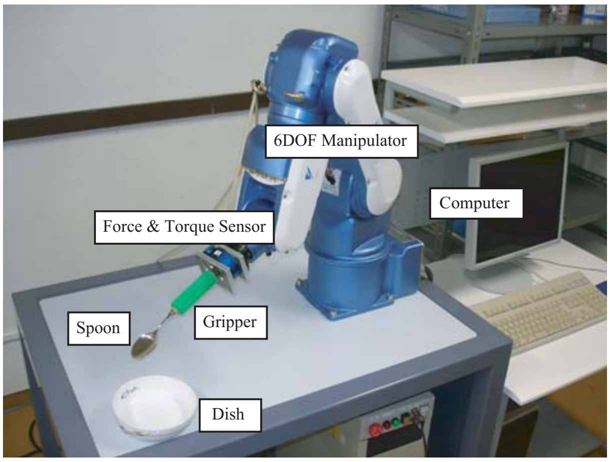

Fig. 2. Upper extremity assist robot

input voltage $u_{1\sim6}(t)$ of the servo motors to the rotational velocity $\dot{\theta}_{1\sim6}(t)$ of the motors can be expressed as a first-lag system as in (1), where the motor gain from the 1st axis to the 6th axis K_m and time constant T_m is expressed as listed in Table 1. Based on this, it is assumed that $\theta = \theta_{1\sim6}$.

$$G_\theta(s) = \frac{K_m}{T_m s + 1} \tag{1}$$

Table 1. Parametars of each motor

	K_m [deg/sV]	T_m [s]
1st motor	-29.63	0.018
2nd motor	-15.95	0.0030
3rd motor	24.69	0.025
4th motor	-28.38	0.017
5th motor	37.23	0.0010
6th motor	43.20	0.0030

3. DESIGN OF HAPTIC CONTROL SYSTEM

Impedance control is used in the system to allow an operator to move the manipulator freely. This provides drive torque so that the displacement by external force may serve as a response to the spring-mass-damper system shown in Fig. 3. The equation of motion in the x direction is expressed by (2). In this system, the force F_x in the x direction is measured by the force/torque sensor.

$$J_m\ddot{\tilde{x}} + d_m\dot{\tilde{x}} + k_m\tilde{x} = F_x \tag{2}$$

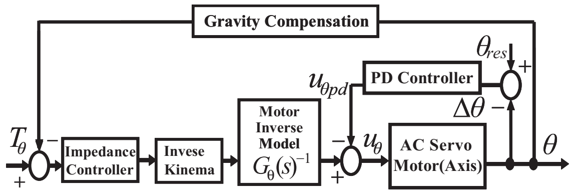

Fig. 3. Impedance control system

where $\tilde{x}$: position from x origin, J_m: inertial moment, d_m: viscous coefficient, k_m:spring constant. These parameters are obtained by simulation analysis and expressed in Table 2. Especially, in order to stop in the place when the hand was released during the device's operation, the spring constant was established as 0. The initial coordinates of the manipulator were determined based on {x, y, z, roll, pitch, yaw}={0.40[m], 0.15[m], 0.20[m], 20[deg], 20[deg], 0[deg]} in consideration of the meal position.

Table 2. Parameters of impedance control

	Inertial moment	Viscous coefficient	Spring constant
unit	[kg· m^2]	[N· m·s/rad]	[N/m]
x	0.00125	0.06	0
y	0.00125	0.06	0
z	0.00125	0.06	0
roll	0.0025	0.04	0
pitch	0.0025	0.04	0
yaw	0.0025	0.04	0

4. ASSISTANCE CONTROL SYSTEM USING THE POTENTIAL METHOD

In this study, the potential approach using a diffusion equation (Suzuki et al.(2000) is employed to restrict velocity so as to avoid collisions between the spoon and tableware and the user considering the safety of the system, thus controlling the velocity. By using the potential field for the velocity restriction, the potential field can be easily calculated even when an obstacle's shape is complex or several obstacles exist. The purpose for employing a diffusion equation when the potential field is obtained is to have to input only obstacle information to distribute the restriction velocity values in each point of three-dimensional space. Because the diffusion equation is an expression showing the distribution of the diffusion in the natural world, the restriction velocity is expressed from the obstacle. An operator can feel obstacle information from the end effector of the manipulator with the force signal. The velocity of the end effector is then smoothly decelerated toward the mouth and in the area of tableware. Thus, a safe human machine interface is realized.

4.1 Derivation of Concentration Gradient by Potential Approach

The three-dimension diffusion equation in the Cartesian coordinate system is expressed by the following equation:

$$\frac{\partial C(x,y,z)}{\partial t} = D\nabla^2 C(x,y,z) - GC(x,y,z)$$
$$= D(\frac{\partial^2 C}{\partial x^2} + \frac{\partial^2 C}{\partial y^2} + \frac{\partial^2 C}{\partial z^2}) - GC \tag{3}$$

Equation(3) is obtained by the forward difference and central difference of (4) when the sample time is Δt, and the grid width of the axes are Δx, Δy, and Δz, respectively. Moreover, D is the diffusion coefficient, while G is the attenuation coefficient.

$$\frac{\partial C_{t+1,i,j,k} - \partial C_{t,i,j,k}}{\triangle t} = D\Big(\frac{C_{t,i+1,j,k} - 2C_{t,i,j,k} + C_{i-1,j,k}}{\triangle x^2} + \frac{C_{t,i,j+1,k} - 2C_{t,i,j,k} + C_{i,j-1,k}}{\triangle y^2} + \frac{C_{t,i,j,k+1} - 2C_{t,i,j,k} + C_{i,j,k-1}}{\triangle z^2}\Big) - GC_{t,i,j,k} \quad (4)$$

where the diffusion parameter R is defined as

$$R \equiv D\frac{\triangle t}{\triangle x^2} = D\frac{\triangle t}{\triangle y^2} = D\frac{\triangle t}{\triangle z^2} \quad (5)$$

and $C_{t+1,i,j,k}$ are derived from (4). Then,

$$C_{t+1,i,j,k} = (1 - 6R - G)C_{t,i,j,k} + R(C_{t,i+1,j,k} + C_{t,i-1,j,k} + C_{t,i,j+1,k} + C_{t,i,j-1,k} + C_{t,i,j,k+1} + C_{t,i,j,k-1}) \quad (6)$$

is obtained, where $C(x, y, z)$ is the solute density, and $C_{t,i,j,k}$ is the solute density of the i, j, k th grid at a sampling grid time t. The mesh width is set to $\Delta x = \Delta y = \Delta z = 0.02$[m]. R and G are unknown parameters in (6). These parameters are obtained by the optimization method. In the case of a manual operation system, an operator decides a goal point and transfer path arbitrarily. In other words, a goal point cannot be set when the potential field is calculated offline. Namely, an initial condition and a boundary condition of a full automatic system cannot be used. Therefore, in this system, an initial condition and a boundary condition are given as follows: The initial concentration is set to $C_{0,i,j,k} = 1$

Boundary condition
$$C_{t,i,j,k} = 0(\text{Wall, Obstacles})$$
Initial condition
$$C_{0,i,j,k} = 1(\text{Without Wall, Obstacles})$$

as a boundary condition. In the boundary condition, the concentration of wall and obstacle points is set to $C_{t,i,j,k} = 0$. In a full automatic system, the concentration rises from the goal point to the transportation area when diffusion is performed. On the other hand, obstacles and walls become absorption points in this condition; the concentration of the near-side of obstacles decreases when diffusion is performed. As a result, it becomes possible to generate a potential field without setting a goal point. Parameters R and G can be obtained by minimizing the cost function J as shown in (7),

$$J = N_D + J_p \quad (7)$$

where N_D is the number of diffusions (i.e., the number of times diffusion is performed) shown in (8).

$$N_D = n \text{ subject to } 0.05 \le e_x \le 0.2, \quad 0.05 \le e_y \le 0.2 \quad (8)$$

e_x and e_y are concentration rates in the x directions and y directions, respectively. Much time is required to derive a potential field if the number of diffusions is large. Therefore, the optimum R and G, which realize the minimum number of diffusions, are calculated to derive the potential field quickly. J_p is the penalty function shown in (9). $w_i = 10^8$ is a penalty to be imposed when a design specification is not satisfied in (9).

$$J_p = \omega_1 + \omega_2 + \cdots + \omega_i + \cdots \quad (9)$$

Design specifications

i) Diffusion is stable
It is known that coefficient R and $(1-6R-G)$ in (6) must be positive so that a solution obtained by an explicit method is stable at a constant value. Therefore, the penalty $w_1 = 10^8$ is imposed when (10) is not satisfied.

$$0 < R < \frac{1 - G}{6} \quad (10)$$

ii) Constraint of concentration rate in the x direction
It is necessary to satisfy the acceleration constraint in order to prevent a collision with an obstacle by overshoot. In addition, the concentration gradient becomes low when the diffusion rate of the concentration is too large. As a result, the constraint of velocity is performed when the the end effector of the manipulator is far from an obstacle, and the transfer time increases. Therefore, the concentration gradient must be set to make possible both the shortening of the transfer time and prevention of overshoot, having satisfied the acceleration constraint. Thus, the concentration rate of the x direction is set with $e_{x1} = \left|(C_{t,i=8} - C_{0,i=8})/(C_{0,i=8})\right|$, $e_{x2} = \left|(C_{t,i=16} - C_{0,i=16})/(C_{0,i=16})\right|$, and the penalty $\omega_2 = 10^8$ is imposed when (11) is not satisfied, where (11) was obtained by simulation analysis.

$$0.05 < e_x < 0.5 \quad (11)$$

iii) Constraint of concentration rate in the y direction
As in the concentration rate in the x direction, constraint is established in the y direction concentration rate in order to prevent overshoot. The concentration rate of the y direction is set with $e_y = \left|(C_{t,j=8} - C_{0,j=8})/(C_{0,j=8})\right|$,$e_y = \left|(C_{t,j=12} - C_{0,j=12})/(C_{0,j=12})\right|$, and the penalty $\omega_3 = 10^8$ is imposed when (12) is not satisfied, where (12) was also obtained by simulation analysis.

$$0.05 < e_y < 0.2 \quad (12)$$

This is expressed as the following optimization problem with constraints to derive the parameters R and G of the diffusion equation.
Cost function: minimize the number of diffusions N_D
Subject to (10)–(12)
Moreover, the potential field for the mobility limit can be obtained by assuming the constrained condition of constraint of the concentration rate constant to be $0 < e_{t,i,j}$ when there is no obstacle.

4.2 Environmental map and Potential field

In this study, Fig. 4 shows the location of a dish which is 0.14[m] in diameter and 0.045[m] in height at the center of a table. When an environmental map is made, it should be considered so as not to allow the spoon to hit dish when operating the manipulator. In making a potential field, the dish area was set to 0.145[m] in height in consideration of the safety rate. The original point of the obstacle map was decided to be x =0.2[m], y =0.0[m], z =0.0[m] from the manipulator's original point. The grid number is 25(x axis) × 25(y axis) × 15(z axis) = 9,375 points. To optimize the cost function, the simplex method was applied to the present problem, where the reflection coefficient α=1.0, the expansion coefficient β=0.5, and the contraction coefficient γ=2.0. The potential field of initial simplex values are $R = (0.01, 0.08, 0.3)$ and $G = (0.01, 0.1, 0.05)$.

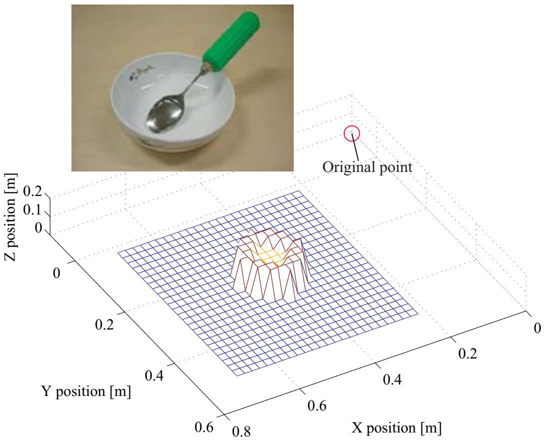

Fig. 4. Environmental map

Figure 5 – 7 show the potential field of the result of the calculation. Figure 5– 7 shows the one of the three feature grids taken from 15 grids. Each height is z =0.14[m], z =0.12[m], and z =0.08[m]. The computation time to obtain the optimal solution was around 1 second with a PC running a with Celeron D 2.93[GHz]. As a result of the calculations, the smallest number of diffusions was N_D=4; then $R = 0.1250$ and $G = 0.0938$.

Figure 6 and Fig. 7 show the potential of the situation (z=0.12[m]) in which the manipulator end effector is lower than the height of the dish. It is seen that it is the obstacle space and the concentration is 0. On the other hand, it can be confirmed that the concentration is high even at the dish position in potential field when the end effector of the manipulator are higher than dish height(z=0.16 [m]) as seen in Fig. 5 because the end effector never touches dish. The potential field where the concentration in the mobility limit and the area of the obstacle gradually decreased was obtained. As a result, the velocity of the manipulator's end effector gradually decreases as it approaches the dish, and does not touch the dish. However, the reference velocity of the end effector is 0 whenever it reaches the area of velocity restriction 0 in the obstacle area. When the effector moves away from the obstacle, the velocity restriction is imposed. It is not possible to move away quickly in the case in which the manipulator's direction is not toward the obstacle. Therefore, it is necessary to correct the potential field in which the manipulator's direction of movement was considered. Figure 8 shows the result of the correction. Figure 8(a) shows the potential field when the

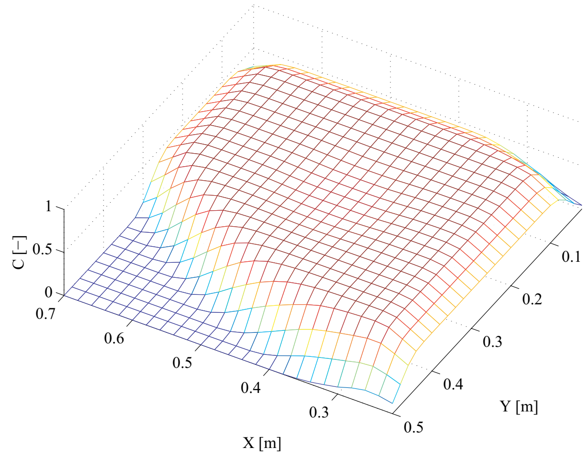

Fig. 5. Optimal potential field (z=0.16[m])

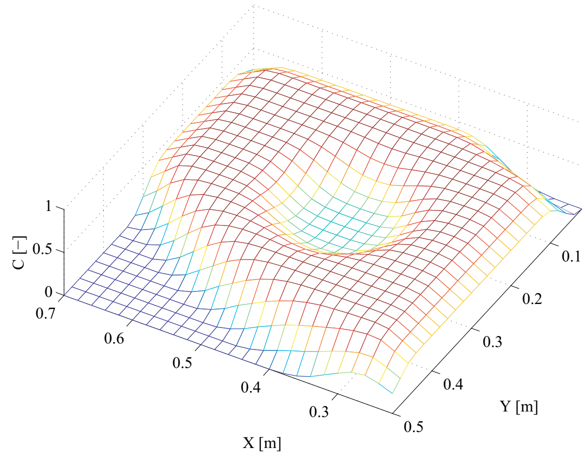

Fig. 6. Optimal potential field (z=0.14[m])

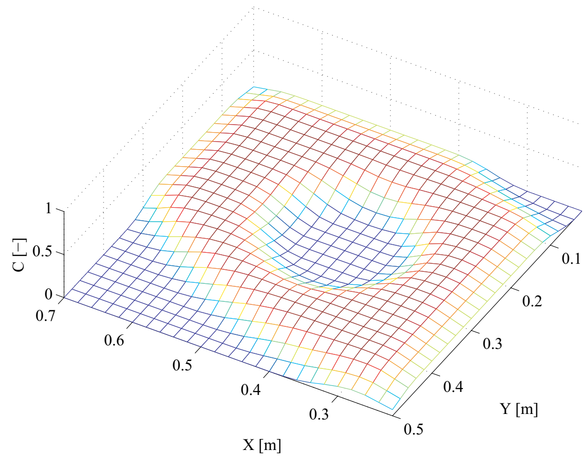

Fig. 7. Optimal potential field (z=0.08[m])

manipulator's end effector is moved in the plus direction of the x axis. The maximum vfalue in each grid is applied when the manipulator's end effector is moved in the plus direction of the x axis in the concentration point of 0. The velocity restriction is not imposed to the same degree in a direction away from the dish. In the same way, Figure 8(b) shows the potential field as it is moved in the minus direction for the x axis. Figure 8(c) shows the potential field when it is moved the plus direction for the y axis.

And Fig. 8(d) shows the potential field when it is moved in the minus direction for the y axis.

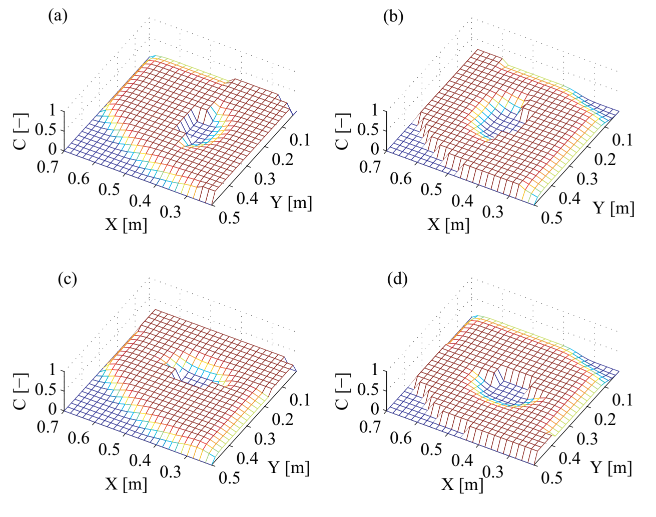

Fig. 8. Optimal potential field (z=0.08[m]

4.3 Interpolating of a Potential field

Through the use of a potential approach based on a diffusion equation, a diffusion process is performed and a potential field is generated in discretized space. Velocity control must be performed smoothly via the operation of the haptic joystick when the concentration of a potential field is used as a velocity constraint. As a method to smooth a change in the concentration, this method can make the mesh width very small. However, it increases the computation time. Therefore, in this study, the concentration of an arbitrary point $C_{x,y,z}$ is calculated by interpolating the concentrations of its neighbors. The concentration of an arbitrary point $C_{x,y,z}$ in the concentration space shown in Fig. 9 is derived from (13).

$$
\begin{aligned}
C_{x,y,z} = {} & C_a + (C_b - C_a)p + (C_c + C_a)q + (C_e - C_a)r \\
& + (C_a - C_b - C_c + C_d)pq \\
& + (C_a - C_b - C_e + C_f)pr \\
& + (C_a - C_c - C_e + C_g)pr \\
& + (C_a - C_b - C_c + C_d \\
& - C_e + C_f + C_g - C_h)pqr
\end{aligned} \tag{13}
$$

where i, j, k are the grid numbers of the x, y, and z axial directions, respectively, $C_{a\sim h}$ is the concentration in (i, j, k), and $p = \hat{x} - i$, $q = \hat{y} - j$, and $r = \hat{z} - r$ are the fractions of the arbitrary point that is quantized in the configuration space of the potential field. Equation (13) is derived by linear interpolation using the concentration of 8 points $C_a \sim C_h$ around the point.

5. EXPERIMENTAL RESULTS OF UPPER EXTREMITY ASSISTANCE

A three-dimension potential field was applied to a 6 DOF manipulator, and the operation assistance control was performed. The restriction velocity coefficient of the velocity control via the potential field is the potential concentration value $C_{x,y,z}$ at a reference velocity at the

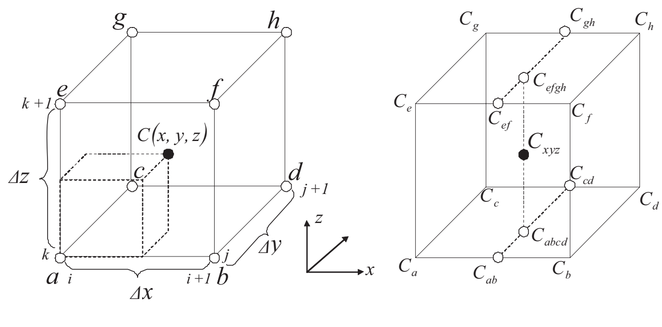

Fig. 9. Interpolation of concetration

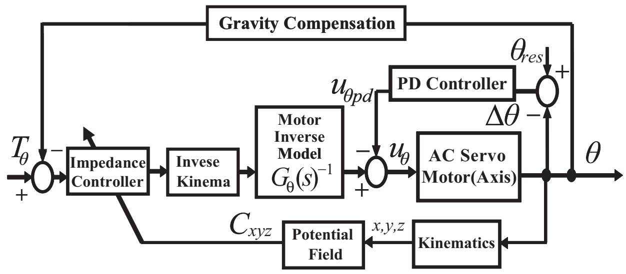

Fig. 10. Control system through the use of potential field

time calculated based on the user's force information and the reference position. The value of the multiplication of the reference velocity by the potential concentration as (14) is input to the manipulator. A simplified depiction of the operation support system through the use of potential field is shown in Fig. 10.

$$\dot{\theta} = C_{x,y,z} \times \dot{\theta}_{ref} \tag{14}$$

Figure 11 – 14 show the results of the control experiment. The spoon is moved from the manipulator's initial position to the dish, and is then carried to the mouth. The manipulator's end effector position for the x axis is plotted in Fig. 11(a). The force put at that time is plotted in Fig. 11(b), while the reference velocity by the user's force and the velocity restricted by the potential field is shown in Fig. 11(c), namely the velocity of the manipulator is actually input. In interval (i) and interval (ii), it can be confirmed that the potential concentration is decreased because the manipulator's end effector approaches the area of the dish, and the input velocity to the manipulator is decreased along with it, as well. Figure 12 and Fig. 13 as well as Fig. 11. Fig. 14 show the end effector position in three dimensions by control of the potential field. It is understood that the manipulator end effector draws a round orbit along the dish. The results show that by means of the proposed method, the velocity determined the potential field in the area of the obstacle is sufficiently decreased to avoid contact with the obstacle.

6. CONCLUSION

In this study, a velocity control system realizing obstacle avoidance and haptic control using the potential field by through the utilization of a diffusion equation was developed. As a result, an operator support system that combines safety and usability was demonstrated as the end effector's velocity smoothly decelerated as it approached the mouth and the area of a dish. The effectiveness of the

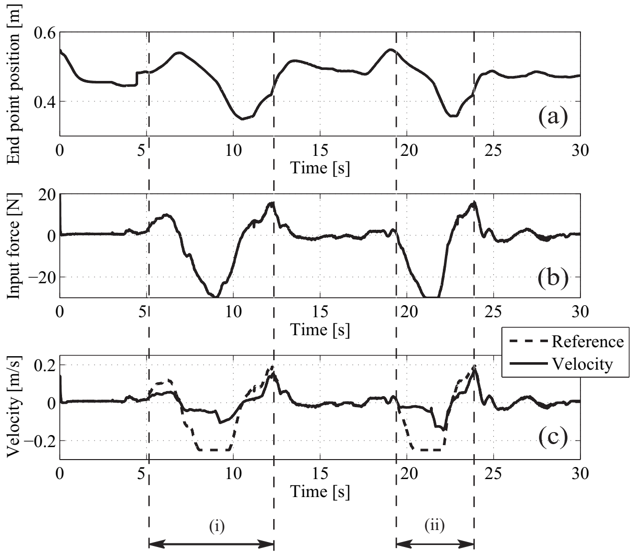

Fig. 11. Experimental result of end effector velocity at x axis

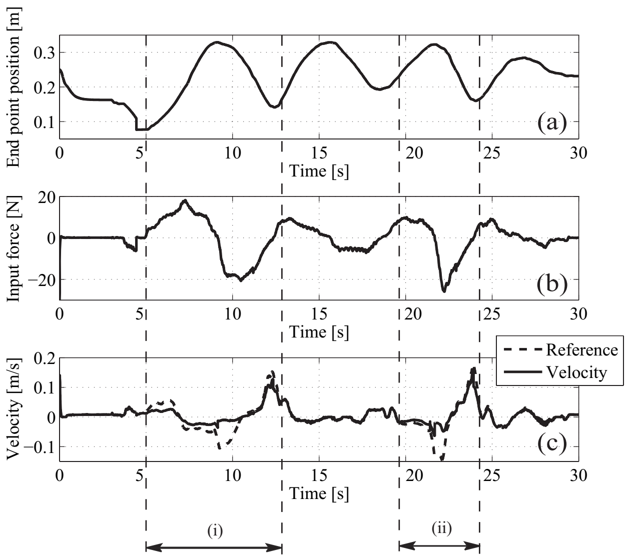

Fig. 12. Experimental result of end effector velocity at y axis

proposed upper extremity operation support system was shown through meal support experiments.

This work was supported by GIFU & OGAKI Robitics Advanced Medical Cluster.

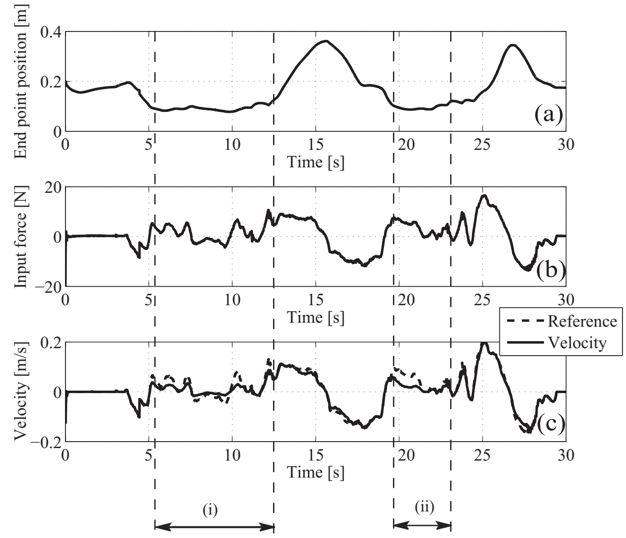

Fig. 13. Experimental result of end effector velocity at z axis

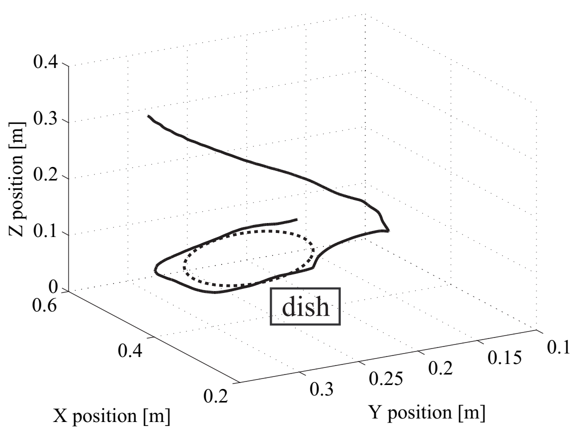

Fig. 14. Experimental result of end effector position

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