Presenting grasping and resultant forces for rigid body manipulations with multi-finger haptic interfaces

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ABSTRACT

We measure grasping and resultant forces and reveal that the grasping force is kept stable while subjects shake objects. Then, we propose a new method to feedback grasping and resultant forces for multi-finger object manipulation. While shaking an object, the proposed method keeps the grasping force and eliminates the influence of the resultant force to the distance between fingers. We do an experiment to evaluate proposed method. The result shows that the grasping force and the distance between fingers become stable with the proposed method.

Keywords: grasping force, multi-finger, haptic interface

1 AIM AND BACKGROUND

In this paper, we propose a new feedback force calculation method, which achieves natural manipulation of dynamic virtual objects.

When we manipulate an object in the three-dimensional real world, we use multi-fingers to grasp the object. Therefore, it is good for natural virtual object manipulation with force display to grasp virtual object directly with multi-fingers.

Ishii et al. [1] proposed a method of feedback force calculation for multi-finger grasps. Their method just feed backs grasping force and normal force. It can't feed back forces, which comes from dynamics model such as inertial forces. Maekawa and Hollerbach [2] proposed a force display and a control method. Their method realizes grasping manipulation by thumb and index finger. Because their method requires contact mode and grasping mode, their method is difficult to extend for generic problems. Yoshikawa and Ueda [3] proposes a modeless method, which feed back resultant force and grasping force. Because their method does not separate the feedbacks of resultant forces and grasping force, there is a problem. When the user moves the object, the user feels that the object became soft. Kawai and Yoshikawa [4] propose a new method, in which the coupling impedance is calculated separately for grasping and resultant forces. Because the coupling impedances are connected serially, the resultant force gives some influences on the impedance of the object. In this paper, we propose a new force calculation method, in which the feedback of the resultant force doesn't affect the feedback of grasping force. In addition, we show that the proposing method can be extended to apply to multi-finger cases.

2 GRASP IN THE REAL WORLD

'Pick and place' is one of the most basic manipulation for many applications in multi-finger direct manipulation environments. To understand the influence of acceleration of grasped object during horizontal shaking motion straightforwardly, we focus on horizontal 1 DOF (degree of freedoms) grasp and a task of shaking the object.

2.1 Model of grasping

When we grasp a rigid body in the real world, the distance between the thumb and the index finger is fixed to a constant by the shape of the grasped object regardless of forces from the fingers. The equation of motion of the grasped rigid body is

$$m\ddot{x} = f_1 + f_2, \tag{1}$$

where f_1, f_2 are the forces from the fingers, x is center position of the rigid body. While the resultant force from the fingers to the rigid body is $f_1 + f_2$, the sum of the forces from the fingers $|f_1| + |f_2|$ is larger than the resultant force. The difference between the sum of the forces $|f_1| + |f_2|$ and the resultant force $f_1 + f_2$ have no effect on the resultant force but keep the normal forces between the fingers and the object and keep the grasp stable. Therefore, we call this 'grasping force'. The grasping force is formulated by

$$f_g = \begin{cases} |f_2| & (|f_1| > |f_2|) \\ |f_1| & (\text{otherwise}), \end{cases} \tag{2}$$

and the resultant force is formulated by

$$f_r = f_1 + f_2. \tag{3}$$

Therefore, the same resultant force (f_r) can be generated by various forces from fingers (f_1, f_2), according to the grasping force (f_g).

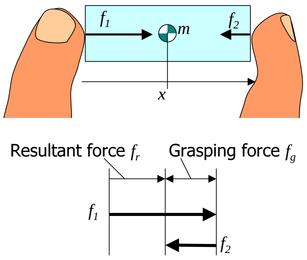

Figure 1: Grasping force on a grasp of a rigid body in 1DOF

2.2 Measurement of grasping force

If we reveal the relation between grasping forces and resultant forces, we can control grasping forces according to resultant forces to improve sense of manipulation in grasping manipulation environments. Therefore, we measure grasping force during grasping manipulation.

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2.3 Measurement setup

We measured forces from thumbs and index fingers, when subjects shake an object of 1kg mass and 0.2kgw weight. The rotation and depth slide motions are constrained. Therefore the object moves only in up-down and left-right directions. To avoid the influence of the mass of the force sensor, we employ a sheet type force sensor, FlexiForce [5]. The sensor has unevenness and non-linearity. We calibrate the sensor with an ordinary force sensor.

We employ an OPTOTRAK (optical position measurement tool [6]) to measure the position of the object.

We ask subjects repeat a sequence of shaking the object eight times and waiting two seconds. We measure four subjects. Fig. 2 shows the setup of the measurement.

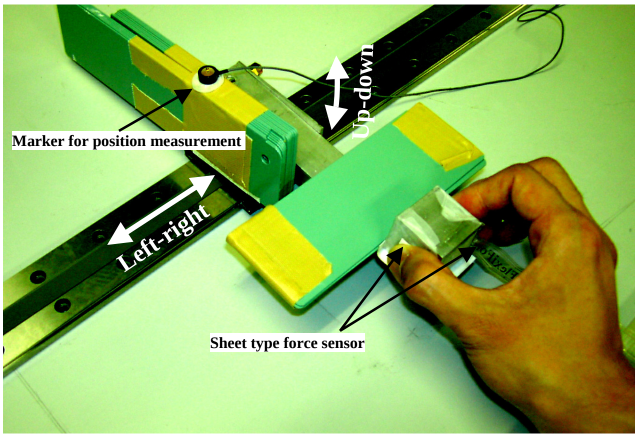

Figure 2: Measurement of finger force on real object grasping

2.4 Results of the measurement

Fig. 3 shows an instance of the measurement result. The graph shows that the grasping force during shaking the object is larger than that of waiting. This means that the subject generates the resultant force by increasing the finger force. The subject does not decrease the grasping force. The measurements for other three subjects show the same tendency. Thus, we found that human generates grasping force by increasing forces from the fingers to the object to keep the grasping forces.

3 PROBLEMS ON PRESENTATION OF GRASPS WITH HAPTIC INTERFACES

When a haptic interface presents shapes of virtual objects, feedback forces are calculated with spring models. God Object Method [7] and Virtual Proxy [8] are one of the typical method for this calculation. If an virtual object have appropriate mass and freedom and the motion of the virtual object follows the laws of motion, the user can grasp and manipulate the virtual object [3].

In this case, equations of the motion of the object are

$$\begin{aligned} m\ddot{x} &= f_1 + f_2 && (4) \\ f_1 &= k(x_1 - (x - l/2)) && (5) \\ f_2 &= k(x_2 - (x + l/2)). && (6) \end{aligned}$$

We can rewrite the forces from the fingers (f_1, f_2) by the resultant force (f_r) and the grasping force (f_g) by

$$f_1 = f_g + f_r, f_2 = -f_g \tag{7}$$

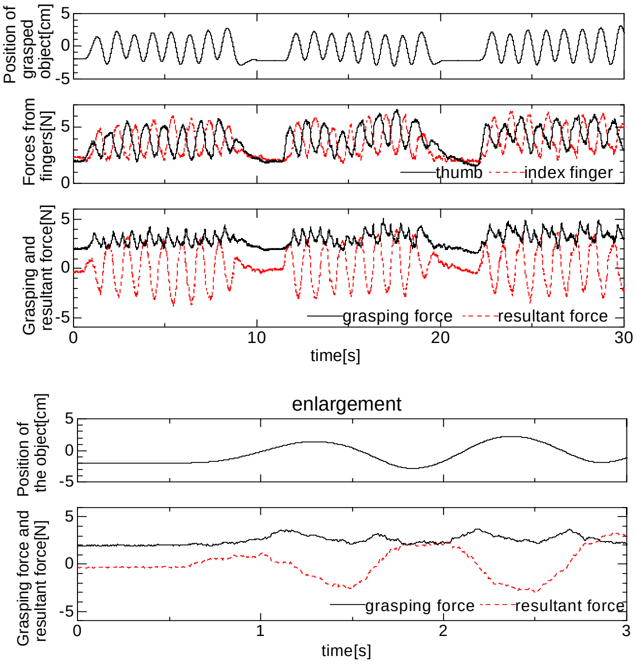

Figure 3: Finger forces on object grasping in the real world

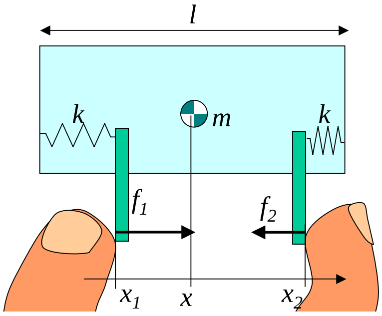

Figure 4: Presentation of grasp with spring models

(in the case of $|f_1| > |f_2|, f_1 > 0, f_2 < 0)$. Therefore, the distance between the thumb and the index finger becomes

$$x_2 - x_1 = l - \frac{2f_g + f_r}{k}. \tag{8}$$

This equation represents that when the resultant force f_r increase, the grasping force f_g or the distance between the fingers $(x_2 - x_1)$ decreases. The results of the measurement in section 2.2 show that the amount of the grasping force f_g is kept, even when a resultant force acts on the object. This means that when the fingers add resultant force to the object, the distance between fingers will be decrease. This causes a problem. When the user accelerates or shakes the object, the object is observed softer and smaller.

4 PROPOSAL ON RESULTANT FORCE DISTRIBUTION

When fingers give a resultant force to the grasped object, the gap between fingers is changed by the resultant force which changes the length of spring models to present the shape of the object. The change of the gap between the fingers can be eliminated by directly giving the resultant force from the fingers to the dynamics model of the object.

4.1 Calculation of grasping force

Previous methods calculate resultant force and the grasping force with the same spring model. We calculate the grasping force independently from the resultant force to eliminate the effect of the resultant force from the spring model to present the shape of object. Therefore, we divide the model of the grasped object into two part, the shape and the dynamics.

The grasping force calculate from a mass-less shape model. We call this shape model 'shape shell'. The shape shell represents the shape of the object without the content and mass.

The balanced position of the shape shell can be calculated from the finger positions and spring models by statics. The grasping force can be calculated as forces acting on the fingers here.

4.2 Calculation of resultant force

The resultant force is calculated from the equation of motion of the grasped object. The equation of motion of the object can be represented as

$$m\ddot{x} = f_r + f_e \tag{9}$$

where, x represents the position of object , f_r represents the resultant force given to the object from the finger, f_e represents other external forces acting on the object. Therefore, the resultant force to feed back to the finger is $m\ddot{x} - f_e$.

The position of the shape shell is in the balanced position calculated from finger position of the user. Therefore, the acceleration of the shape shell can be calculated from the accelerations of fingers. However, most haptic interfaces can not measure acceleration of fingers. Then, it is not easy to find the acceleration of the shape shell. Thus, we suppose a spring model for dynamics between the shape shell and the mass and use the force from the spring model instead of $m\ddot{x}$.

4.3 Feedback of the resultant force

The calculated resultant force should be fedback to the fingers without passing through the spring models for grasping force calculation. The resultant force should be fedback not to decrease grasping force for each finger. Otherwise, the resultant force decreases grasping force and the distance between fingers will change. Fig. 5 summarizes above. The force from each finger (f_1, f_2) is represented by

$$\begin{aligned} f_1 &= -(k_g d_1 + k_d d_d + f_e), \\ f_2 &= -k_g d_2 && (\text{in case } k_d d + f_e \leq 0) \quad (10) \\ f_1 &= -k_g d_1, \\ f_2 &= -(k_g d_2 + k_d d_d + f_e) && (\text{in case } k_d d + f_e > 0) \quad (11) \end{aligned}$$

where k_d, k_g represent spring coefficients, d_d, d_1, d_2 represent spring expansions. In addition, the distance between the thumb and the index finger is represented by

$$x_2 - x_1 = l - \frac{2f_g}{k_g}. \tag{12}$$

This shows that the influence of resultant force is eliminated.

5 EXTENSION FOR 6 DOF MULTI-FINGER GRASP

This section extends the resultant force distribution proposed in section 4 to 6 DOF multi-finger grasps.

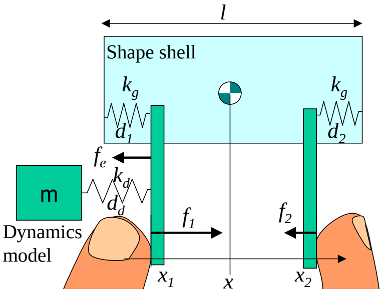

Figure 5: Presentation of grasp with resultant force distribution

5.1 Calculation of grasping force

Following shows the calculation of balanced posture of the shape shell in cases of n fingers. Notations are described in Fig. 6.

The resultant force $\boldsymbol{F}$ and torque $\boldsymbol{N}$ of the forces from the fingers to the shape shell are

$$\boldsymbol{F} = \sum \boldsymbol{f_i} \tag{13}$$

$$\boldsymbol{N} = \sum \boldsymbol{r_i} \times \boldsymbol{f_i}, \tag{14}$$

where, r_i is the position of one of the finger, f_i is the force adding from the fingers to the shape shell.

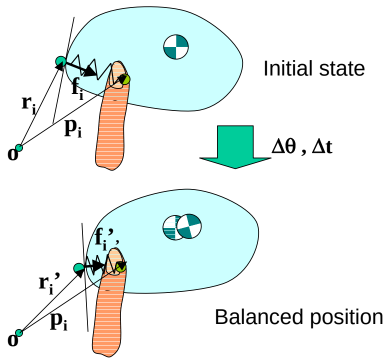

Figure 6: Balanced position of the shape shell

At the balanced position, the resultant force and torque are zero. Therefore, we get conditions of balance

$$\mathbf{0} = \sum \boldsymbol{f'_i} \tag{15}$$

$$\mathbf{0} = \sum \boldsymbol{r'_i} \times \boldsymbol{f'_i}, \tag{16}$$

where r'_i is position of the god object for each finger after balanced, f'_i is forces from the finger to the shape shell after balanced, Δt and $\Delta\theta$ are translation and rotation of shape shell to move the shape shell to the balanced position.

The balanced position of the object r'_i approximates to

$$\boldsymbol{r'_i} \approx r_i + \Delta\theta \times r_i + \Delta t \tag{17}$$

because $\Delta\theta$ is small. Then, the forces after balanced f'_i become

$$\boldsymbol{f'_i} = k(\boldsymbol{p_i} - \boldsymbol{r'_i}). \tag{18}$$

The balanced posture of the shape shell is obtained by solving Eq. 15 and Eq. 16 for Δt and $\Delta\theta$. Then, the posture of the shape shell is moved to balanced position and the god objects follow the shape shell. The grasping forces are given by the forces from the spring damper model for god object method, which connect the god objects and the fingers.

5.2 Calculation of the resultant force and torque

The resultant force and torque of a six DOF object are the sum of the forces and torques from the fingers, from the inertia of the object and from other external causes. Three DOF translation and rotation spring damper model between the shape shell and the mass and inertia are employed to calculate the inertial force of the six DOF object. The sum of this inertial force and torque and other external forces and torques should be exerted to the fingers.

5.3 Distribution of resultant force and torque

The proposal in section 4 was that the resultant force should distribute to each finger regarding human grasping natures to realize stable grasps. Therefore, the distribution of the resultant force in six DOF multi-finger grasping should be in the same manner. The requirements for the distribution of the resultant force are:

1. A distributed force does not decrease the grasping force.
2. The sum of the distributed forces approximates the resultant force.
3. The change of the force presented to a finger is continuous.
4. The distributed force is proportional to the grasping force.

These requirements are formulated in

$$\begin{aligned} P = {} & (\boldsymbol{F} - \sum k_i \boldsymbol{n_i})^2 + \gamma_1(\boldsymbol{N} - r_i \times \sum k_i \boldsymbol{n_i})^2 \\ & + \gamma_2(\sum (k_i - k|\boldsymbol{f}_{gi}|)^2 + \gamma_3(\sum k_i^2 + k^2) \\ & \text{Find } k_i,\ k\ (k_i, k \geq 0) \text{ which minimize } P, \end{aligned} \tag{19}$$

where r_i is the position of the god object for each finger, n_i is the normal of the surface at r_i, f_{gi} is the grasping force from each finger, $k_i\boldsymbol{n_i}$ is the distributed resultant force for each finger, $\boldsymbol{F} and \boldsymbol{N}$ are the force and the torque to distribute. This formulation is quadratic programming problem and can be solved. γ_1, γ_2 and γ_3 are weight parameter to adjust weights of four requirements above.

6 EVALUATION OF THE PROPOSED METHOD

We present a rigid body with three translational DOF grasped by thumb and index finger with two haptic interfaces named SPIDAR [1]. We compare the proposed and the conventional methods.

6.1 The setup of the experiment

The shape of the rigid body is a rectangular parallelepiped of 6cm width × 10cm height. The acceleration of gravity is set to 2.0 m/s^2 because the output force of the haptic interface is limited. The spring coefficients of the spring models for the grasping force calculation and inertial force calculation are 800N/m. Friction forces between the fingers and the rigid body are considered. The friction coefficient is 1.0 .

Subjects see a realtime computer graphics which shows the grasped object and the positions of fingers in the virtual world. Fig. 7 shows the setup of the experiment. We ask subjects to repeat a sequence of shaking the object eight times and waiting two seconds, which was done in the measurement in section 2.2. Five subjects participate to the experiment.

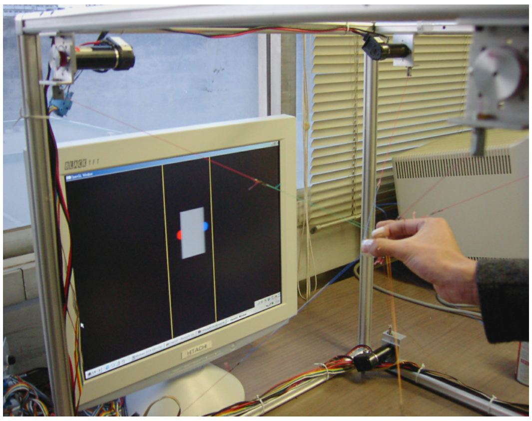

Figure 7: The setup of the experiment for comparison

Table 1: Averages and standard deviations of the grasping forces

subject	A	B	C	D	E
ave.(conv.)[N]	2.0	2.0	1.7	1.8	4.1
ave.(prop.)[N]	2.2	2.4	1.6	1.6	4.7
dev.(conv.)[N]	0.39	0.35	0.28	0.35	0.77
dev.(prop.)[N]	0.34	0.29	0.21	0.22	0.35

6.2 The result of the experiment

Fig. 8 and Fig. 9 shows an instance of the result of the experiment. In addition, table 1 and table 2 shows averages and standard deviations of 0 to 30 second in the grasping force and the distance between the fingers. Standard deviations on table 1 and table 2 and Fig. 8 show that changes (deviations) on the grasping force and the distance between the fingers are smaller (different in significance levels of 10This shows the grasp presented by proposed method is more stable and better approximation of real grasps.

The enlargement (Fig. 9) shows that in the conventional method, there are problems of the decreases of grasping forces and the distances between fingers, when the resultant forces are large (grayed areas of the figure). On the other hand, the decreases of the grasping forces are smaller and the distances between the fingers increase in the proposed method. This result agrees on the hypothesis, which is shown by the equation of the relation between the grasping force and the distance between fingers (Eq. 8).

The equation of the distance between the fingers (Eq. 12) means the grasping force and the distance does not depend on the resultant force. However, the result shows that the grasping force decreases a little and the distance increases and make up the rest. In addition, the distance between the fingers in the conventional model of Fig. 8 is remarkably smaller during the shaking periods (grayed areas of the figure) than that of the waiting period. This result can be explained by a supposition that the subject keeps the distance between the fingers small to keep the grasping force for holding object during shaking. These decreases during shaking are not found in the

Table 2: Averages and standard deviations of the distances between the fingers

subject	A	B	C	D	E
ave.(conv.)[cm]	5.0	5.4	5.5	5.4	4.8
ave.(prop.)[cm]	5.4	5.4	5.6	5.6	4.8
dev.(conv.)[cm]	0.10	0.089	0.076	0.074	0.16
dev.(prop.)[cm]	0.085	0.073	0.054	0.056	0.087

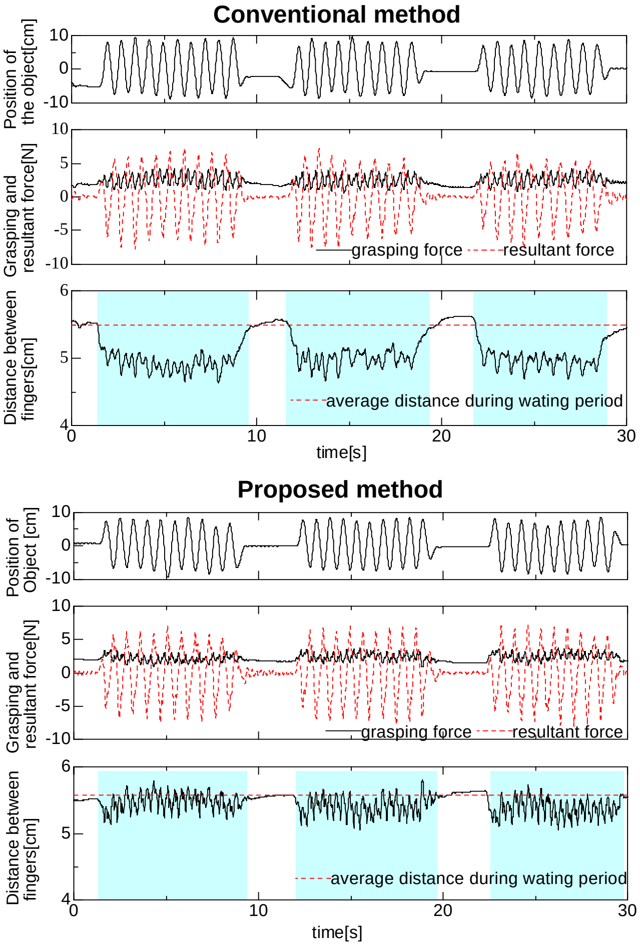

Figure 8: Comparison between the conventional and the proposed method

proposed method.

After the experiment, we aske the subject the impressions of the grasps. Subjects report that the object is more rigid in the proposed method, the object is heavier in the proposed method, and the sensation of the shaking is closer to real objects in the proposed method. There was a subject who reported that he can not distinguish the difference. However, the results of the experiments of him also show the same tendency to the results in Fig. 8.

7 DISCUSSION

There are upper limits in the coefficients of springs in spring models for haptic interfaces. They cause problems on changes of the distance between fingers and grasping forces when the resultant forces are presented. If we grasp and manipulate soft objects in real world, these phenomena will appear. However, most objects to be manipulated in real world are rigid. Therefore, they become problems, when we create a manipulation environment which mimics the real world with haptic interfaces. The proposed method can be understood as a method which transmits the resultant forces more directly to the fingers without increases of spring coefficients.

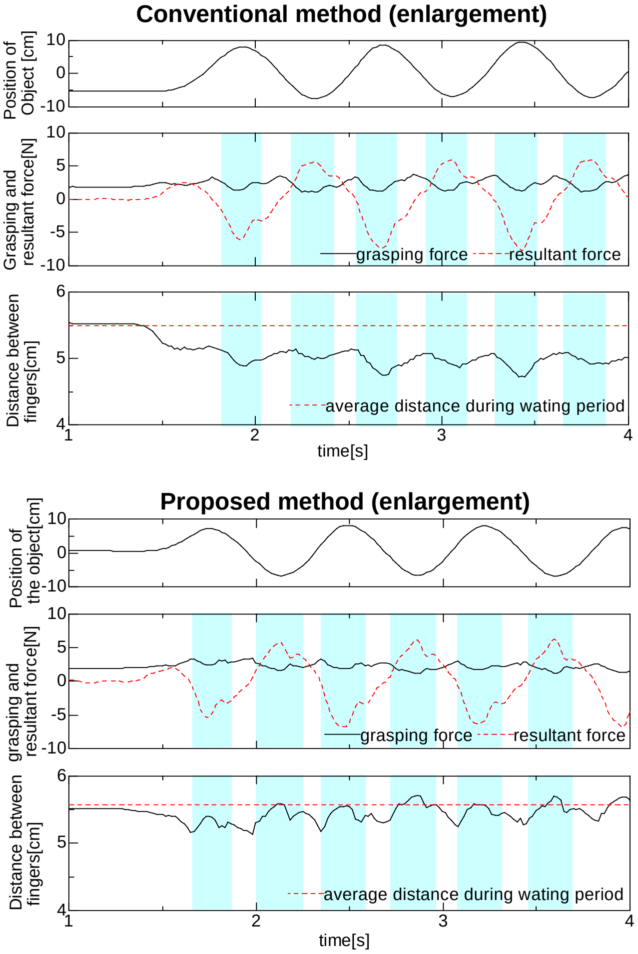

Figure 9: Comparison between the conventional and the proposed method (enlargement)

8 CONCLUSION

In this paper, we measured grasping force during a grasping manipulation in the real world. Then, we pointed out a problem that the resultant forces decrease grasping forces and distances between the fingers in conventional methods for grasp presentations.

Next, we propose to eliminate the influence of the resultant force in the grasping forces by independently calculating the grasping forces and the resultant force and give the resultant force directly to the fingers without passing through the spring models to present the shape. Finally, we confirmed the effectiveness of the proposed method with an experiment.

9 FUTURE DIRECTIONS

In this paper, we discussed about a resultant force which is parallel to the direction of the grasp. Flanagan et.al [9] reports that grasping forces are changed when resultant forces of orthogonal direction to the grasping direction are added. By controlling the presentation forces according to the direction of the grasp and the resultant force, the change of the distance between fingers will become smaller and the better sensation of manipulation will be achieved.

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