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Motion Control of Passive Haptic Device Using Wires with Servo Brakes

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Abstract— **In this paper, we introduce a passive haptic device which consists of wires with servo brakes and its control method for physical support of human being. Since servo brakes control a point constrained by wires, this passive system is intrinsically safe and has a wide operating range. We especially develop a motion support system controlled on plane and conduct a path following experiment for illustrating a possibility of the passive haptic device with wires. We also analyze the system's characteristics by calculating the feasible braking force, and then improve the operating range of the system based on the analysis. Experimental results on path following function illustrate the validity of the system and its control method.**

I. Introduction

Most of robots have been used as industrial robots in factories to replace humans doing tasks which humans do not want to do, or could not do. However, in recent years, we expect to utilize robot systems not only in industrial fields, but also in homes, offices and hospitals in cooperation with humans. Many robot systems have been researched to realize a physical support for human being.

The haptic device is one of the robot systems that could realize the physical support for human being. Haptic devices are expected to apply to virtual reality, rehabilitation, sports training, and so on. They could display a force to user of those devices. In sports training and rehabilitation, especially, system realizes physical support for human to improve the motion of users. For example, sports trainers support motion of players physically, when they teach perfect form. Caregivers also support motion of patients in rehabilitation of the handicapped. In above situations, haptic devices could support human motion physically by displaying forces to users. Many researchers have researched haptic devices based on various themes. Most of the haptic devices researched so far are driven by servo motors. Although haptic devices with servo motors are useful for realizing the several functions, they have serious potential to injure its operator if we cannot control the servo motors appropriately.

From the safety point of view, Furusho et al. have proposed an arm-type haptic device based on a concept of passive robotics [1], PADyC, Passive Arm with Dynamic Constraints has been proposed as an assistant tool for surgeons [2], Applications of the concept to haptic display have been proposed based on Cobot architecture in [3], and dissipative haptic devices using either brakes or clutches have proposed to dissipate or redirect energy in the required direction in [4], [5], [6]. In the concept of passive robotics [7], systems move passively based on external force without using any servo motors. These passive systems are intrinsically safe because they cannot move automatically with driving force. However, the large scale arm-type haptic devices affect the high-speed operation of them because of their large inertia. If we need large operating range and high speed operation of the system in such as sports training, arm-type haptic device could not suitable for the physical support of the human motion.

On the other hand, wire-type haptic devices realize large operating range and high speed operation, because of its small inertial effect. Bouguila et al. and Kawamura et al. proposed large scale wire-type haptic devices [8], [9]. But wire-type haptic devices researched so far are driven by servo motors. They still have serious potential to injure its operator if we cannot control servo motors appropriately.

In this research, we develop a new passive haptic device which consists of wires with servo brakes for physical support of human being. This system is intrinsically safe and has wide operating range because of using wires controlled by servo brakes. However, the control of system using wires with servo brakes is challenging, because servo brakes cannot generate driving force and wires generate only tension. If we control this system based on the concept of passive robotics, it is useful for physical support of human motion with keeping the safety and wide operating range.

In this research, we especially develop a motion support system that consists of wires with servo brakes controlled on plane as shown in Fig.1 for investigating the possibility of wire-type passive haptic device. This paper is organized as follows. Firstly we introduce the motion support system controlled on plane, and then propose its fundamental motion control algorithm. Next, we propose a path following

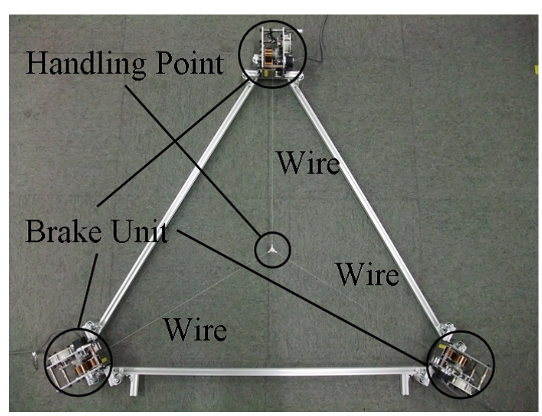

Fig. 1. Motion Support System using Wires with Servo Brakes

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function by displaying a force to user. We also analyze the system's characteristics by calculating the feasible braking force, and improve the operating range of the system based on this analysis. Finally, experimental results on path following motion control illustrate the validity of the proposed system and algorithm.

II. Motion Support System Controlled on Plane

A. Motion Control Requirements of System with Wires

Since wires generate only tension, n wires cannot realize motion control with n degrees of freedom. In motion control with n degrees of freedom, we need at least $n+1$ wires satisfying following conditions [9]. When we set a directional unit vector of $n+1$ wires as $\boldsymbol{w}_i (i = 1, 2, ..., n+1)$, each set of n vectors in $n+1$ vectors are linearly independent and the wires have to satisfy the following condition.

$$\boldsymbol{w}_i = -\sum_{j=1(j \neq i)}^{n+1} \alpha_j \boldsymbol{w}_j \qquad (\alpha_j > 0 \quad for \quad any \quad i) \tag{1}$$

That is, for controlling a motion control with 2 degrees of freedom on plane, we need at least 3 wires.

B. Developed Motion Support System

Based on the condition explained above, we develop a motion support system using three wires with servo brakes as shown in Fig.1 for controlling position of the handling point on plane. The system consists of three brake units, three wires, aluminum frames and a controller. We control the motion of handling point which is the intersection of wires. A distance between two brake units is 1 m.

The brake unit is shown in Fig.2. The brake unit consists of a powder brake, a constant force spring, an encoder, a pulley, three gears and a wire. We used Powder Brake (MITSUBISHI Corp., ZKG-5YN, Maximum on-state Torque: 0.5 Nm) as the servo brake. It provides high response and good linearity on controlling the braking torque of brake units. The wire pulled out from the brake unit and reeled. A braking force transmitted from the powder brake to the pulley through gears. We have to apply tensions to wires in order to control motion of the handling point of the system. However, the powder brake cannot reel in the wire because it cannot generate driving force. To overcome this problem, the constant force spring apply a constant tension to each wire and handling point is balanced through the wires with constant tensions. The constant force spring can reel in a wire speedily, because the torque/inertia ratio of the output part is very high. The system provides high response and could be applied to the high speed operation such as sports training.

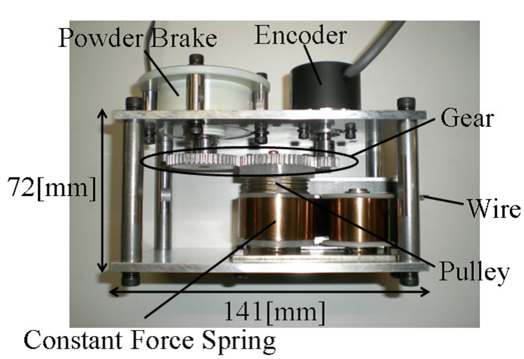


Fig. 2. Brake Unit using Constant Force Spring

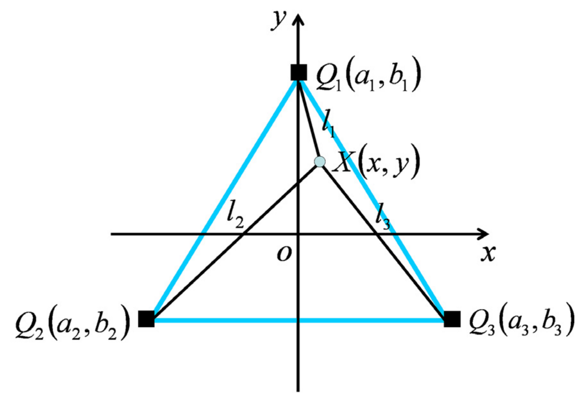


Fig. 3. Coordinates of Support System with Three Brake Units

III. Fundamental Motion Control Algorithm

A. Kinematics of System with Brake Units

The coordinate system of passive motion support system is set as shown in Fig.3. $Q_i(a_i, b_i)$ is a position of i-th brake unit. l_i is a wire length which is calculated by using encoder information. $X(x, y)$ is a position of the handling point constrained by wires. The relationship between $Q_i(a_i, b_i)$, l_i and $X(x, y)$ can be expressed as following equations.

$$(x - a_1)^2 + (y - b_1)^2 = {l_1}^2 \tag{2}$$

$$(x - a_2)^2 + (y - b_2)^2 = {l_2}^2 \tag{3}$$

$$(x - a_3)^2 + (y - b_3)^2 = {l_3}^2 \tag{4}$$

B. Relationship between Tensions and Force Applied to Handling Point

A directional unit vector of i-th wire is expressed as the following equation.

$$\boldsymbol{w}_i = \frac{\overrightarrow{XQ_i}}{\overline{XQ_i}} = \begin{bmatrix} w_{ix} \\ w_{iy} \end{bmatrix} \tag{5}$$

We define wire matrix W as follows:

$$W = \begin{bmatrix} \boldsymbol{w}_1 & \boldsymbol{w}_2 & \boldsymbol{w}_3 \end{bmatrix} \tag{6}$$

When $\boldsymbol{t}$ is a vector of wire tensions and $\boldsymbol{f}$ is a resultant vector of forces acting on the handling point, $\boldsymbol{t}$ and $\boldsymbol{f}$ are expressed as follows [9]:

$$\boldsymbol{f} = W\boldsymbol{t} \tag{7}$$

$$\boldsymbol{t} = W^{\dagger}\boldsymbol{f} + (I - W^{\dagger}W)\boldsymbol{k} \tag{8}$$

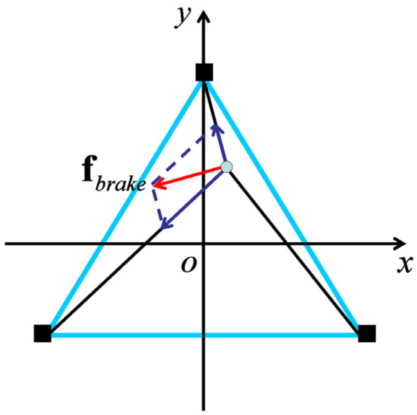


Fig. 4. Decomposition of Desired Force along Wire Directions

where,

$$\boldsymbol{f} = \begin{bmatrix} f_x & f_y \end{bmatrix}^T, \quad \boldsymbol{t} = \begin{bmatrix} t_1 & t_2 & t_3 \end{bmatrix}^T \tag{9}$$

$W^{\dagger}$ is pseudo-inverse matrix of W, $I \in R^{3\times3}$ is a unit matrix and $\boldsymbol{k}$ is a three-dimensional non-unique vector. The second term of right side in eq.(8) is tension component acting system as internal force [9], [10].

Different from the system using servo motors, powder brakes and constant force springs of the proposed passive system provide tensions to wires. We explain a method of the proposed system to apply a desired force to the handling point. Let $\boldsymbol{t}_{brake}$ be a vector of wire tensions applied by braking forces generated by powder brakes, and $\boldsymbol{t}_{spring}$ be a vector of wire tensions applied by constant force springs. Let $\boldsymbol{f}_{brake}$ be the resultant vector of forces acting on the handling point which applied by $\boldsymbol{t}_{brake}$, and $\boldsymbol{f}_{spring}$ be the resultant vector of forces acting on the handling point which applied by $\boldsymbol{t}_{spring}$.

When we assume that an internal force applied by the constant force spring is small in this paper, we ignore $\boldsymbol{f}_{spring}$ for controlling the motion of the system. Therefore, when we let $\boldsymbol{f}_{desired}$ be a vector of desired force acting on the handling point, we regard $\boldsymbol{f}_{brake}$ as follows:

$$\boldsymbol{f}_{brake} = \boldsymbol{f}_{desired} \tag{10}$$

We decompose $\boldsymbol{f}_{brake}$ along wire directions as shown in Fig.4 and obtain $\boldsymbol{t}_{brake}$. We apply $\boldsymbol{t}_{brake}$ to wires by controlling powder brakes. Actually we should consider the influence of the resultant force applied by the constant force spring for displaying the desired force accurately to the handling point. We will analyze its resultant force and propose a motion control method considering it in the next stage of our research.

C. Constraint of Servo Brakes

In the proposed system, we can control of motion of the handling point by using braking forces generated by powder brakes. However, $\boldsymbol{t}_{brake}$ has to satisfy following conditions, because servo brakes cannot generate driving force and wires

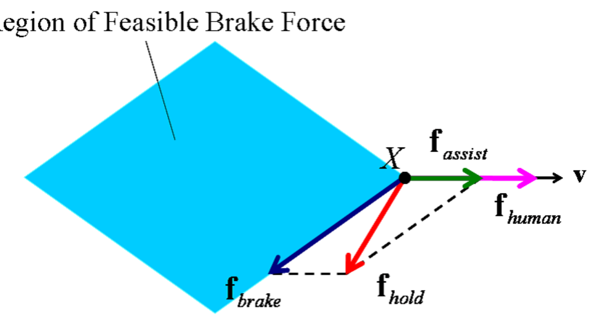


Fig. 5. Region of Feasible Braking Force

can only generate tension.

$$t_{i,brake} = \frac{\tau_{i,brake}}{r} > 0 \tag{11}$$

$$\tau_{i,brake}\ \omega_i \leq 0 \tag{12}$$

where, $t_{i,brake}$ is a wire tension applied by the brake unit i, $\tau_{i,brake}$ is a brake torque generated by the powder brake installed in the brake unit i, r is a radius of pulley, ω_i is an angular velocity of the pulley of the brake unit i. We derive following equations from eq.(11) and eq.(12).

$$t_{i,brake} > 0,\ \tau_{i,brake} > 0,\ \omega_i \leq 0 \tag{13}$$

According to eq.(13), it is obvious that we can only apply $\boldsymbol{t}_{brake}$, when the wire pulled out from the brake unit. That is, $\boldsymbol{f}_{brake}$ cannot realize arbitrary force in a plane. This is a brake constraint and makes it difficult to control the motion of the system.

D. Motion Control Method based on Feasible Braking force

By considering the problem of brake constraint, in this section, we propose a motion control method to guide the handling point. In our previous researches, we proposed motion control algorithms for omni-directional mobile robots with servo brakes [11]. We extend the proposed control method of the passive mobile robot to the control of wire-type passive haptic device.

Firstly, we consider feasible braking forces. The brake constraint expressed in eq.(13) is determined by the position and direction of velocity of the handling point, that is, the feasible braking forces are depended on them. A set of vectors of the feasible braking force at a certain moment make a region in opposite direction of velocity of the handling point as shown in Fig.5. This region is a set of force vectors and call as the feasible braking force region.

Let $\boldsymbol{f}_{hold}$ be a vector of a desired force to hold handling point on a path, when we realize a path following function, and $\boldsymbol{f}_{human}$ be a vector of force applied by human. We assume that direction of $\boldsymbol{f}_{human}$ and direction of velocity of the handling point are in the same direction, because an inertia of the handling point is small. For an active type system using servo motors, we just simply command to servo motors of the system to generate torques for realizing this desired force $\boldsymbol{f}_{hold}$. However, in the control of the passive

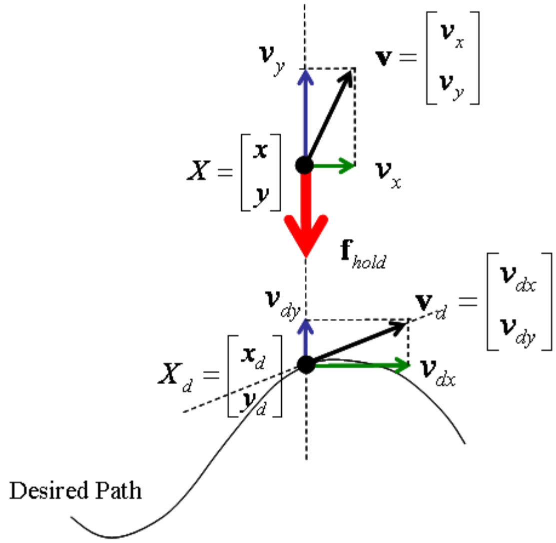
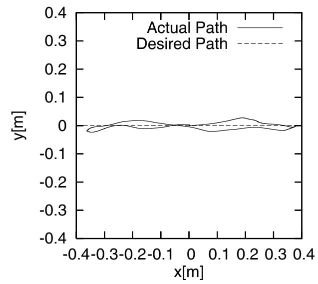
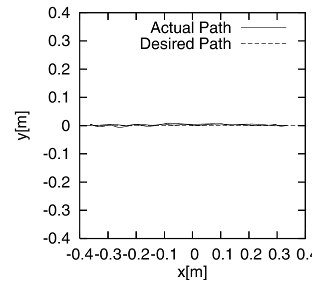


Fig. 6. Method for Path Following Control

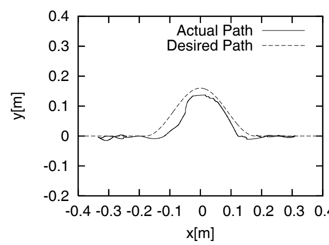


(a) Without Control

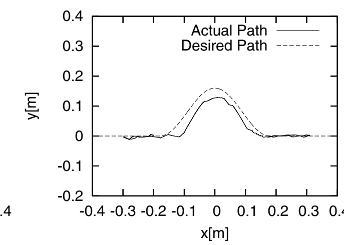


(b) With Control

Fig. 7. Experimental Results for Straight Line Following



(a) Without Control



(b) With Control

Fig. 8. Experimental Results for Curve Following

system, the feasible braking forces always depend on the current motion of the system. If the desired force $\boldsymbol{f}_{hold}$ is within the feasible brake force set, we can command the braking force directly as $\boldsymbol{f}_{brake} = \boldsymbol{f}_{hold}$.

On the other hand, of course, many cases exist that the desired force $\boldsymbol{f}_{hold}$ is located out of the feasible set of the force as shown in Fig.5, and cannot be generated by servo brakes. When $\boldsymbol{f}_{hold}$ is located out of the feasible set of the force, we utilize a part of $\boldsymbol{f}_{human}$ to compensate the insufficient braking force. The force applied by the human $\boldsymbol{f}_{human}$ could be divided into two elements. One is the driving force utilized for moving the handling point along the direction of the force applied by the human, and the other is the human assist force $\boldsymbol{f}_{assist}$ which compensates the insufficient braking force for realizing the $\boldsymbol{f}_{hold}$ as shown in Fig.5. This means that the desired force could be generated by the composition of the feasible braking force and the assistive force, which is a part of the force applied by the human, even when the desired force is out of the feasible braking force region.

IV. Path Following Control

A. Algorithm for Path Following Control

In this section, we propose a function to guide human's hands along a path by displaying a force. This function is useful for training to acquire correct form in sports and rehabilitation. In this function, the human moves the handling point to follow the path preferably. The system supports the human motion by displaying a force and the precise path following of the handling point is realized.

In this paper, we prepared a straight line and cosine curve for the path following control experimentally. In this experiment, we did not show the desired paths explicitly on the experimental plane, and tell the user about only the kinds of following line such as straight line and cosine curve. The users conducted the experiments after several practices to follow the path.

We explain how to define the force $\boldsymbol{f}_{hold}$ to support the human motion below. Let $X = \begin{bmatrix} x & y \end{bmatrix}^T$ be a position of the handling point, and $X_d = \begin{bmatrix} x_d & y_d \end{bmatrix}^T$ be a position of the desired point on the desired path, which is at the same x-coordinate as $X = \begin{bmatrix} x & y \end{bmatrix}^T$. Let $\boldsymbol{v}$ be a normalized vector of velocity of the handling point, and $\boldsymbol{v}_d$ be a unit vector of tangential direction on the desired point. Then we apply a force $\boldsymbol{f}_{hold}$ shown in eq.(14) along y-axis to the handling point. We show the concept of this algorithm in Fig.6.

$$\boldsymbol{f}_{hold} = K_p(y_d - y) + K_d(v_{dy} - v_y) \tag{14}$$

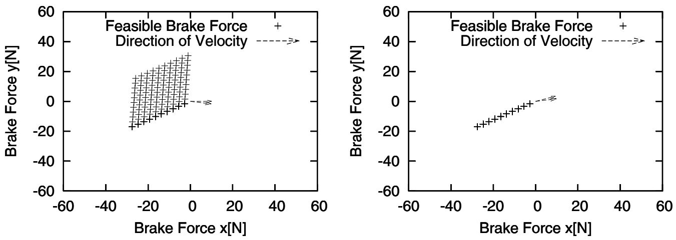
where K_p and K_d are gains. And then, $\boldsymbol{f}_{brake}$ is generated based on the method proposed in previous section.

B. Experimental Results

We conducted the straight line following experiment and cosine curve following experiment to verify the validity of the proposed algorithm. The straight line path is $y = 0$, and the cosine curve path is expressed as follows:

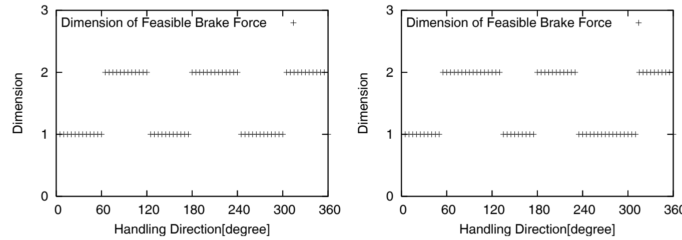
$$y = B\cos\left(\frac{\pi}{A}x\right) + B \tag{15}$$

We set A=0.18[m], B=0.08[m] in this experiment. The human operator moves the handling point to follow the path preferably, and the system supports the human motion by displaying the force $\boldsymbol{f}_{hold}$ defined above to handling point.



(a) x=-0.03, y=0.0 (b) x=-0.03, y=0.116

Fig. 9. Feasible Braking Force by Three Brake Units



(a) x=-0.03, y=0.0 (b) x=-0.03, y=0.116

Fig. 10. Dimension of Feasible Brake Force by Three Brake Units

Experimental results are illustrated in Fig.7 and Fig.8. We set $K_p = 1000$, $K_d = 100$ in the straight line following and $K_p = 800$, $K_d = 80$ in the cosine curve following.

Fig.7(a) is experimental result without support force $\boldsymbol{f}_{hold}$ and Fig.7(b) is experimental result with a support force $\boldsymbol{f}_{hold}$ in straight line following. Fig.8(a) is experimental result without support force $\boldsymbol{f}_{hold}$ and Fig.8(b) is the experimental result with support force $\boldsymbol{f}_{hold}$ in cosine curve following. The dotted line expresses the desired path and the solid line expresses actual path. From Fig.7, following capability to the desired path is increased by controlling the support force in straight line following. However, from Fig.8 following capability to the desired path is not so increased in cosine curve following, even when we control the support force. This system might not generate arbitrary forces, because the number of brake units to generate braking force is shortage. In next section, we analyze these experimental results and show a possibility to solve this problem.

V. Analysis of Feasible Braking Force

A. *Feasible Braking Force in Path Following Experiments*

A region of feasible braking forces acting on the handling point at a certain moment is determined by the position and direction of velocity of the handling point as mentioned above. We calculate the feasible brake forces in the experiments in section IV.B. Calculation results are illustrated in Fig.9. Fig.9(a) expresses the feasible braking force, when the handling point located at (x=-0.03, y=0.0) in the straight line following experiment shown in Fig.7(b). Fig.9(b) expresses the feasible braking force, when the handling point located at (x=-0.03, y=0.116) in the cosine curve following experiment shown in Fig.8(b). We calculate these feasible braking forces according to the actual position and direction of velocity of handling point in the experiments. The starting point of the vector expresses the handling point, the direction of the vector expresses the direction of velocity, and the set of points expresses the set of vectors of feasible braking forces in Fig.9.

From Fig.9(b), the feasible braking force is one direction, that is only one wire is pulled from the brake unit. We define it as one-dimensional feasible braking force. In the experiment as shown in Fig.8, the system has to generate a positive force along y-axis to move the handling point closer to the desired cosine curve based on the path following algorithm. However, the system cannot generate that force even if the system utilize the human assist force $\boldsymbol{f}_{assist}$ explained in section III.D, because the system can only generate the braking force in one direction shown in Fig.9(b). Therefore, the following capability to the desired path is low in the experiment of the cosine curve following.

On the other hand, in Fig.9(a), the system can generate feasible braking force in several directions and it is defined as two-dimensional feasible braking force. In this case, the system can generate desired force to the handling point by using the method proposed in section III.D. Therefore, we can see that the following capability to the desired path is high in the straight line following experiment. From these results, we find that the following capability to the desired path depends on dimensions of region of the feasible braking forces.

B. *Analysis of Region of Feasible Braking Force*

We analyze how much the situation of one-dimensional feasible braking force is happened based on change of the velocity direction of the handling point, because that situation causes the low following capability. The result is illustrated in Fig.10. Fig.10 expresses whether feasible braking force is one dimension or two dimensions in each directions of velocity of the handling point. We change the direction of velocity of the handling point from 0 deg to 360 deg every 5 deg. The number of vertical axis of the experimental results expresses dimension of the feasible braking force. Fig.10(a) is the calculated result at the position(x=-0.03, y=0.0) and Fig.10(b) is the calculated result at the position (x=-0.03, y=0.116). They are the same positions in Fig. 9.

From Fig.10, the feasible braking force is one dimension in half of whole angle of direction of velocity. This fact indicates that the system cannot generate the desired force frequently and the following capability would be decreased. When the desired path is simple such as straight line shown in Fig.7, the system could support the motion of the human, because the direction of velocity would not change so much. However, if the desired path become complex, the following capability would be low.

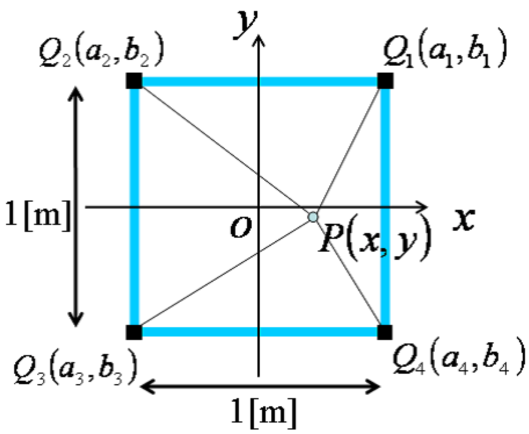
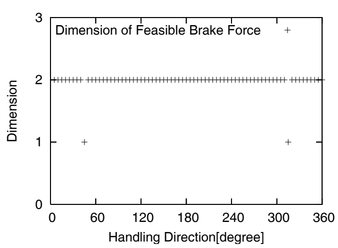
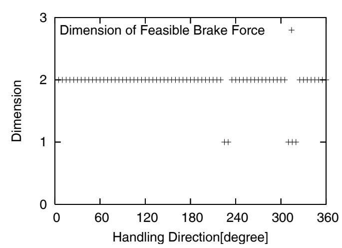


Fig. 11. Coordinates of Support System with Four Brake Units

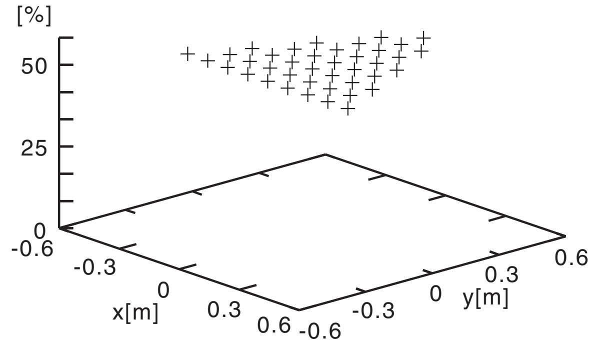


(a) x=-0.03, y=0.0

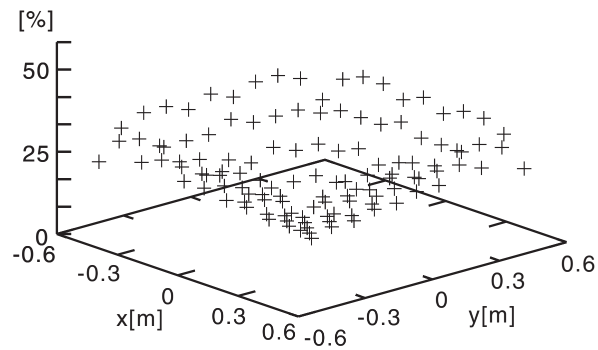


(b) x=-0.03, y=0.116

Fig. 12. Dimension of Feasible Brake Force by Four Brake Units



(a) Three Brake Units



(b) Four Brake Units

Fig. 13. Rate of One-dimensional Feasible Braking Force in Operating Range

VI. Improvement of Control Performance by using Additional Brake Units

A. Analysis of Region of Feasible Braking Force

In this section, we intend to solve the problem of one-dimensional braking force region explained in previous section. We intuitively think that this problem could be solved by increasing the number of the brake units. For analyzing and investigating the performance of the system with different number of the brake units, we develop a motion support system with four brake units and analyze the feasible braking forces. The coordinate system is set as shown in Fig.11. A distance between each adjacent brake units is 1 m. We extend the motion control algorithm proposed in section III to the system with four brake units.

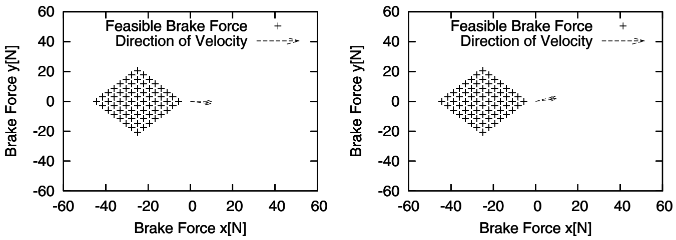
We also calculate dimensions of feasible braking force and show the calculated results in Fig.12. Fig.12 expresses whether feasible braking force is one dimension or two dimensions in each directions of velocity. We calculate at positions (x=-0.03, y=0.0) and (x=-0.03, y=0.116), and they are the same positions in Fig.10.

Fig.12(a) expresses that feasible brake force is one dimension in 5.6 % of whole angle of direction of velocity, and Fig.12(b) expresses that feasible braking force is one dimension in 13.8 % of whole angle of direction of velocity. From the results, by using four brake units, we reduce directions of velocity in which the feasible braking force is one dimension compared to the result in Fig.10. This indicates that capability to realize the desired force would be improved.

We perform this calculation in whole operating range of the system. The calculated results are illustrated in Fig.13. Fig.13 expresses that how much the direction of velocity, in which the feasible brake force is one dimension, exists at each point in the operating range. Fig.13(a) is the result of the system with three brake units. Fig.13(b) is the result of the system with four brake units.

In the system with three brake units, feasible brake force is one dimension in half of whole angles (360 deg) of direction of velocity at all the positions in operating range. In the system with four brake units, the direction of velocity, in which the feasible brake force is one dimension, is especially low at neighborhood of origin and the system has two-dimensional feasible braking force region at the origin with respect to all the velocity directions. This result indicates that the control performance would incense at the neighborhood of origin.

We also calculate the feasible brake forces of the system with four brake units at positions (x=-0.03, y=0.0) and (x=-0.03, y=0.116), they are the same positions in Fig.9. Calculation results are illustrated in Fig.14. In Fig.14(a) and Fig.14(b), the feasible brake forces are two dimensions, so



(a) x=-0.03, y=0.0 (b) x=-0.03, y=0.116

Fig. 14. Feasible Braking Force by Four Brake Units

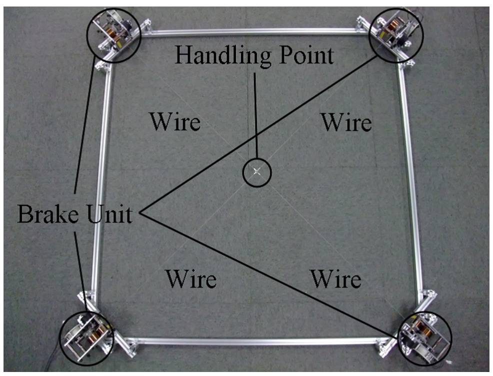
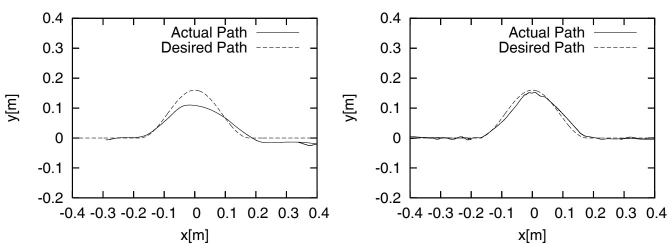


Fig. 15. Motion Support System with Four Brake Units



(a) Without Control (b) With Control

Fig. 16. Experimental Results for Curve Following

that the system could generate braking force along many directions and could guide the handling point by using method proposed in section III.D.

B. Path Following Experiment

We developed the system with four brake units, and conducted the path following experiments that is same as the experiments in section IV. The developed system is shown in Fig.15. The experimental results are illustrated in Fig.16. Fig.16(a) is the experimental result without support force $\boldsymbol{f}_{hold}$ in cosine curve following and Fig.16(b) is the experimental result with support force $\boldsymbol{f}_{hold}$. The performance of path following is improved obviously compared to the experimental results using three brake units shown in Fig. 8(b).

VII. Conclusion

In this paper, we introduced the passive haptic device which consists of wires with servo brakes for the physical support of human being. This system is intrinsically safe and has wide operating range, because of using wires with serve brakes. We proposed the fundamental motion control algorithm of this system, and then we proposed the function to guide human's hand along a path by displaying a force. This function is useful for training to acquire correct form in sports and rehabilitation. The proposed motion control algorithm and the function are implemented to the system actually. We also analyzed system's characteristics by calculating the feasible braking force through experimental results. In this analysis, the problem of one-dimensional feasible braking force is indicated. Then, we developed the system with additional brake units based on the analysis and we conducted the path following experiments. The experimental results illustrated the improvement of the performance by using four brake units and the possibility of the proposed passive system.

As future works, we will consider required number of brake units theoretically for displaying a force accurately. In addition, we analyze the influence of the resultant force applied by the constant force springs and propose a control algorithm considering it. Furthermore, we will extend the 2-D system to 3-D system for realizing the physical support in actual sports training and rehabilitation.

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