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Development of new force feedback interface for two-handed 6DOF manipulation –SPIDAR-G&G system–

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Abstract

In this paper, we developed a new haptic interface SPIDAR-G&G system to take advantage of the user's existing two hands skills for completing the continuous and compound task in a virtual world. A user cannot only manipulate the 3D objects with 6DOF translational and rotational motion by using the grip which located in the workspace of two frames, but also get the 6DOF force feedback, 3DOF for translation force, 3DOF for rotation force. We demonstrate the configuration of our system, also introduce the grip's position and orientation algorithm , and 6DOF force displaying method .
Experiment results show that our system can offer direct two-handed 6DOF manipulation for virtual environment via the sense of touch.

Key words: haptic force feedback interface,two-handed interface, two-handed 6DOF manipulation,6DOF haptic rendering.

1. Introduction

Conventional one-handed interfaces are often less natural and less efficient for compound and continuous tasks than two-handed interface which split these tasks into two-handed subtasks. One of the recent trends in developing human interface is to take advantage of the user's natural bimanual existing skills . Many studies on bimanual action have been proposed and tested, Andrea Leganchuk et al. [1] point out that bimanual manipulation may bring two types of advantages : manual and cognitive. Manual benefits come from increased time motion efficiency, due to the twice as many degrees of freedom simultaneously available to the user. Cognitive benefits arise as a result of reducing the load of mentally composing and visualizing the task at an unnaturally low level imposed by traditional uni-manual techniques.
Most tasks we perform in our everyday lives involve using both hands in different roles, not one hand in isolation. The observation how human distribute tasks between their hands has led to the development of two-handed interface supporting this natural skills.
Many researchers take advantage of several principles developed by Guiard [2] [3] to design two-handed interface. According to Guiard, the most common activities involve a division of task between two hands, and both hands in different roles perform different subtasks to get a complex task done. Overall, two-handed interface can improve the performance for compound and continuous task.

1.1 Related works

There are several representative bimanual developed prototypes. The 3-Draw system [4] for CAD application. The ToolGlass and Magic Lenses system developed by Bier et al. [5], Hinckley at al. designed the neuro-surgical planning system [6], Responsive Workbench system [7]. Additional examples include the 3D CAD system THRED [8], CHIMP system [9] and PolyShop [10] so on. However, to our knowledge these bimanual prototypes are not haptic interface for two-handed 6DOF manipulation.
Our lab developed some string-based haptic force feedback interface for two-handed manipulation. Both-Hands-SPIDAR [11] [12] system which allow the user to perform a kind of assembly task for the cooperative works with two hands. SPIDAR-8 [13] is two-handed, multi-fingered and string-based haptic force feedback interface device, allow user perceive force feedback using fingertip caps. However these devices are limited by its accessibility which means they are not easy to access to or separate from the caps for the user hands. It is also worth mentioning that SPIDAR-G developed by Kim et al [14] is a 6DOF force feedback haptic device, but it is only for one-handed 6DOF manipulation.

1.2 Our Approach

We think that an effective device for VR application on desktop should satisfy the following requirements:

(1) The device should allow natural translation and rotational manipulation of virtual objects with one hand or two hands depending on users preference.
(2) The device should provide force and torque feedback. In fact the lack of force and torque feedback would make it difficult to control virtual objects in a simulation.

Considering above we developed the tension based haptic force feedback interface called SPIDAR-G&G system with a pair of grips ,for more natural and effective two-handed 6DOF manipulation. The name of SPIDAR is for Space Interface Device for Artificial reality. It can provide force and torque feedback within its workspace of translation and rotation motion. We use the incremental method for tracing the grip's position and orientation, and the quadratic programming method for find the tentions of strings to display the force feedback.

Two-handed manipulation leads faster completion time than the one-handed manipulation within the context of the interface. It is concluded that our system takes advantages of the user's existing bimanual skills, and it is highly intuitive two-handed interface with 6DOF motion and 6DOF force feedback.

We believe that our SPIDAR-G&G system is to be effectively used for a number of application such as virtual prototyping, virtual sculpturing, free form modeling, medical simulation, molecular simulation, and tele- operation et al.

2. 6DOF Force Feedback interface –SPIDAR-G

The SPIDAR-G has ability to control the 6DOF position and to propose the 6DOF forces. The overview of the system is shown as Fig.1.

The SPIDAR-G has a grip. We use the grip like a trackball to control motion and orientation of a virtual object wihtin SPIDAR-G. A grip is attached to 8 strings. Each string set up from a motor and an encoder to a grip shown in Fig.2. The strings length got from each encoder's data is used to measure the grip's position. The strings tension from each motor is displayed the feedback forces.

Fig. 1: Overview of SPIDAR-G

The device has following advantages. (1)The user can easily use to access by just grasping the grip. (2)The device can be intutively control controlled by the user.

In this section, we describe the algorithm how the SPIDAR-G display the 6DOF force as 2.1 ,and how the SPIDAR-G gets the position and orientation as 2.2.

2.1 Displaying 6DOF force

In this section, we will show how to determine the tension for all strings to display the 6DOF force, 3DOF for translation force, 3DOF for rotation force.

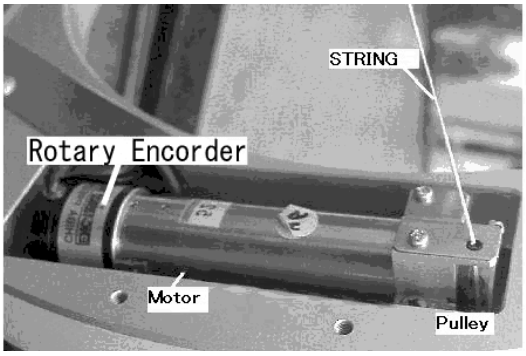


Fig. 2: Moter and Encoder on the frame

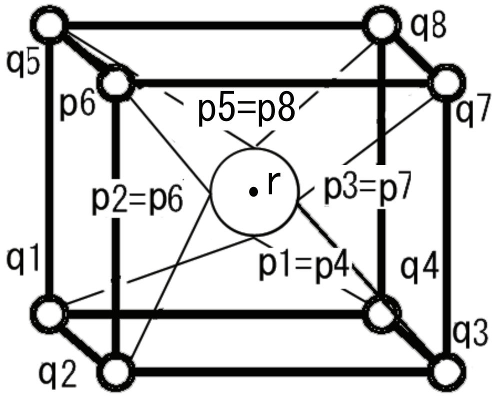


Fig. 3: Basic structure of SPIDAR-G

The basic structure of the SPIDAR-G is shown in Fig.3. We defined the tension τ from each string to the grip by

$$\boldsymbol{\tau} = (\tau_1, \tau_2, \cdots, \tau_8). \tag{1}$$

To calculate the direction of each string, we define the unit vector from motors to contact positions of grip $\boldsymbol{\alpha}_i$ by

$$\boldsymbol{\alpha}_i = \frac{\boldsymbol{q}_i - \boldsymbol{p}_i}{\|\boldsymbol{q}_i - \boldsymbol{p}_i\|}, \tag{2}$$

where $\boldsymbol{q}_i$ is position of the motor, $\boldsymbol{p}_i$ is position vector of the attached point of the grip and each strings at the initial position.

The translation force displayed from the grip $\boldsymbol{F}_t = (f_x, f_y, f_z)^T$ and rotation force displayed from the grip $\boldsymbol{F}_r = (m_x, m_y, m_z)^T$ are

$$\boldsymbol{F}_t = \sum_{i=1}^{8} \tau_i \boldsymbol{\alpha}_i \tag{3}$$

$$\boldsymbol{F}_r = \sum_{i=1}^{8} \tau_i \boldsymbol{\alpha}_i \times \boldsymbol{d}_i \tag{4}$$

To find the suitable force is found by using a some quadratic programming method. The tension vector can be obtained by solving the following problem, minimize;

$$\begin{aligned} J = \quad & \lambda_t \| \sum_{i=1}^{8} \tau_i \boldsymbol{\alpha}_i - \boldsymbol{F}_t \|^2 \\ & + \lambda_r \| \sum_{i=1}^{8} \tau_i \boldsymbol{\alpha}_i \times \boldsymbol{d}_i - \boldsymbol{F}_r \|^2 \\ & + \lambda_s \sum_{i=1}^{8} \tau_i^2 . \end{aligned} \tag{5}$$

subject to;

$$\tau_{min} \leq \tau \leq \tau_{max},$$

where the $\boldsymbol{d}_i$ is vector of the center of grip $\boldsymbol{r}$ to attached position of the grip and string in the initial position.
We set three parameters $(\lambda_t, \lambda_r, \lambda_s)$ to determine the trade-off between stability, accuracy of the presenting force and accuracy of the presenting torque.

2.2 Getting the grip's position and orientation

In this section, we will show how to get the posture of the grip $\boldsymbol{r} = (x, y, z, \theta_x, \theta_y, \theta_z)$ from the all strings $\boldsymbol{l} = (l_1, l_2 \cdots, l_8)^T$.
The relation between the grip's posture $\boldsymbol{r}$ and length of each string $\boldsymbol{l}$ is

$$\boldsymbol{l} = \boldsymbol{f}(\boldsymbol{r}). \tag{6}$$

It is difficult to find directly the posture $\boldsymbol{r}$ from all string length $\boldsymbol{l}$. So, to find the the posture $\boldsymbol{r}$, we calcurate the differential length of string $\Delta\boldsymbol{l}$ and differential posture $\Delta\boldsymbol{r}$ from time t to Δt, by using the Jacobian matrix,

$$\Delta\boldsymbol{l} = \boldsymbol{J}\Delta\boldsymbol{r}, \tag{7}$$

where $\boldsymbol{J}$ is

$$\boldsymbol{J} = -\left[\begin{array}{cccc} \boldsymbol{a}_1 & \boldsymbol{a}_2 & \cdots & \boldsymbol{a}_8 \end{array} \right]^T, \tag{8}$$

where the $\boldsymbol{a}_i$ is

$$\boldsymbol{a}_i \equiv \left[\begin{array}{c} \boldsymbol{\alpha}_i \\ \\ \boldsymbol{\alpha}_i \times \boldsymbol{d}_i \end{array} \right]. \tag{9}$$

The derivation method of the Jacobian Matrix is described in Appendix.
To find the $\Delta\boldsymbol{r}$,(7) is

$$\Delta\boldsymbol{r} = \boldsymbol{J}^{+}\Delta\boldsymbol{l}. \tag{10}$$

Then the position of the grip can be found as

$$\boldsymbol{r} = \boldsymbol{r}' + \Delta\boldsymbol{r}, \tag{11}$$

where $\boldsymbol{r}'$ is the measured posture $\boldsymbol{r}$ from time t.
Using above incremental method, we can trace the grip's 6DOF posture at every time.

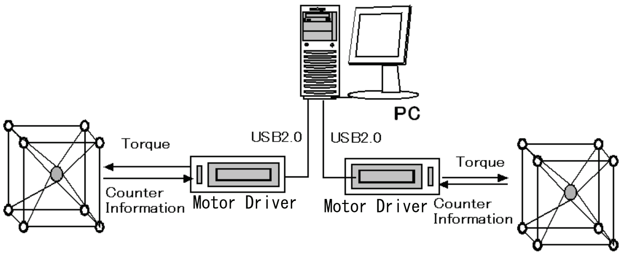


Fig. 4: System configuration for SPIDAR-G&G system

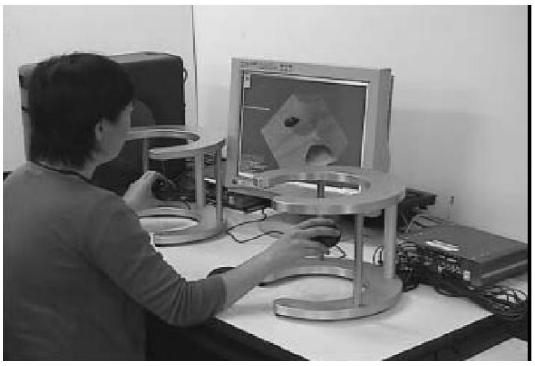


Fig. 5: Overview of SPIDAR-G&Gsystem

3. The SPIDAR-G&G system

3.1 The system configuration

The developed SPIDAR- G&G system is shown as Fig. 4, The system has two SPIDAR- G and two motor driver developed by CyVerse Corp. [15]. From each motor driver use the USB2.0 to connect with the computer.
The concrete system configuration is shown as Fig.5. The length for the frames is 20 $[cm]$. The form of grip is a sphere, and its radius is 3.25$[cm]$. The grip allows the user to manipulate virtual object with 6DOF in the workspace of every frame by grasping it between the thumb and other fingers.
At setting location of the SPIDAR-G&G system, two SPIDAR-G is put on the both side of a display monitor. The user manipulate some virtual object by each SPIDAR-G using each hand ,looking at the display monitor.

3.2 The process of SPIDAR-G&G

The process of the system that work as Fig.6. Each SPIDAR-G are worked the same algorithm for both.
At first the system get the position and orientation by measuring the string's length. Secondly, the system calculates collision detection between the objects on a virtual environment and update them. Finally, the system proposes the suitable feedback forces by the string's tension. The rendaring rate is executed at 1$[kHz]$ over again during running of a virtual environment.

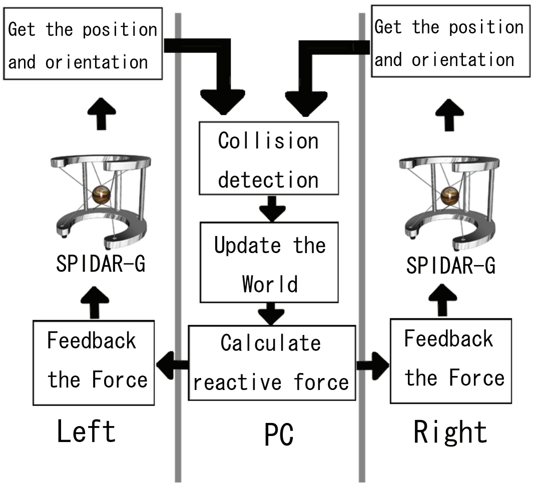


Fig. 6: The system process of SPIDAR-G&G

4. Evaluating the System

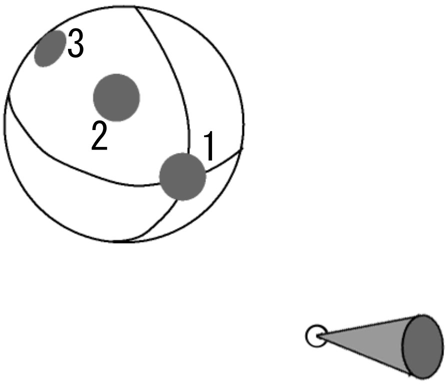
4.1 Evaluation experiment

In order to verify the efficiency of the proposed system, we performed an evaluation experiment with two different task conditions; one bimanual task with using SPIDAR-G&G, the other uni-manual task with using SPIDAR-G and a keyboard. A subject was asked to bring the pointer to the targets positioned on a sphere and contact each other on three-dimensional virtual space. We call this '3D pointing task'. We also tried to investigate the influence of haptic feedback on task performance by comparing two conditions, with haptic feedback and without it. We measured the time required to complete the task and considered that an evaluation index.

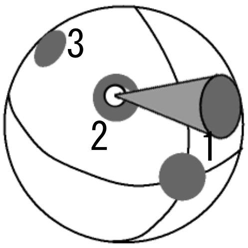
4.2 Subjects and general procedures

Two healthy men and a woman between 23 and 25 years of age participated in the experiments after providing informed consent. The subjects were all right-handed. The subject sat at a table and pushed the 'spacebar' of the keyboard, and then the initial scene was displayed on a computer monitor located in front of the subject. The initial scene displayed a pointer representing the grip position of the SPIDAR-G manipulated by the right hand and a sphere that contained the targets as three-dimensional images shown in Fig. 7. The pointer was represented as a corn shape, and targets were red circles with radius of 1-cm in the sphere which had 9.5-cm radius, and the sizes of pointer and targets were varied according to the spacial movement in the direction of z-axis. The targets were set at three spots of the virtual sphere; the center of front (target 1), the upper side from target 1 (target 2) and the opposite side to target 1 (target 3). The subject was required to change the target position by rotating the sphere.

In the case without haptic feedback, the subject perceived the completion of the task by visual feedback whether the pointer went into the target. In the case with haptic feedback, the subject could recognize the completion of the task by haptic feedback. The task time was recorded from the moment the pointer started to move till the moment of the contact with a target occurred.



(a) Initial positions of the targets and the pointer



(b) The position that the pointer has pointed on the target

Fig. 7: The 3D pointing task

4.3 3D pointing tasks

Before the tasks, the subject was given several minutes to explore the virtual space while receiving visual and haptic feedback. After that, the experiments were performed in the following order.

1. Bi-manual task using SPIDAR-G&G without haptic feedback.
2. Uni-manual task using SPIDAR-G and keyboard without haptic feedback.
3. Bi-manual task using SPIDAR-G&G with haptic feedback.
4. Uni-manual task using SPIDAR-G and keyboard with haptic feedback.

In each session, the subject performed 20 trials from the target 1 to target 3 in alternation for a total of 60 trials. When performing the bimanual task, the sphere that contains three targets was controlled by the left hand, and the pointer was manipulated by the right hand simultaneously. In uni-manual task, on the other hand, the pointer and the sphere were controlled just by right hand. At the initial condition, the pointer was controlled by a SPIDAR-G. Therefore, the subject was required to switch the control mode from the pointer to the sphere. Switching between two control modes was achieved by pushing the 'c' of the keyboard.

4.4 Experimental results

The result of this experiments are shown as Fig.8 and Fig.9 for each subject. The average task times are illustrated in Fig. 10 for all three participants as Fig.8 and Fig.9. The upper panel shows the result with haptic feedback, and the panel below without haptic feedback. Each number of a horizontal axis denotes the target respectively. As expected, the task time of the uni-manual manipulation by using a SPIDAR-G was longer than the bimanual manipulation by using SPIDAR-G&G over most task conditions, because it was performed in sequence to switch from the pointer to sphere. We found, in the case of SPIDAR-G, the task time showed a tendency to increase as task requirement gets difficult. On the other hand, in the case of SPIDAR-G&G, it took a short time to complete the task. There was also a slight difference in task time among the three targets. It means that the bimanual manipulation using the SPIDAR-G&G promotes the task efficiency because it enables the user to execute the spatial and temporal bimanual cooperation task simultaneously.

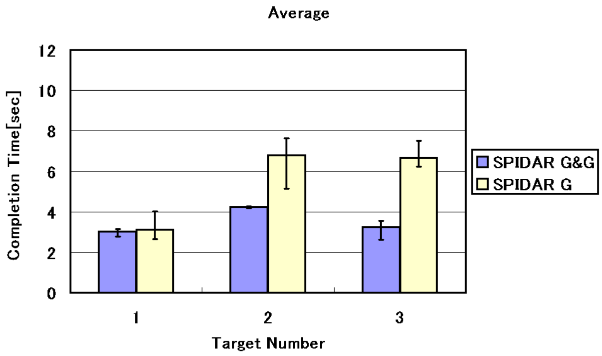
Fig.11 shows the task time rate between using haptic feedback and not using haptic feedback. We observed that the task time decreased when haptic feedback was provided over all task conditions. It clearly shows that task efficiency largely depends on the haptic feedback in 3D pointing task.

From these results, we found that our proposed system, SPIDAR-G&G, is relatively effective for performing 3D pointing task compared with conventional uni-manual haptic interface.

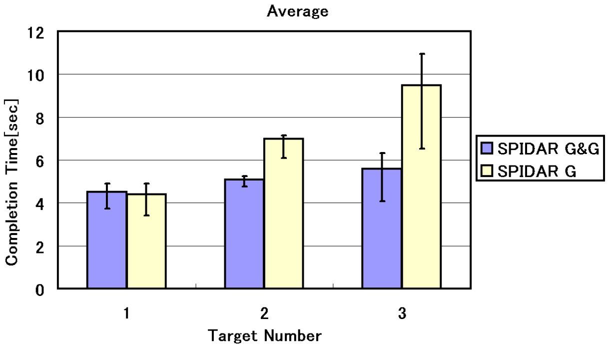
5. Conclusion and future work

In this paper, we described our new haptic force feedback interface SPIDAR-G&G system for two handed 6DOF manipulation. Our system has a number of distinct advantages as following

- System takes advantage of the user's existing bimanual skills.
- User can express complex spatial relation with two easy-to-use grips and control the motion of virtual object.
- User can intuitively manipulate the objects with the grip's translation and rotational motion.



(a) haptic on



(b) haptic off

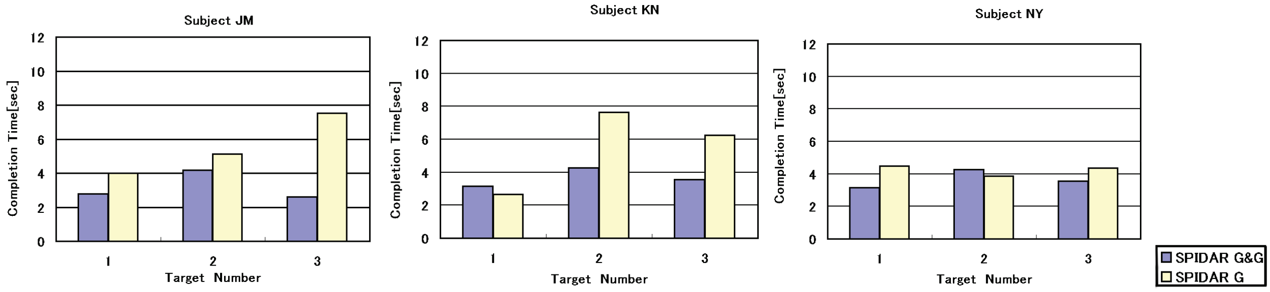
Fig. 10: Average for the subjects

- User can manipulate the virtual object with 6DOF haptic force feedback with some kind of virtual sensation.

We use more stable incremental algorithm to get the grip's position and orientation at every frame time, and based on these information, the appropriate force can be displayed by the tension of string. The application examples show that our system is more intuitive and efficient for two-handed 6DOF manipulation.

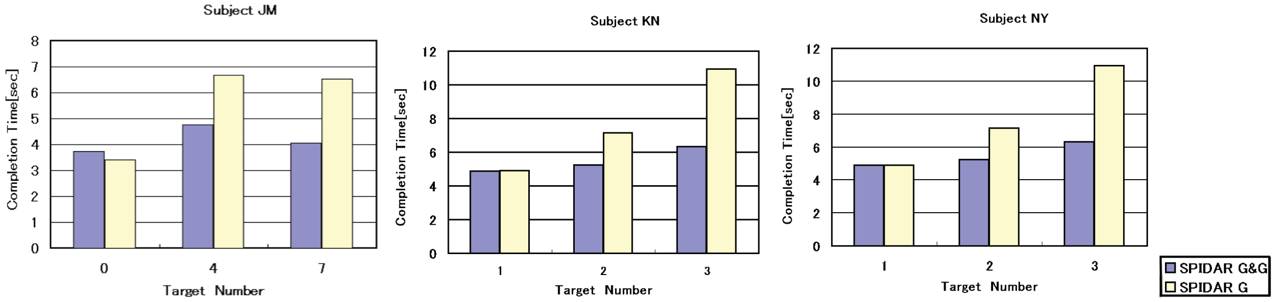
As we believed that the tension based haptic force feedback interface has many good advantages, such as scalable, smooth, safety, no inertia, no backlash and speedy reaction and so on. However the workspace for displaying appropriate force is limited by the area computed from directions of strings, so how to control the force stability is still need to be addressed in future.

Furthermore, clutch functionality to control the grip closed or released state when many object is on a virtual space need to be added in future.



(a) Subject JM (b) Subject KN (c) Subject NY

Fig. 8: Completion time:With haptic



(a) Subject JM (b) Subject KN (c) Subject NY

Fig. 9: The Completion time:Without haptic

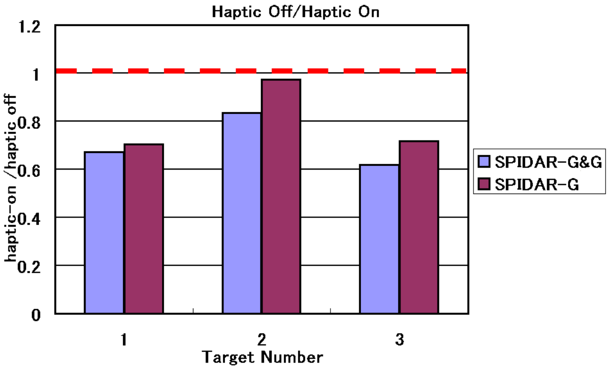


Fig. 11: Rate between when adding the haptic and when not adding the haptic

Appendix

Derivation of $\boldsymbol{J}$

This appendix is described about derivation of the Jacobian Matrix$\boldsymbol{J}$ to find the posture of the grip.

$$\Delta \boldsymbol{r} = \begin{bmatrix} \Delta x \\ \Delta y \\ \Delta z \\ \Delta\theta_x \\ \Delta\theta_y \\ \Delta\theta_z \end{bmatrix} = \begin{bmatrix} \Delta \boldsymbol{r_t} \\ \Delta \boldsymbol{\theta} \end{bmatrix}. \tag{12}$$

At first, the differential posture of the grip $\Delta\boldsymbol{r}$ is devided into the translation distance $\Delta\boldsymbol{r_t} = (\Delta x, \Delta y, \Delta z)^T$ and the differential rotation angle $\Delta\theta = (\Delta\theta_x, \Delta\theta_y, \Delta\theta_z)^T$ Here, we consider the attached position of the grip $\boldsymbol{p}_i = (p_{ix}, p_{iy}, p_{iz})$ and the each string i.

$$\boldsymbol{p}_i \quad = \begin{bmatrix} x \\ y \\ z \end{bmatrix} + \boldsymbol{R}(\theta_x)\boldsymbol{R}(\theta_y)\boldsymbol{R}(\theta_z)\cdot\boldsymbol{d}_i, \tag{13}$$

The differential position of $\Delta\boldsymbol{p}_i$ is

$$\Delta\boldsymbol{p}_i = \Delta\boldsymbol{r_t} + \boldsymbol{d}_i \times \Delta\boldsymbol{\theta}. \tag{14}$$

Next,we consider the differential length Δl_i of each string. The length of each string l_i is

$$l_i^2 = \|\boldsymbol{p}_i - \boldsymbol{q}_i\|^2. \tag{15}$$

Each differential string Δl_i is

$$\begin{aligned} l_i \Delta l_i &= (\boldsymbol{p}_i - \boldsymbol{q}_i)^T \Delta \boldsymbol{p}_i \\ \Delta l_i &= \frac{(\boldsymbol{p}_i - \boldsymbol{q}_i)^T}{\|\boldsymbol{p}_i - \boldsymbol{q}_i\|} \Delta \boldsymbol{p}_i \\ &= -\boldsymbol{\alpha}_i^T \Delta \boldsymbol{p}_i. \end{aligned} \tag{16}$$

From (14) ,(16)and (9), Δl_i is

$$\begin{aligned} \Delta l_i &= -\boldsymbol{\alpha}_i^T (\Delta \boldsymbol{r_t} + \boldsymbol{d}_i \times \Delta \boldsymbol{\theta}) \\ &= -\boldsymbol{\alpha}_i^T \Delta \boldsymbol{r_t} + (-\boldsymbol{\alpha}_i^T \times \boldsymbol{d}_i)^T \Delta \boldsymbol{\theta} \\ &= \begin{bmatrix} -\boldsymbol{\alpha}_i^T & (-\boldsymbol{\alpha}_i^T \times \boldsymbol{d}_i)^T \end{bmatrix} \begin{bmatrix} \Delta \boldsymbol{r_t} \\ \Delta \boldsymbol{\theta} \end{bmatrix} \\ &= -\boldsymbol{a}_i^T \Delta \boldsymbol{r}. \end{aligned} \tag{17}$$

So that, the Jacobian matrix $\boldsymbol{J}$ is

$$J = -[\boldsymbol{a}_1, \boldsymbol{a}_2, \cdots, \boldsymbol{a}_8]^T. \tag{18}$$

By Using this Jacobian Matrix $\boldsymbol{J}$ as (18), the grip's posture is found.

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