ICAT 2002
December 4-6, Tokyo, JAPAN

A wearable force display based on brake change in angular momentum

Hideyuki Ando, Kazutoshi Obana*, Maki Sugimoto, Taro Maeda

Human and Information Science Laboratories, NTT Communication Science Laboratories /
3-1, Morinosato Wakamiya, Atsugi-si, Kanagawa Pref.243-0198 Japan
{hide, sugimoto, maeda}@avg.brl.ntt.co.jp
* School of Information Science and Technology, The University of Tokyo
7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033 Japan
kaz@star.t.u-tokyo.ac.jp

Abstract

Research on wearable non-grounded force display is carrying out recently. We propose a small and lightweight wearable force display to present motion timing and which joint and direction to move directly. This display outputs a torque using rotational moment and mechanical breaks.

Key words: Force display, Wearable devices, Parasitic humanoid, Angular momentum, Behavior induction system

1. Introduction

Recent developments in wearable computing have produced a multitude of information display devices to appeal to the visual and auditory senses. However, these displays are often unsuitable for information pertaining to motion, because the need to interpret audiovisual cues may divert attention and distract the user. For example, when practicing golf or tennis, instruction videos and expert advice lose their effectiveness. We believe that the display of force sensory information is important to assist instruction related directly to motion [1][2]. There have been a number of proposals for information displays using an inner force sensation [3][4]. The display of force indicates direction, part, timing, and direction of motion, which facilitates intuitive understanding of motion in the same direction as the force. Further, the reaction time is reduced because there is no delay for interpretation [5].

Previous research in wearable force display devices has considered support of the body and amplification of power [6], although there have been relatively few developments aiming to display the timing and direction of motion.

We propose a wearable inner force display device for producing motion sensory information that can be intuitively interpreted. This arm-mounted device (illustrated in Fig. 1) can display a perceivable inner force sensation with arbitrary direction and arbitrary timing, to assist in guidance of the arm.

Fig.1 Outline of wearable force information display

2. Previous force display devices

2.1 Classification of force display devices

To date, there have been essentially three types of force displays. The first is the earth-grounded type, which fixes the fulcrum of a device to the ground, such as Phantom and Haptic Master. Although this method can display arbitrary force in an arbitrary direction, the fixation to the ground limits its applications as a wearable device. The second type is the body-grounded type like HapticGear [7], which fixes the fulcrum to the user's body. This method can display arbitrary force sensations, but the force generated from action-reaction effects is displayed to the user as well. This is undesirable since it complicates the accurate display of the direction of motion. The third type employs a moment force generated by the effects of a gyro [4] and changes in angular velocity of a rotating disk [3]. This method circumvents the earth-grounded device's need for a fixed fulcrum, as well as the body-grounded device's reaction force effects. However, it is difficult for an ungrounded device using angular moment to maintain the display of force for extended intervals.

In this research, we adopted a display method using angular moment that can be readily miniaturized for the purposes of wearable computing. We developed a device that displays forces with arbitrary timing and arbitrary direction at short intervals.

2.2 Principle of display using angular moment

A force display using angular moment has effects of a gyro and change in angular velocity of a rotating disk. The following examines these principles in detail.

2.2.1 Method by angular velocity change

Consider a wheel with moment of inertia J [kg-m^2] rotating with angular velocity ω [rad/s], as shown in Figure 2. Here, the torque needed to change the velocity of the wheel is given by the following expression:

$$T = J\frac{d\omega}{dt} \tag{1}$$

To change the velocity of the wheel, it is necessary to output a torque T [N-m] with a motor or brake. If the motor is fixed to the wearer's body, it transmits a torque of -T [N-m] in the opposite direction of the wheel's rotation. Force displays using angular velocity change, such as GyroCube [3], make use of this torque.

2.2.2 Method by effect of gyro

Now consider the same wheel rotating as shown in Figure 3. As shown Figure 3, the wheel of moment of inertia J [N-m] rotates by angular velocity ω [rad/s]. The unit vector in the direction of $\mathbf{x}$, $\mathbf{y}$, $\mathbf{z}$ is $\mathbf{i}$, $\mathbf{j}$, $\mathbf{k}$, the angular velocity around $\mathbf{y}$ axis of gimbals is $\dot{\theta}$ [rad/s], and the angular velocity around $\mathbf{z}$ axis is $\dot{\psi}$ [rad/s]. The angular momentum H_0 of the wheel is expressed as:

$$H_0 \cong J\omega\,\mathbf{i} \tag{2}$$

The angular velocity ω_p [rad/s] expressed from the outside to the wheel becomes:

$$\omega_p = \dot{\theta}\,\mathbf{j} + \dot{\psi}\,\mathbf{k} \tag{3}$$

To conserve angular momentum, a torque T [N-m] is generated in the direction of the cross product of the rotation axis and the gimbals:

$$-T = H_0 \times \omega_p \tag{4}$$

Combining expressions (2), (3) and (4) yields:

$$-T = J\omega\,\dot{\theta}\,\mathbf{k} - J\omega\,\dot{\psi}\,\mathbf{j} \tag{5}$$

GyroDisplay[4] is an example of a force display device that uses this torque.

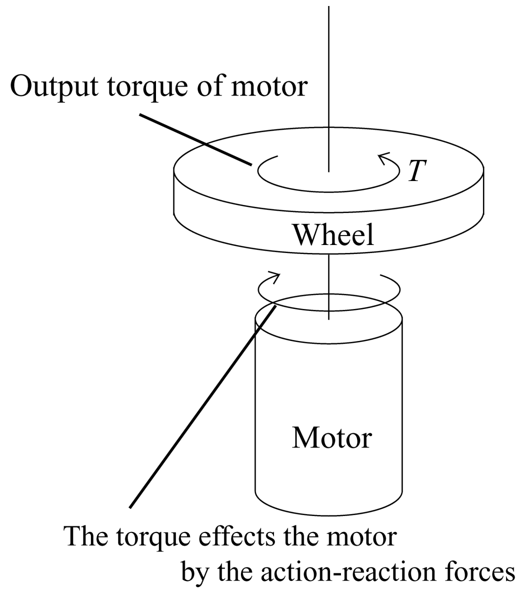

Fig.2 Angular velocity change method

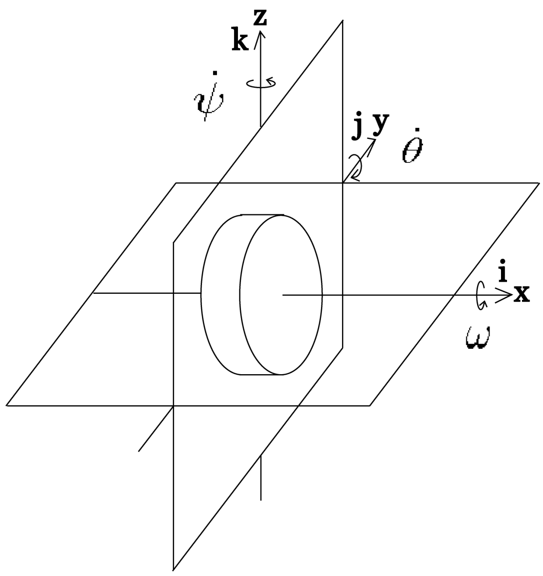

Fig.3 Gyro Effect method

3. Proposed force display device

3.1 Adopted principle

Our goal is a lightweight and wearable device to display force with arbitrary timing and direction. For the power display device using change in a wheel's angular velocity, the output torque is given by expression (1), [moment of inertia] × [change in angular velocity]. On the other hand, for a force display device using the gyro effect, the output torque is given by expression (5), [moment of inertia] × [change in angular velocity] × [angular velocity of gimbals]. Thus with the same wheel and motor, the gyro effect method can output much greater torque than the angular velocity change method.

Because this device is to be mounted on the arm and/or foot, the device must not protrude from the body, and its shape must not disturb behavior. Although the gyro effect method may generate torque more effectively, it requires a gimbals mechanism with enough size and strength to rotate the wheel and the motor, which is difficult to miniaturize. Since the angular velocity change method can be accomplished simply with a small and lightweight wheel and motor, we adopted this method for a wearable force display device.

For a force display device using the angular velocity change method, there are two ways to increase the output torque: increase the wheel's moment of inertia, or increase its rate of change in angular velocity. We have chosen the latter, in order to avoid the associated size and weight costs of enlarging the wheel. GyroCube [3] changes wheel angular velocity through voltage changes of the motor, so the maximum rate of change in angular velocity depends on the torque of the motor. However, in order to generate a large torque, the motor must have a large volume and weight. For example, to generate an output torque of 0.5[N-m] by angular velocity change would require a motor with a starting torque of 0.5 [N-m], which would need about 0.5 [kg] per unit. It is evident that the weight of the entire device would become several kilograms.

The proposed device uses a mechanical brake to produce large deceleration of torque at relatively little cost in size and weight. When the device is moved in a direction orthogonal to the rotation axis, extraneous force is generated by the gyro effect. Therefore, we used two wheels with different directions of rotation to counteract the gyro effect.

The threshold of the torque that the human perceives is reported to be about 0.1[N-m]. In this research, we develop a device that outputs torque between 0.1 and 0.5 [N-m] with arbitrary timing via brake control. The output torque of the device depends on the deceleration torque of the brake, and the device is controlled from an external PC with a control frequency of 1000 [Hz].

3.2 Composition of device

In this section, we describe the composition of the device, illustrated in Figure 4. Each unit is composed of a wheel, motor, and brake. To counteract the gyro effect, two units with a different direction of rotation are combined. If the gyro effect inclines the rotation axis of the wheel with an equal angular velocity, force is generated in an orthogonal direction. The angular momentum of the entire device, or H_0 from expression (2), vanishes if the two wheels rotate in mutually opposite directions, so when the wearer moves, the gyro effect does not generate unnecessary force. To display force, the momentary rate of rotation changes to generate the gyro effect.

One set enables the force display of one axis. If two sets are arranged orthogonally, it is possible to display force in an arbitrary direction orthogonal to the arm. Figure 5 shows an example of how the device can be worn.

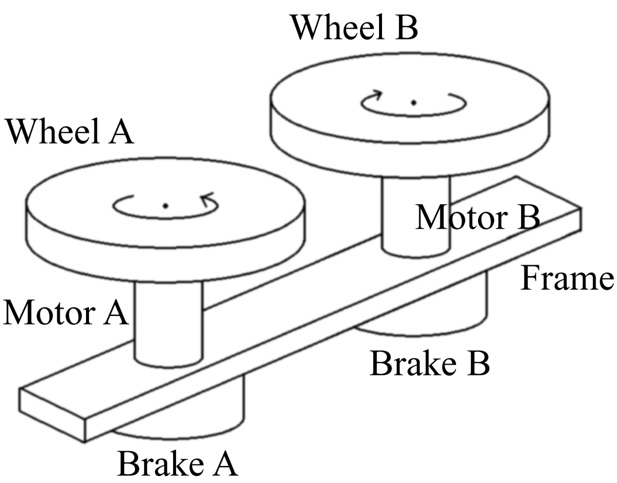

Fig. 4 Outline figure of proposed device

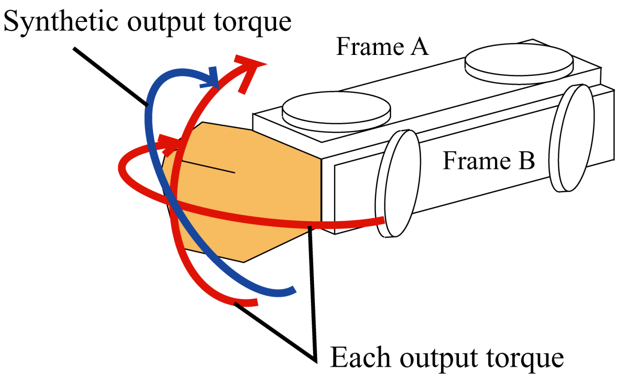

Fig.5 Outline figure of synthetic output torque

4. Experiment 1: change at time of output torque

The proposed device displays force sensation of one axis by using two units, each composed of a wheel, motor, and brake. The two units are aligned to synthesize force in orthogonal directions, which are used to display force in an arbitrary direction. The accuracy of strength and timing of the each axis force is important to display force in an arbitrary direction. We measured the output torque characteristics of a single unit to be used to display force sensation. Figure 6 (top) shows the schematic of the unit used to experiment. Figure 6 (bottom) shows the photograph of the experimental device, and Table 1 describes its specifications.

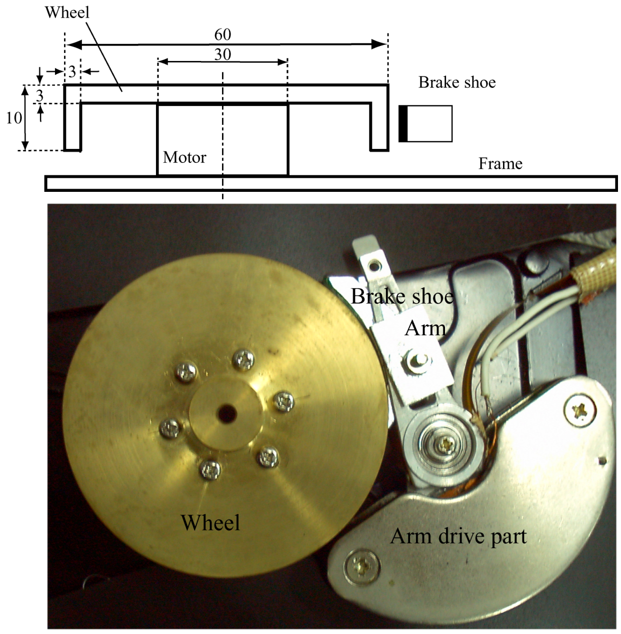

Fig. 6 Experimental model device

Table 1. Specification of the device

Wheel	Weight 120[g] Thickness 10[mm] Diameter 60[mm] Moment of inertia 1.03×10^{-4} [kg-m^2]
Stationary rotation of the wheel	5400[rpm]
Motor	Spindle motor for HDD Revolution speed 5400[rpm] Starting torque 0.046[N-m]
Break	Head arm motor for HDD Servobrake with brake shoe Pressing force/ Tensility 4.0[N]
Weight	Total of motor and wheel 200[g]

4.1 Procedure of experiment

To verify the operation characteristics of the device, when the rotating wheel was decelerated with the brake, the time change of the output torque was measured. We expect the output torque to increase from zero to a maximum, and to return to zero as the rotation slows due to the brake. The rotational speed in the stationary rotation of the wheel is set to 5400 [rpm]. The output torque until the wheel running stops when decelerating from a stationary rotation with the brake is measured by force sensor (made by Nitta corporation). The measurement value passes the low-pass filter of the cutoff frequency 30[Hz].

4.2 Experiment result

Figure 7 is a change at the time of the output torque obtained from the experiment. The output torque stands up at the same time as using the brake. And, the after of the peak attenuates. To final the torque is zero, and the wheel has stopped at this time. The vibration was observed in figure 7. But, this vibration is unrelated to the output torque. This vibration occurred because of the mass of the frame and the dynamic characteristic of the force sensor. The maximum output torque was about 0.7[N-m]. Therefore, The maximum deceleration torque of the brake is presumed to be about 7[N-m].

It is necessary to control the output torque to use this unit for the force display device. Inspecting Figure 7, we can confirm a nearly linear relation between torque output start time (A) and maximum torque output time (B). Therefore, the strength and timing of the output torque can be controlled according to the brake application time. Next, we experimented to examine a linear relation between the brake effecting time and the output torque.

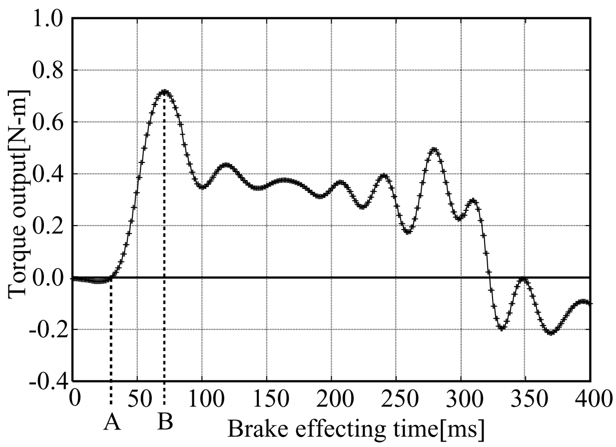

Fig. 7 Time response of torque output

5. Experiment 2: Control of output torque

5.1 Procedure

In experiment 1, we applied the brake until the wheel stopped rotating. The brake application time is set, and after that time, the brake is released under the same environment as experiment 1. At the same time, the output torque at each set time is measured. Set time has increased from 5[ms] to 31[ms] by 2[ms], and tried ten times respectively. We calculate the mean value and the standard deviation of the maximum output torque from the output torque measurement value at each brake effecting time. We calculated the mean value and standard deviation from the operation instruction time to the max torque output time of the brake.

5.2 Experimental results

Figure 8 shows the result of calculating the mean value and the standard deviation of the brake effecting time and the maximum output torque from the measurement value. We understand this relation is linear from figure 8. And, when the output torque increases, standard deviation increases. Therefore, the accuracy of the torque output value lowers when the target price of the torque output increases. Figure 9 shows the result of calculating the mean value and standard deviation from the operation command time to the max torque output time of the brake. We understand the time characteristic also has linear. However, the accuracy at the brake effecting time is about 1-2 [ms] according to the standard deviation of about 1-2 [ms]. This is a factor which influences the output torque. We think that these two causes exist. The first is a mechanical response error to operate the brake. The second is a slow control cycle.

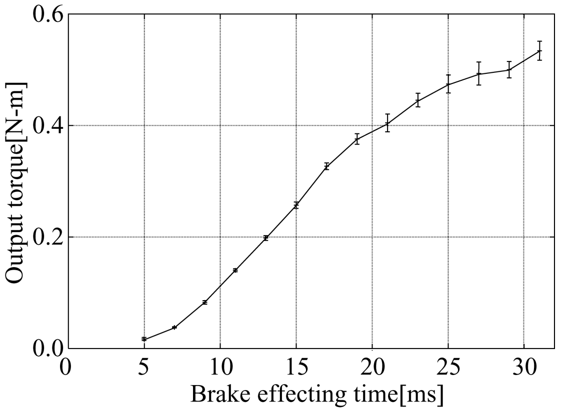

Fig. 8 Brake application time vs. torque output

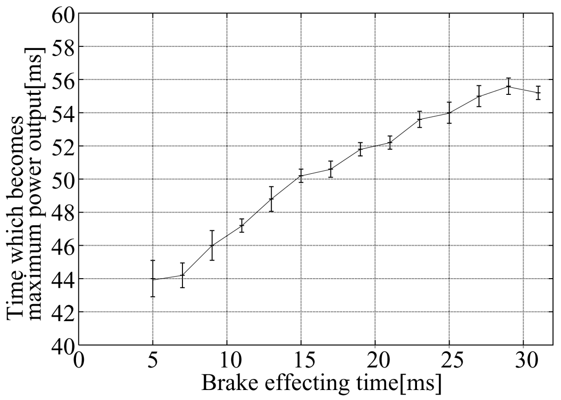

Fig. 9 Break application times vs. timing of maximum torque output

6. Synthesis of torque

While the preceding section was an evaluation of a single unit, the device proposed in our research is comprised of four such units, as shown in Figure 5. This device may then synthesize the output torque in an arbitrary direction. The accuracy of this synthetic output torque depends on the accuracy of each individual output torque. Therefore, we calculate the angle resolution of the synthetic output torque. The output synthetic torque direction angle is shown in the following expressions.

$$\phi = \tan^{-1}(T_1 / T_2) \qquad (6)$$

Here, T_1 and T_2 are each output torques, and ϕ is a synthetic output torque direction angle. The angle resolution of the synthetic output torque is calculated from the standard deviation result of the command of the output torque in the preceding section. Figure 10 shows the relationship between the magnitude of a synthetic torque and the angle accuracy of the synthetic output torque. The target direction of the synthetic torque output was selected at an angle of 45[deg]. Figure 11 shows the relation between the angle of the target and the angle accuracy in the direction where a synthetic torque is output with a magnitude of 0.5[N-m].

The error margin with the angle of the target decreases as the magnitude of the synthetic torque increases, as indicated in Figure 10. The angle error margin has increased as the angle of the target in the direction of the synthetic torque output approaches 45[deg] from Figure 11. 45[deg] or more was a tendency to symmetry though not shown in the figure.

The angle error margin increases when the synthetic output torque is reduced more than 0.3[N-m]. However, the human does not easily perceive the direction at the torque of 0.3[N-m] or less (See experiment 3). The maximum value of the angle error was 10 [deg] at the torque of 0.3[N-m] or more. The angle resolution of the force of a possible display is about 20 [deg].

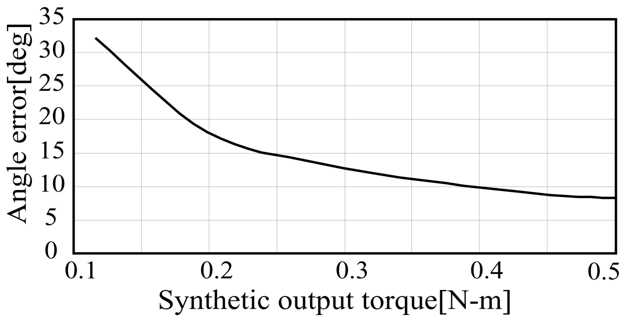

Fig. 10 Angle resolution vs. torque output

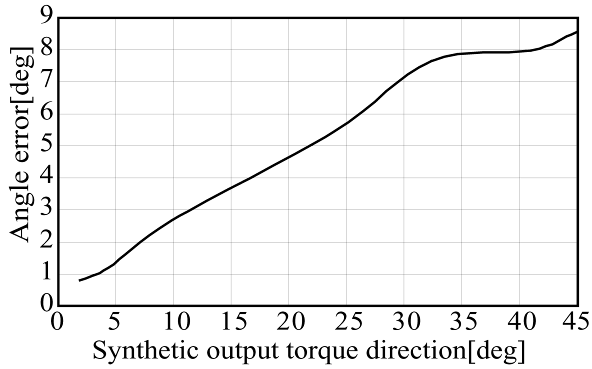

Fig. 11 Angle resolution vs. torque angle

7.Experiment 3:Perception experiment of torque

We installed the device in the trial subject, and examined the perception of the torque. The set composed of two units shown in Figure 4 was installed in the arm of the trial subject in the experiment. At this time, the audiovisual was cut with the blindfold and the headphone. We generated the torque in either of two units and had the trial subject answered the direction of the torque. The brake control time was set from the relation between the brake effecting time and the output torque. The output torque was assumed to be four kinds (0.1, 0.25, 0.4, and 0.5 [N-m]). We generated a random torque in either set, and examined the correct answer rate of ten trials. The trial subject answers the direction without fail. Therefore, The correct answer rate when not perceivable is 50[%].

7.1 Experimental results

Table 2 shows the experimental result of the three trial subjects. The torque output is perceived from 0.2[N-m]. At this magnitude, the direction is not accurately recognized, although the correct answer rate improves when force is increased. The human is perceivable of the direction because the correct answer rate is 80 [%] at the output torque of 0.4 [N-m] or more.

This device needed a strong torque for perception, compared with literature [3]. We consider that this cause is the force transmission depends on the wear method. If we display force in short course, the method of the wear is a weighty consideration. It is necessary to consider in a suitable wear form for the transmission of the torque to the human.

Table 2. Subject accuracy ratio

Subject	Correct answer rate [%]			
	0.1[N-m]	0.25[N-m]	0.4[N-m]	0.5[N-m]
O	60	70	80	100
I	60	70	90	90
Z	50	50	90	100

8. Summary

We proposed a wearable force display device. This device used the rotation moment and the machine type brake. And, the dynamic characteristic of one unit was measured. This result showed that an arbitrary torque was able to be output at arbitrary time. And, we experimented on perception to the trial subject. As a result, we confirmed the perception of the direction. We will complete the device shown in figure 12 in the future. And, we will do the navigation of behavior with this device.

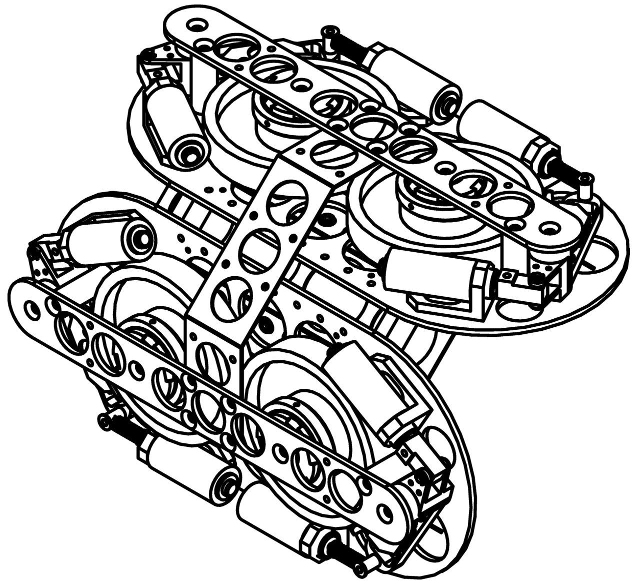

Fig.12 Force display device using angular moment and mechanical brake

Acknowledgments: This work was supported by the project of JST, PRESTO.

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