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The Pinch Sensor: An Input Device for In-Hand Manipulation with the Index Finger and Thumb

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***Abstract*—This paper presents the Pinch Sensor, an elastic input device to sense the fine motion and pinch force of the index finger and thumb - the two most used digits of human hands for in-hand object manipulation skills. In addition to open and close, the device would allow a user to control a robotic or simulated two-finger hand to reorient an object in three different ways and their combinations. A unique design of elastic sensing provides the users a high degree of perception resolution, as well as the sensation of holding an object with a certain level of stiffness between the index finger and thumb. These characteristics help the users to fine control the pinch force while carrying out manipulation skills. The design features a small size that allows it to be integrated to a handheld controller. Commonly available off-the-shelf components for consumer electronics are used to achieve affordability and reliability.**

***Index Terms*—input devices, in-hand manipulation, haptics, teleoperation, virtual reality, design, sensing**

I. Introduction

Despite a significant need, robots and virtual reality agents are still at a primitive stage of replicating the fine motor capabilities of human hands. The bottleneck is largely due to the lack of proper control approaches. Along the development of autonomous control methods, human controlled agents in virtual reality and teleoperated robots play an important role. They offer capable and reliable functions before autonomous control methods become mature [1]. Meanwhile, the sensorimotor data collected from human controlled operations can be used to generate autonomous control strategies through techniques such as Robot Learning from Demonstration [2]. Many input devices have been developed to sense human actions, ranging from gaming gadgets such as gamepads and joysticks to mechanical and optical motion capture systems. Nevertheless, there lacks devices for fine control of simulated and robotic hands for in-hand manipulation of objects.

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The two major types of hand skills are grasping and in-hand manipulation, where the latter requires finer motor skills. Common classification systems consider human in-hand manipulation skills in three groups - translation, shift, and rotation [3]. This paper presents the Pinch Sensor, a 4-DOF elastic input device to sense the fine motion and pinch force of the index finger and thumb, which facilitate some of the most frequently used in-hand manipulation skills of humans [4], especially those in the group of rotation skills. If integrated to a position and orientation sensing handheld controller (e.g., one that is similar to the handheld controllers of Oculus Quest or HTC VIVE), the system would allow a user to control a robotic/simulated arm and a multi-DOF two-finger gripper (e.g., the ones introduced in [5]) to pick up an object and conduct precision in-hand object reorientation in three different ways (Fig. 1). Note that terms referring to these moves vary from study to study. For example, the moves illustrated by Fig. 1-A and B are called "lid turn" and "knob turn" respectively in [6].

II. Related Technologies

Among commercial products on the consumer electronics market, the ones that can best sense the fine motion of fingers to sub-mm level use a variety of working principles, including optical sensing (e.g., the Leap Motion controller [7]), millimeter-wave (e.g., Google's Soli [8]), inertial measurement (e.g., Tap Strap [9]), and so on. These technologies aim at gesture recognition without providing any haptics, which is indispensable to in-hand object manipulation or even just to maintain grasping of an object [10]. Attempts to develop input devices for fingers with actuated haptic feedback use motorized cable systems, servos, brakes or their combinations to provide force feedback to fingers. Representative projects include CyberGrasp [11], HIRO III [12], CapstanCrunch [13], CLAW [14], Wolverine [15], and so on. Besides reliability and maintenance concerns, the complex mechanical mechanisms

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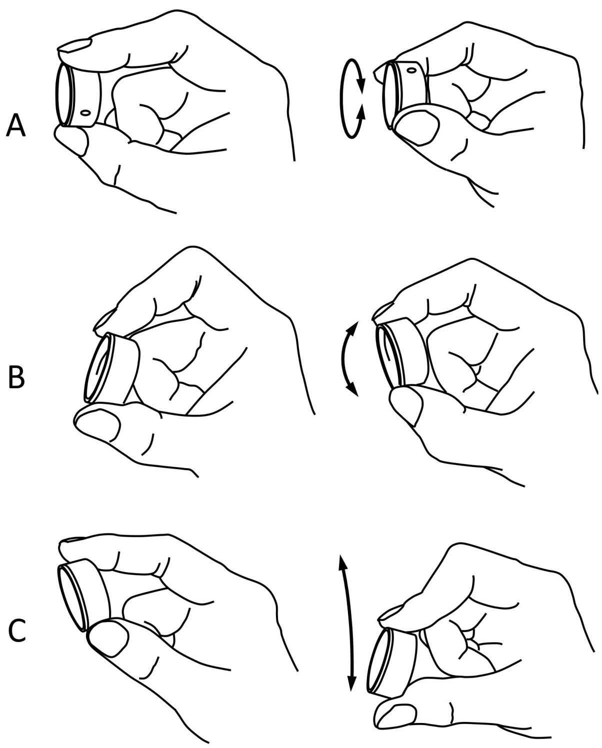

Fig. 1. Three ways of in-hand manipulation using the index finger and thumb - A. twist, B. tilt, C. swing

of such systems hamper the user's hand to perform fine motion, making them not quite practical to be integrated to a handheld controller to control a robotic/simulated arm together with a hand. Among the ones listed above, CapstanCrunch [13] and CLAW [14] have actually managed to realize such an integration, but can only provide a single DOF of sensing and haptic feedback for one finger.

A popular alternative solution to provide haptics when motorized feedback is impractical is through the technique of Pseudo-Haptics. Related to the theories of Cross-Modal Sensory Illusion [16] and Synesthesia [17], pseudo-haptics uses visual, audio, or vibration cues to suggest the strength of contact forces to the user of a so-called isometric or elastic input device [10] [18]. The term isometric means the input device stay (mostly) still and gives resistance when the user operates it (e.g., TrackPoint, SpaceMouse, etc.), while the opposite is called isotonic - i.e., the user feels no resistance when operating the input device [19] (e.g., the Leap Motion controller). It is evident that the resistance from the input device plays an important factor in the implementation of pseudo-haptics. Some research has found that instead of high stiffness isometric input devices, elastic input devices whose sensing components make nontrivial elastic displacements make pseudo haptics even more effective [17] [20]. The advantage comes from the passive haptic feedback given by the elasticity of the sensing components. The feeling of holding an object of a certain level of stiffness helps the user to fine control the applied forces with a high perception resolution [21]. The relatively simple structure of passive elastic input devices brings affordability, reliability, makes them user friendly and can be easily miniaturized to be integrated to handheld controllers. These advantages open up opportunities for a widespread use in impactful future applications of robotics and virtual reality such as Remote Labor [1] and Crowdsourced Learning [22].

III. Design Specifications and Constraints

This project develops the Pinch Sensor, a 4-DOF elastic input device for controlling robotic and simulated in-hand manipulation. It is first of its kind specifically purposed for in-hand object reorientation skills using the index finger and thumb. The fundamental hypothesis is that an elastic "dummy object" held by the users on the input device would help them fine regulate the grasping force while they are controlling the in-hand manipulation actions. The design specifications and constraints are as follows:

- DOFs of sensing: The device shall be able to sense the motion of the index finger and thumb when reorienting an object in the three different ways illustrated in Fig. 1 and their combinations, as well as the open-and-close motion of the two fingers when picking up and dropping an object.
- Elastic sensing: The pinch motion and force between the index finger and thumb shall be measured by elastic components with nontrivial strokes, so as to provide the users a good perception resolution to carry out fine manipulation skills.
- Dummy object: The device shall give users a sensation that they are holding an object between the index finger and thumb.
- Spring loaded returning: All sensing components should automatically return to their neutral positions when released by the user. Although mechanically related, this feature has a purpose different from that of elastic sensing.
- Size: The device shall be small enough to be installed on a handheld controller.

In addition, the device should be affordable, reliable, and easy to use, so as to bear the potential of a widespread adoption on the market of consumer electronics.

IV. Design Rationale

A core feature in the design is the dummy object that gives the users a feeling that they are holding an object between the index finger and thumb. As illustrated in Fig. 2, this can be realized with a spring shared between the buttons pressed by the digits. While the buttons move independently to facilitate the swing action (Fig. 1-C), the index finger and thumb feel the same resistance force throughout various motion, and obtain a sensation of holding an object. In addition, the spring in-between serves another three functions:

- Providing elastic sensing for a good perception resolution;
- Allowing the pinch force to be measured from its deformation; and
- Returning the buttons to their neutral positions when released by the user.

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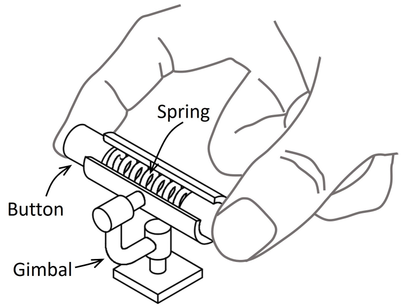

Fig. 2. A dummy object held between the index finger and thumb

Using potentiometers (instead of encoders) to measure small displacements in limited spaces is a common practice in handheld controllers such as gamepads and joysticks. Thanks to the booming game industry, miniature potentiometers with excellent repeatability, linearity, and durability have become widely available with a great variety. Nevertheless, it is still quite challenging to pack multiple potentiometers into the tight space between the index finger and thumb, which can be roughly considered as a spherical space of a diameter less than 100mm (for adults). In order to facilitate the control of swing actions (Fig. 1-C), instead of measuring the distance in-between (which would be enough if just for object picking), the displacement of the two buttons should be measured individually, which requires two sensors and makes the accommodation even harder.

For the sake of affordability and reliability, existing off-the-shelf components for consumer electronics are preferred. The smallest linear potentiometers on the current market have a size about 15mm×10mm×4mm (not including wiring and the lever/nipple) with a 8mm sensing stroke. A representative product is the RD7 series by ALPS ALPINE (Fig. 3-A), which is a leading supplier of precision miniature potentiometers for controllers. Considering the additional space needed for wiring and mounting as well as for the buttons and the spring, they would consume most of the space available between the index finger and thumb, leaving little room for any other features such as the gimbal. Alternatively, if the linear motion of the buttons could be converted to rotational, rotary potentiometers can be used, which are of considerable smaller sizes (Fig. 3-B). Note there are many rotary potentiometers on the market that have even smaller sizes, but are of nontrivial friction when turned and would significantly affect the haptic perception of the users. The one shown in Fig. 3 is particularly designed to have barely any friction.

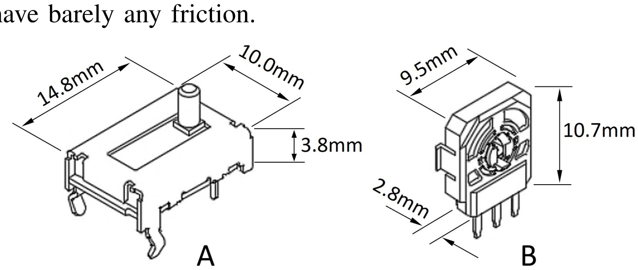

Fig. 3. Some of the smallest designs of off-the-shelf potentiometers for consumer electronics - A. linear, B. rotary (by ALPS ALPINE)

As illustrated in Fig. 2, the dummy object should be mounted on a gimbal with 2-DOF sensing to facilitate the control of twisting and tilting (Fig. 1-A, B). An ideal option is to make use of the off-the-shelf 2-DOF sensors (Fig. 4) used for thumbsticks on gamepads such as the ones on PlayStation and Xbox gamepads. Other than affordability and reliability, these thumbstick sensors offer a high degree of integration that includes three functions:

- Providing a gimbal mounting;
- Sensing 2-DOF rotation; and
- Spring loaded automatic returning to the neutral position when released.

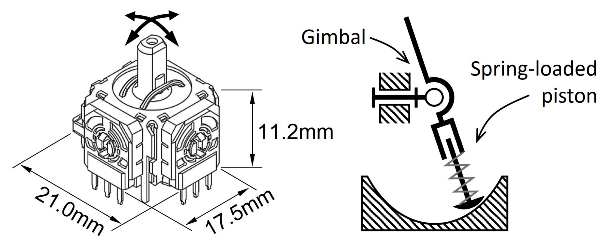

Fig. 4. A popular 2-DOF sensor for thumbsticks on gamepads

The challenge, however, comes from making the stick double-ended to accommodate the tube-shaped dummy object. As explained in Fig. 4, the spring loaded returning function of a thumbstick sensor relies on the particular shape of its inside bottom surface, which forbids it from being cut open to let through a double-ended stick. Two solutions to work around this issue are illustrated in Fig. 5-A and B. Note that the horn setup shown in Fig. 5-(C) will not work because one of the two DOFs of the thumbstick sensor is not oriented correctly, not to mention that its double-ended stick does not pass through the rotation center of the gimbal.

A major issue of the parallel setup is that the two pivots connecting the double-ended stick and the thumbstick sensor must be very precisely constrained other than their pivoting DOF (i.e., no slack). Otherwise, the thumbstick sensor would not be able to accurately sense the rotation of the double-ended stick. Considering the miniature size and the expected frequent motion of the pivots, this requirement can be extremely challenging in terms of being fabricated to meet the desired precision and reliability. In addition, the need of a separate gimbal is a waste of the gimbal on the thumbstick sensor and significantly increases the overall size. Meanwhile, the hollow setup, though dodges these issues, makes it impossible to place the spring of the dummy object (Fig. 2) directly between the two buttons. Instead, Fig. 6 explains a design to bridge the spring. The design also allows the use of rotary potentiometers (smaller than linear potentiometers) to sense the motion of the buttons; as well as an extension spring, which does not have the stability issue of compression springs.

With all the considerations explained above, the specific designs of all parts/components and their assembly are illustrated in Fig. 7. The distance between the tips of the buttons measures 74mm when the buttons are released and 60mm when pressed

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to the bottom on both ends. The frame can rotate $\pm 23°$ around each axis of the gimbal. The thumbstick sensor connects to the base via a printed circuit board.

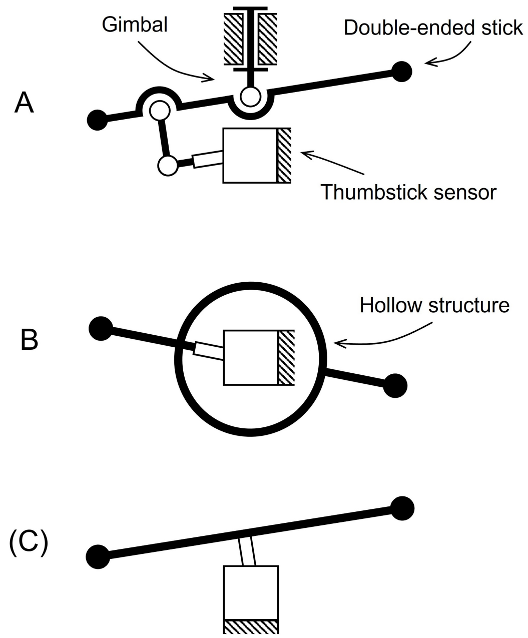

Fig. 5. Double-ended realization using an off-the-shelf thumbstick sensor - A. parallel setup, B. hollow setup, (C). horn setup

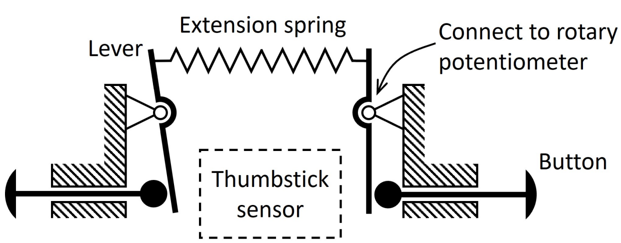

Fig. 6. Bridging the spring of the dummy object

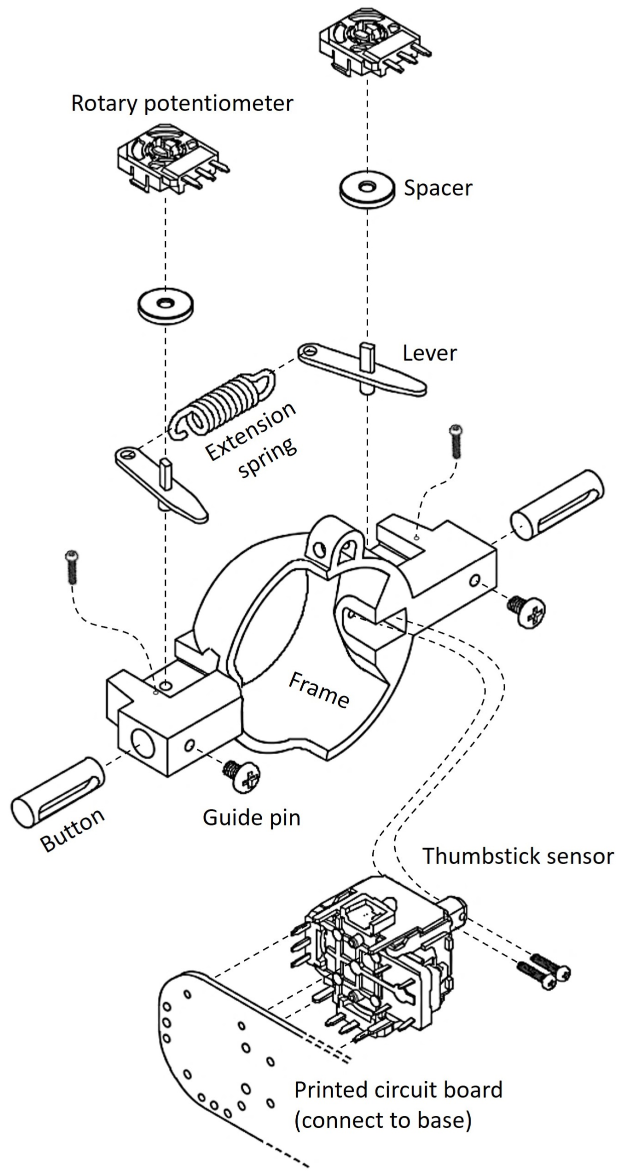

Fig. 7. The proposed design

V. The Prototype and Testing

Figure 8 shows a prototype of the proposed input device. It is mounted on a fixed top and cabled through terminal blocks for testing. If integrated to a handheld controller as envisioned, the terminal blocks and extended circuit board are not necessary. Tests are conducted to verify the hypothesis that the proposed design can allow a user to fine regulate the pinch force while controlling in-hand manipulation skills with the index finger and thumb. Specifically, a user is asked to maintain a certain level of pinch force between the index finger and thumb while conducting

- Simultaneous twisting and tilting, i.e., spherical rotating of an object (Fig. 9-A); and
- Swinging (Fig. 9-B).

(The terms “twist”, “tilt”, and “swing” are defined as in Fig. 1.)

Figure 10 shows the variation of the pinch force during the two tests. In plot A (spherical rotating), θ and ϕ are the rotating angles of the gimbal. f_p is the pinch force calculated from the extension of the spring, which can be inferred from the readings of the potentiometers connected to the pivots of the levers. The pinch force varies over a range of 6.1%, indicating an effective perception resolution brought by elastic sensing and the dummy object. In plot B (swinging), the “swing travel” is the displacement of the center position between the two buttons. The variation of the pinch force is at a greater level of 13.7% compared to the spherical rotating test. The lower performance is mainly caused by the friction when the buttons slide in their tunnels, which jeopardizes the haptic fidelity of the dummy object.

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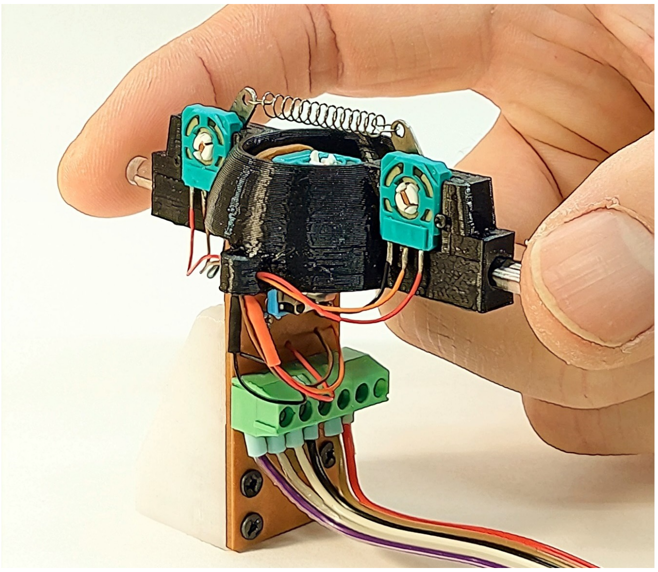

Fig. 8. The prototype

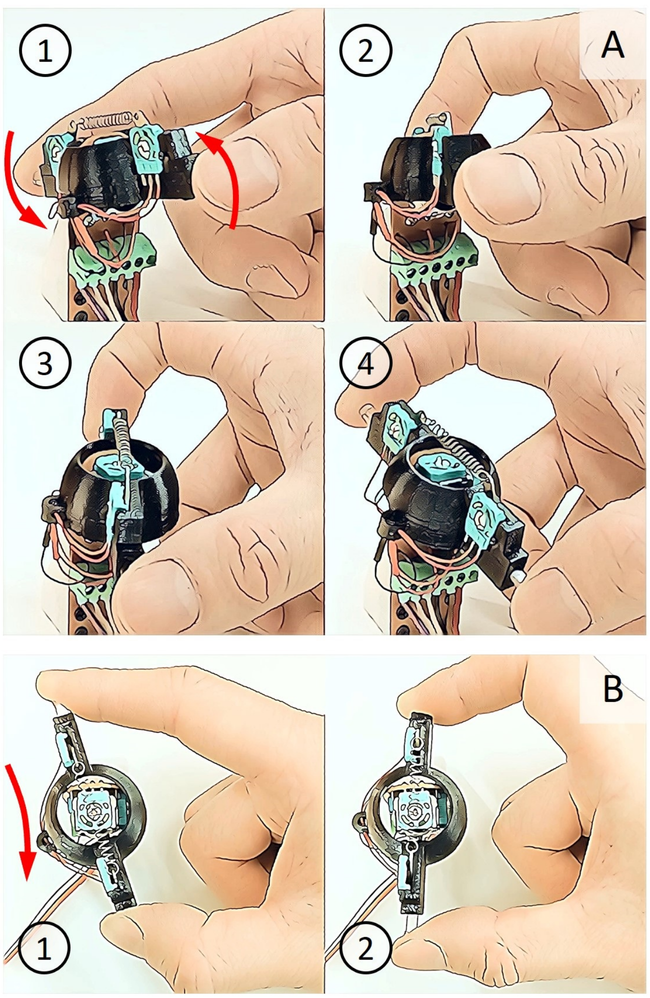

Fig. 9. Testing scenarios - A. spherical rotating, B. swinging

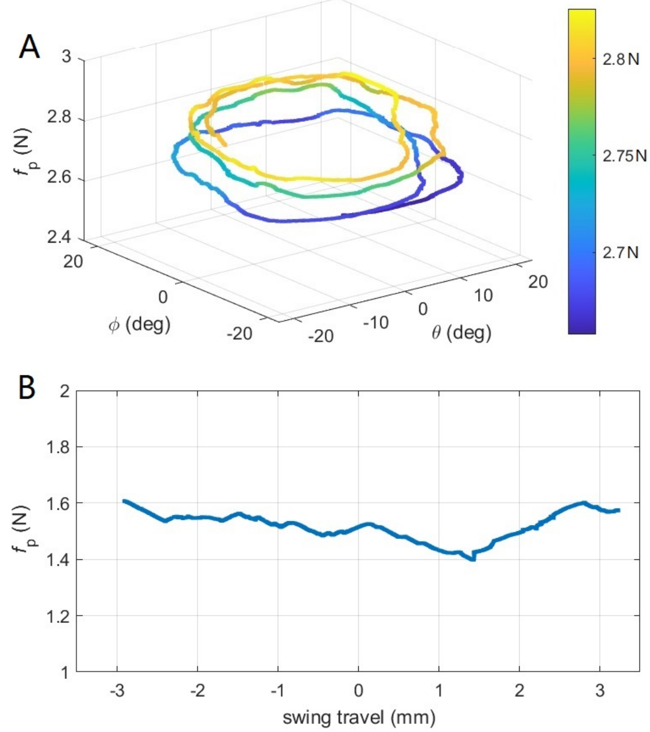

Fig. 10. The pinch force during A. spherical rotating, B. swinging

VI. Conclusions and Future Work

This paper presents the design, prototyping, and testing of the Pinch Sensor, an elastic input device to sense the fine motion and pinch force of the index finger and thumb, which are the two digits for some of the most used in-hand manipulation skills. In addition to open and close, the device would allow a user to control a robotic or simulated two-finger hand to reorient an object in three different ways, including twisting, tilting, and swinging, as well as their combinations. A unique design feature gives the users a sensation of holding an object with a certain level of stiffness between the index finger and thumb, and helps users to fine control the pinch force while carrying out manipulation skills. The design makes use of off-the-shelf components for consumer electronics for affordability and reliability. Next, the study will continue to improve the design, including

- Redesigning the buttons to minimize the friction when they slide, so as to improve the haptic fidelity of the dummy object; and
- Optimizing the dimensions of the frame, levers, and buttons, so as to reduce the distance between the buttons and allow the handling of smaller objects.

In addition, the device will be integrated to a position and orientation sensing handheld controller (Fig. 11) to allow simultaneous control of a six-axis robotic or simulated arm that carries a multi-DOF two-finger hand.

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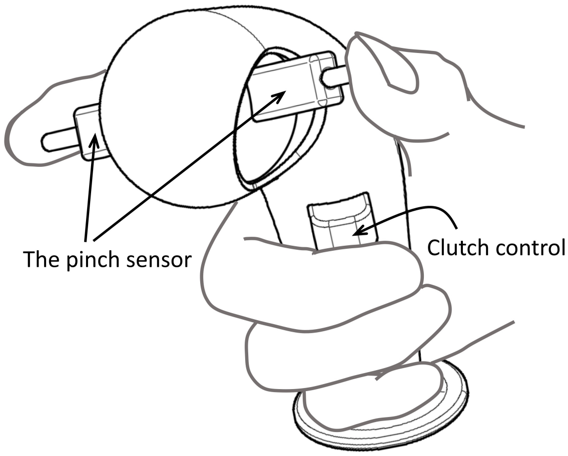

Fig. 11. Integrating the pinch sensor to a handheld controller

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