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Method for Extracting Intentional Motion Using Force Sensor in Hand-held Robotic Forceps and Its Effect on Performance

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To enhance the performance of multi-degree-of-freedom hand-held forceps that support minimally invasive surgery, it is important to correctly sense the operator's intended operation input. In our hand-held robotic forceps that use a force sensor as an input device, it was necessary to solve the problem of unintended operation input due to gripper operation to move the joint of the forceps. We describe a method for eliminating this unintended input to the interface of the hand-held robotic forceps and present the results of an evaluation of its performance. We used a virtual grasp-and-reach task with cursor manipulation of the forceps' input device in our experiments and evaluated the throughput on the basis of Fitts' law, which is used to evaluate human interfaces; the evaluation was based on the results of manipulations by two participants. The results showed that the mean throughput was 1.5 to 2 times higher when the proposed processing was used. This suggests that the proposed processing of the operational input of the interface contributes to the improvement of performance with the hand-held robotic forceps.

1. Introduction

Laparoscopic surgery is a type of minimally invasive surgery in which surgical instruments are inserted into the abdominal cavity through small holes in the patient's skin. It has the advantage of faster postoperative recovery of the patient compared to conventional laparotomy, but there are restrictions on the direction of the forceps tip, requiring surgeons to have more advanced skills. One solution is to use hand-held forceps that have a multi-degree-of-freedom (DoF) articulation at the tip and that can be operated by the surgeon with a handle. Some commercially available hand-held forceps have a joint between the handle and the shaft that mechanically transmits the movement of the handle to the joint at the tip,[(1)] but the method of operation is hardly intuitive. A more intuitive method of operation involves forceps that are attached to the surgeon's forearm and move the tip in the same direction as the surgeon's hand,[(2)] but some effort is required to attach it before use.

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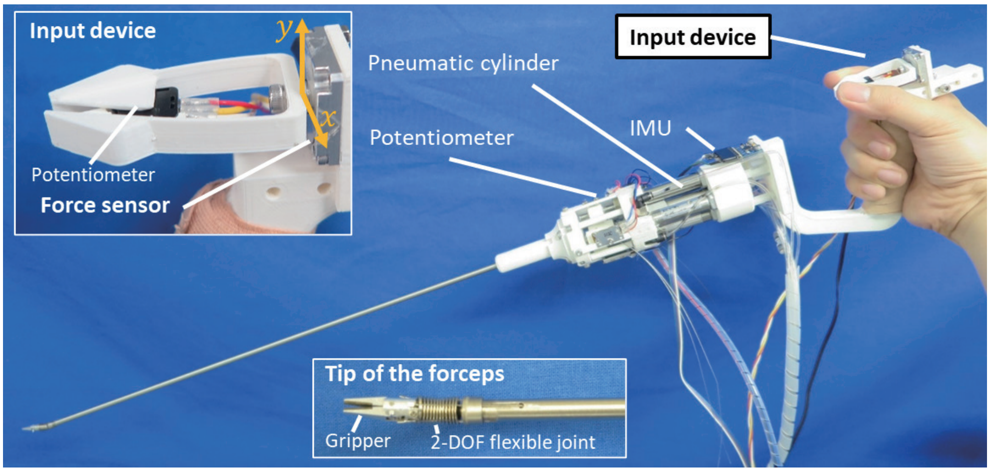
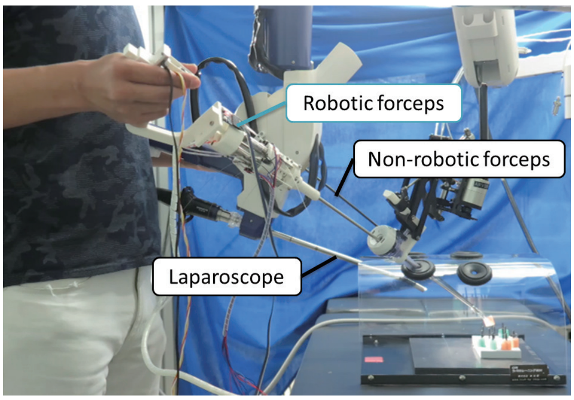
To realize hand-held forceps with high performance, a method that electronically senses the operator's movements and moves the actuator-driven robotic forceps would be effective. Our group has developed robotic hand-held forceps that can be controlled using a joystick and a grasper controller.(3) These robotic forceps can be controlled by combining a joystick and a grasping controller to open and close the grasp and to control the tip orientation. These robotic forceps have the potential for intuitive operation because the surgeon can mimic the motion of the forceps tip with his or her fingers. However, the thumb and index finger, which have a narrow range of motion, require abduction and adduction movements, and finger fatigue is a concern.

We previously proposed robotic hand-held forceps that use a force sensor as a user interface [Fig. 1(a)].(4) In these forceps, instead of a joystick, a force-sensor-mounted operation input device is used to manipulate the posture of the forceps' tip by applying a force in the same direction as the target orientation of the tip. In addition, by adjusting the opening angle of the tip,



(a)



(b)

Fig. 1. (Color online) Hand-held robotic forceps using force sensors as input devices.(4) (a) Overall view and (b) operation by a surgeon.

the forceps can be opened and closed. In the experiment, the surgeon performed the task of moving a block with the robotic forceps in his right hand and regular forceps in his left hand, and as a result, the operator was able to perform the task without any problems [Fig. 1(b)].(4) Note that the method described in this paper was already implemented in a previous study, but the details have not been published and the performance of the method has not been evaluated.

The force sensor attached to this operation input device is exposed to a force that directs the orientation of the joint and the force applied when the tip is opened or closed. Therefore, if the input to the force sensor is directly used as the operation input for the joint, unintended operation input occurs when the operator uses the gripper. Therefore, signal processing to remove this unintended operation input is necessary.

We describe herein the signal processing method developed to realize this force sensor-based operation input device, and also describe the results of experimental verification of the role of signal processing in the user's performance. The purpose of this signal processing is to remove unintended operation input associated with gripper manipulation and to achieve more voluntary forceps manipulation. For verification, we use a virtual reaching task with a cursor, which has been applied to the evaluation of human interfaces such as mice, trackballs,(5) and hand-held forceps.(6) For many interfaces, a proportional relationship exists between the time required for the reaching motion and the difficulty calculated based on the size of the target and the distance traveled (Fitts' law(7,8)). By comparing the index (throughput) that corresponds to this proportionality coefficient, it is possible to compare the performance of different interfaces.(8) In this study, we conducted an evaluation using a virtual reaching task with a tip opening/closing operation with and without the proposed process and determined the effect of the process.

This paper is organized as follows: Sect. 2 provides an overview of the hand-held forceps using a force sensor as an input device; Sect. 3 describes a problem to be solved in implementing the input device for these forceps and the signal processing methods used to solve the problem; Sect. 4 describes the evaluation experiment method using a virtual reaching task; Sect. 5 describes the results; Sect. 6 provides a discussion and the conclusions of this paper.

2. Overview of Hand-held Robotic Forceps

We previously developed hand-held robotic forceps with a gripper and a joint at the tip, which are operated by inputting a force [Fig. 1(a)].(4) The tip has a gripper and a flexible joint with 2-DoF [Fig. 1(a), bottom]. The gripper is driven by a push-pull wire actuated by a single pneumatic cylinder, and the flexible joint is driven by an antagonistic drive with wires actuated by four pneumatic cylinders.

The robotic forceps have an operation input device [Fig. 1(a), upper left] at the back that is pinched by the thumb and index finger. At the base of the device is a force sensor fixed to the handle. Using the xy-component of the measured force as the manipulation input for the forceps tip, the operator can move the flexible joint of the forceps by applying forces in the vertical and horizontal directions without changing the posture of his or her fingers. In our implementation, we adopted position control, in which the magnitude of the force is proportional to the radial angle, instead of using rate control, in which the force is proportional to the speed of the movement. Position control enables the same feeling of operation as in interfaces in which a joystick and the forceps are oriented in the same direction.(3)

The tip of the operation input device is a gripper controller with an opening that incorporates an angle sensor. The elasticity of the thin polylactic acid plate that supports the opening allows the operator to indicate the opening and closing of the gripper by adjusting the opening of the tips of the thumb and index finger. The entire operation input device is shaped to resemble the tip of a pair of forceps, so that the direction of the input of the force and the movement to indicate the opening and closing of the gripper are similar to those of the tip of the forceps, thereby allowing intuitive operation. To prevent unintended changes in the opening/closing angle of the gripper actuator while the operator is changing the force, the fulcrum of the gripper controller is placed near the position where it is pinched by the finger, allowing the operator to change the joint posture while maintaining the input that controls the gripper's opening and closing.

Other features include a foot pedal that enables a "clutch" operation to return the operating force to its original value while the posture of the tip is fixed. We also implemented the active motion transformation,(3) which synchronizes the rotation of the tip with the pronation and supination of the hand holding the handle. This allows the surgeon to twist the forceps tip by rotating the wrist, for example, when inserting a needle into tissue. The focus of this paper is on the signal processing by the force sensor, so these features are not used in the experiments.

3. Unintended Input Attenuator for Input Devices

3.1 Unintended force applied to the input device

When using a force input device with a gripper controller, gripper operation causes unintended operation input that is applied to the force sensor. Figure 2 illustrates this problem. When pinching the gripper controller, force is applied to the controller with the thumb and index finger (blue arrows). In this case, the force applied by the thumb is not equal to the force applied by the index finger, so the gripper controller is pushed by the difference in force between the two fingers. This force is transmitted to the force sensor and results in an unintended operation input (orange arrow). To suppress this unintended operation input caused by gripper operation, we

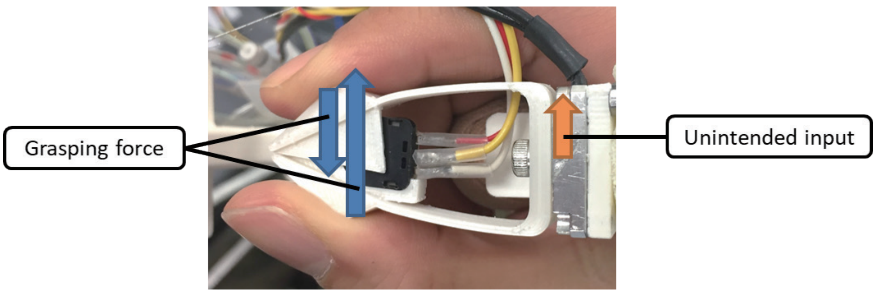


Fig. 2. (Color online) Unintended operation input that occurs during grasping. The difference in the force between the two fingers pinching the gripper controller (blue arrows) is transmitted to the force sensor as an unintended input (orange arrow).

developed an unintended input attenuator (UIA), which is a filter that ignores input during gripper operation.

3.2 Signal processing method

The UIA is intended to do the following:

1. To block changes in the operation input while the opening angle of the gripper controller is changing. This blocks unintended operation input associated with gripper operation by assuming that the joint of the forceps is not manipulated during the opening/closing operation and by ignoring changes in the force sensor value during that time.
2. To correct gradually the gap between the operation input and output caused by the block of the operation input after the gripper is opened. If process 1 is repeated, the difference between the operation input and the actual posture of the forceps increases. To prevent this, the relationship between the operation input and output is gradually restored to its original state when the gripper is not in use.

The algorithm is shown in Fig. 3. Here, $\boldsymbol{q}_{input}$ is a two-dimensional vector representing the operation input, and $\boldsymbol{q}_{offset}$ is an offset added to the operation input. The term C is a soft clutch, which represents whether the operation input is transmitted to the tip or not by a binary value of 0 (OFF: not transmitted) or 1 (ON: transmitted). The operation input $\boldsymbol{q}_{cinput}$ corrected by the UIA is calculated using the following equation.

$$\boldsymbol{q}_{cinput} = \boldsymbol{q}_{offset} + C\boldsymbol{q}_{input}. \tag{1}$$

$\boldsymbol{q}_{\mathrm{offset}} \leftarrow \boldsymbol{0}$
while system is running **do**
    $\dot{q}_{\mathrm{gm}} \leftarrow$ derivative of the angle of gripper controller
    if $|\dot{q}_{\mathrm{gm}}| < T$ **then**
        $C = 1$
    else
        $C = 0$
    end if
    $\boldsymbol{q}_{\mathrm{input}} \leftarrow$ force input
    if $C = 0$ now and $C = 1$ in the previous cycle **then**
        $\boldsymbol{q}_{\mathrm{offset}} \leftarrow \boldsymbol{q}_{\mathrm{offset}} + \boldsymbol{q}_{\mathrm{input}}$
    else if $C = 1$ now and $C = 0$ in the previous cycle **then**
        $\boldsymbol{q}_{\mathrm{offset}} \leftarrow \boldsymbol{q}_{\mathrm{offset}} - \boldsymbol{q}_{\mathrm{input}}$
    else if $C = 1$ and the gripper controller is open **then**
        $\boldsymbol{q}_{\mathrm{offset}} \leftarrow r\boldsymbol{q}_{\mathrm{offset}}$
    end if
    $\boldsymbol{q}_{\mathrm{cinput}} \leftarrow \boldsymbol{q}_{\mathrm{offset}} + C\boldsymbol{q}_{\mathrm{input}}$
end while

Fig. 3. Algorithm for UIA.

The algorithm loops through the following processes.

1. Calculate the derivative of the angle of the gripper controller (line 3)
2. Turn on the soft clutch if the gripper controller opening has stopped; otherwise, turn off (lines 4–8; T is a positive constant).
3. Read the value of the force sensor (line 9)
4. If the soft clutch transitions from ON to OFF, add the operating input at the time of the transition to the offset to maintain the posture at the time of the transition (lines 10–11).
5. If the soft clutch transitions from OFF to ON, subtract the operation input at the time of the transition from the offset to cancel the effect of the force applied to the force sensor at the time of the transition (lines 12–13).
6. When the soft clutch is ON and the gripper controller is open, the offset is exponentially brought closer to 0 to restore the changed offset to its original value (lines 14–16, where r is a constant satisfying $r < 1$).
7. The corrected operation input is obtained using Eq. (1) (line 17).

Figure 4 shows the behavior of the algorithm with an artificial example in which the operator closes and then opens the gripper. For simplicity, the operation inputs and offsets, which are actually two-dimensional, are assumed to be one-dimensional. Also, the threshold T for detecting gripper controller motion is assumed to be small. From the top of the figure, the input to the gripper (open or closed), the angle of the gripper controller, the angular speed of the opening/closing, the state of the soft clutch, the operation input, the offset, and the corrected operating input that is the output of the UIA are shown. Each value varies as follows.

1. Initially, the operation input $\boldsymbol{q}_{input}$ and the corrected operation input $\boldsymbol{q}_{cinput}$ are equal ($t < t_1$).
2. When the gripper controller begins to close, the algorithm turns off the soft clutch and simultaneously adds an operation input to the offset ($t = t_1$).
3. The change in operation input is intercepted and the corrected operation input continues to maintain a constant value ($t_1 < t < t_2$).
4. When the action of closing the gripper controller is completed, the soft clutch is turned on and the operation input is subtracted from the offset ($t = t_2$).
5. The corrected operation input again reflects the change in the operation input at approximately the same position as before the gripper controller was closed ($t_2 < t < t_3$).
6. When the gripper controller has opened again, the soft clutch state and offset are changed, and the operation input is interrupted ($t_3 \leq t < t_4$).
7. The offset is gradually brought closer to zero to correct the accumulated misalignment, and after a short time, the correspondence between the operation input and the corrected operation input is almost restored ($t \geq t_4$).

In the bottom row of Fig. 4, the dotted line shows the original operation input, and the solid line shows the output of the UIA. For $t_2 < t < t_3$, when the gripper is closed, the output reflects the change in operation input while the unintended operation input is suppressed. At $t \geq t_4$, when the gripper is open, the output gradually corrects for the deviation between the operation input and the output caused by the interruption of the operation input.

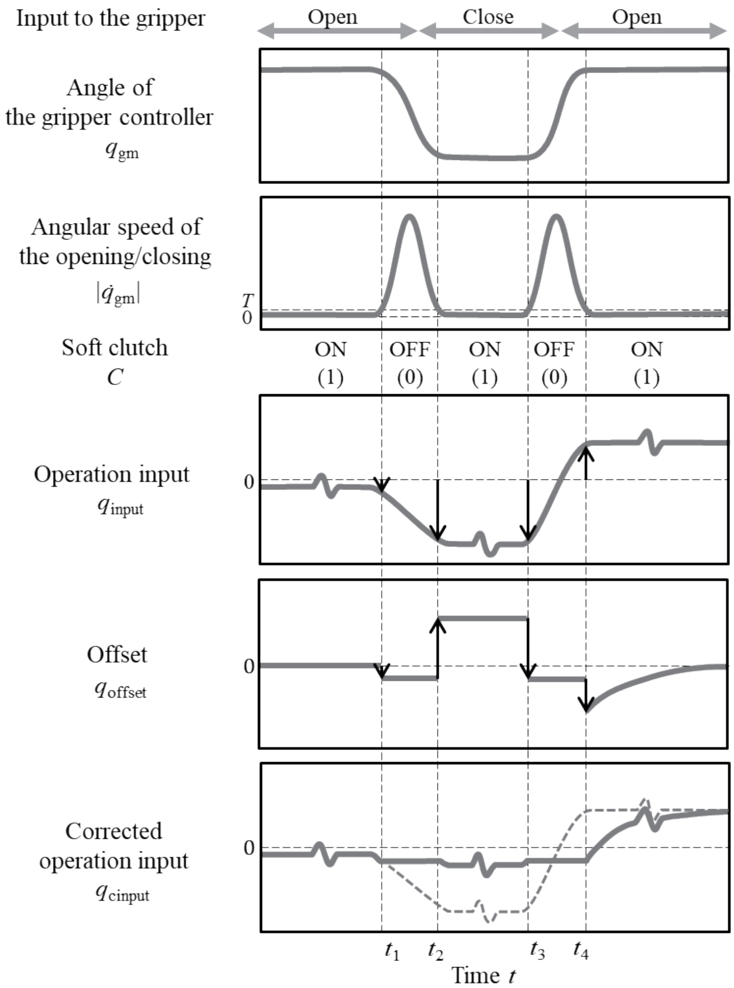


Fig. 4. Diagrammatic explanation of the operation of the UIA. In the bottom row, the dotted line shows the original operation input, and the solid line shows the output of the UIA. For simplicity, the operation input and offset, which are actually two-dimensional, are made one-dimensional. This graph is an example for illustrative purposes only and does not represent actual measured values.

3.3 Implementation of UIA on hand-held forceps

The UIA was implemented in realized hand-held robotic forceps. It was implemented in a 200 Hz periodic loop in Arduino Uno that processes the sensor signal from a force sensor (USL06-H5-50N, Tec Gihan Co., Ltd.). The value of r was set to 0.99, a value at which the time constant for the decay of $|\boldsymbol{q}_{offset}|$ (the time at which the value becomes 36.8 % of the initial value) is about 0.5 s. The value of T was set to the speed at which the angle of the gripper controller changes from maximum to minimum in 1 s. The values of these parameters were experimentally determined as values that would not cause discomfort to the operator.

The attenuation effect of unintended input during the grasping operation is shown in Fig. 5. The operator closed and opened the gripper using the gripper controller and maintained the bending angle of the joint; Fig. 5 shows the angle of the gripper controller, the operation input, the corrected operation input, and the realized angle of the joint. The angle of the gripper controller is normalized to a value between 0 (fully closed) and 1 (fully open). After the start of gripping, the operation input deviated from the initial value (approximately −30 deg in the horizontal angle and +20 deg in the vertical angle) despite the operator's intention to maintain the bending angle, but the unintended input was attenuated in the joint angle. After the opening was completed, the difference between the operation input and the joint angle remained (approximately +5 deg in the horizontal angle and approximately +8 deg in the vertical angle), but the difference was resolved in approximately 1 s. As a result, the operator was able to maintain the joint angle during grasping.

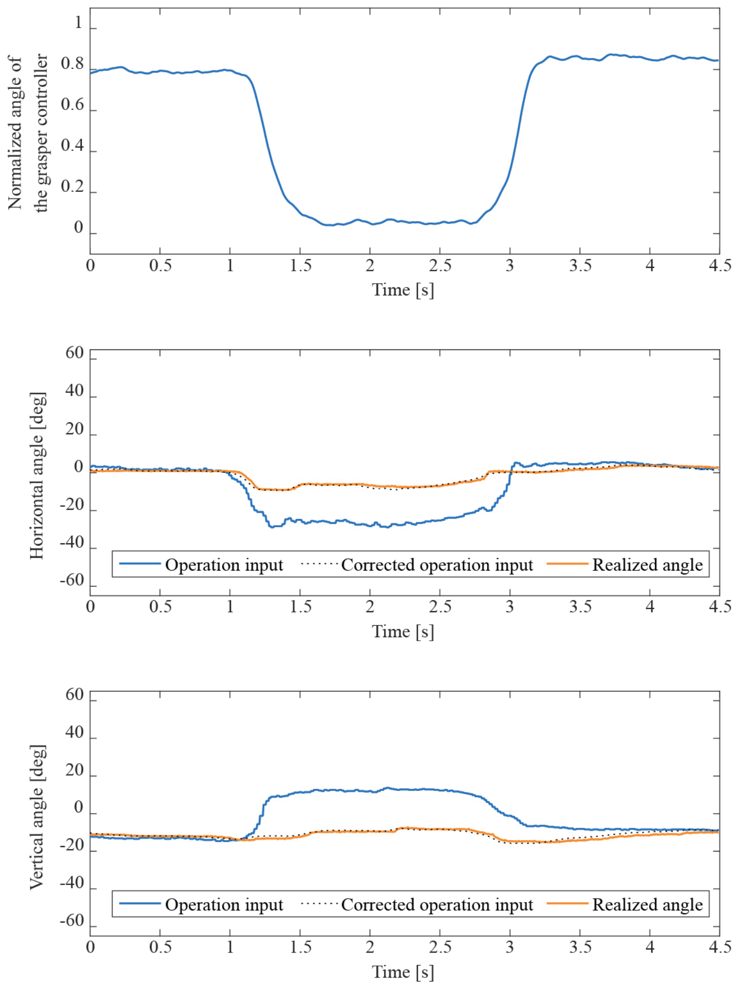


Fig. 5. (Color online) Suppression of unintended operation input during the grasping operation.

4. Experiments for Operational Performance Evaluation

4.1 Experimental methods

To verify the effectiveness of the proposed method in terms of operational performance, we conducted an evaluation using an experimental device with and without this processing. This experiment was reviewed and approved by the Ethical Review Board of the Graduate School of Information Science and Technology, The University of Tokyo (examination number UT-IST-RE-220908).

The overall experimental environment is shown in Fig. 6. Only the interface and handle of hand-held forceps with a force sensor were used in the experiment. At the end of the handle, a part that imitates the section from the front of the handle to the root of the forceps was attached and inserted into a hole fixed on a tabletop. The diameter of the forceps root was 10 mm and the diameter of the hole was 15 mm, allowing the operator to move the forceps freely up, down, left, and right (forward and backward movements are also possible, but were not observed). The hole was fixed at the same height as the abdomen of a patient lying on an operating table. This setup simulated the surgical environment.

During the experiment, the participant stood approximately 1 m in front of the device, wore a nitrile glove, held the input device, and manipulated the cursor in the screen (FlexScan EV3285, EIZO Corp, used at 70 ppi pixel density) instead of the robotic forceps. The distance of the cursor from the center of the screen corresponded to the angle of the joint on the forceps. The experimenter operated the program while viewing the screen on a laptop. The screen display was updated at approximately 60 Hz using a program created in Processing. To remove noise from the device output, the latter was processed through a low-pass filter built into the amplifier of the force sensor (cutoff frequency of 20 Hz) and a low-pass filter implemented in an Arduino program (cutoff frequency of 1.5 Hz); the angle of the gripper controller was processed by a low-pass filter (cutoff frequency 3 Hz) implemented in the Arduino program.

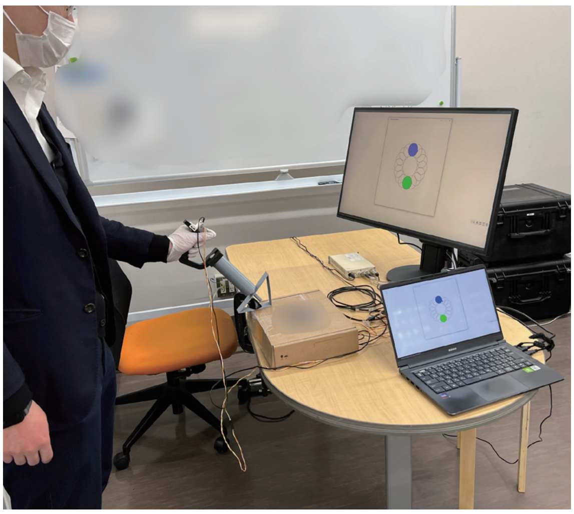
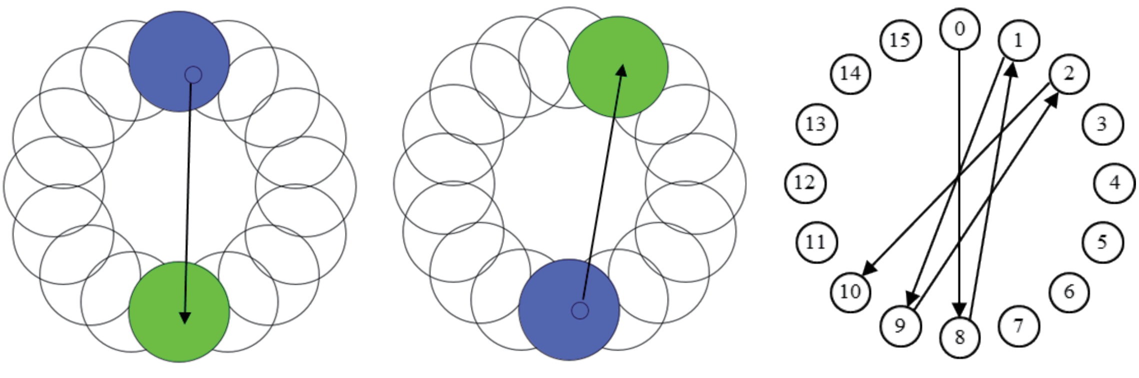


Fig. 6. (Color online) Picture of the evaluation experiment.

The task performed in the experiment was a virtual grasp-and-reach task using a force sensor input device. The task was inspired by the ISO 9241-9 standard(9) and the interface evaluation of hand-held forceps using it.(6) The flow of one block of the task is shown in Fig. 7. The first screen shows 16 circles, equally spaced around the circumference, with the top circle painted blue and the bottom circle painted green. In addition, a small blue circle is shown as a cursor with the center position as its initial position. The participant first moved the cursor into the large blue circle and performed a grasping operation within it [Fig. 7(a)]. If this was successful, the color of the cursor changed to green, and the participant moved the cursor to the green circle with the grasp and released the grasp within it. If this succeeded, the green circle that was the goal turns blue, the circle that was the initial starting point turned transparent, and the circle next to it turned green. The participant then performed the same grasp-and-reach movement as at the beginning [Fig. 7(b)]. This was repeated [Fig. 7(c)]. After the 31st movement, the cursor turned black to indicate the end of the block.

The entire experiment was conducted as follows. After the initial setup regarding the use/non-use of the UIA, a 5-block task was performed as an exercise with a target diameter (W) of 120 pixels and a circle diameter (D) of 300 pixels where the centers of the targets were placed. After a one-min break, a one-block assignment was made for each of the six conditions: (W, D) = (100, 400), (100, 300), (150, 450), (100, 200), (150, 300), and (150, 200) (units: pixels). The order of the conditions was randomized, and there was a one-min break between blocks. After all blocks were completed, a 5-min break was followed by switching to another UIA use/non-use condition, and the task was performed in the same manner as in the first half. Participant A performed in the order of use/non-use and Participant B performed in the order of non-use/use. The participants were not told what conditions would be set for the first and second halves of the experiment. During the experiment, movement times and click positions for successful reaching movements were recorded and used to calculate the evaluation index.



(a) (b) (c)

Fig. 7. (Color online) Description of the grasp-and-reach tasks. (a) First grasp-and-reach movement in the block. (b) Second grasp-and-reach movement in the block. (a) and (b) show the case where W = 120 pixels and D = 300 pixels. (c) Directions of the first five grasp-and-reach movements in the block.

4.2 Evaluation methods

For evaluation, an index called *throughput*,[9] which is obtained from the results of the reaching movement during the task, was used, as shown:

$$Throughput = ID_e \,/\, MT, \tag{2}$$

where MT is the time of the reaching movement and ID_e is the following index, called the *effective index of difficulty*, with bits as the unit:

$$ID_e = \log_2(D \,/\, W_e + 1), \tag{3}$$

where W_e is the width of the 95% confidence interval of the cursor's arrival position along the axis of the reaching motion and is expressed by the following formula:

$$W_e = 4.133\ SD_x, \tag{4}$$

where SD_x is the standard deviation of the click position in the direction of the reaching motion in the block containing the motion of interest, including failed trials. Throughput is a metric often used in human interface evaluation and has its origin in Fitts' law,[7,8] which expresses the trade-off between accuracy required for a reaching movement and the speed of the movement. In many cursor manipulation interfaces, a proportional relationship has been found between the effective index of difficulty ID_e and the movement time MT.[8] At the interfaces, the throughput, which is the inverse of the proportionality coefficient, is higher for devices that allow faster and more precise movements.

In this experiment, throughput was obtained from each of the successful grasp-and-reach movements ($31 \times 6 = 186$) in each of the six blocks with and without UIA, excluding practice blocks, and the assessment of the presence of any difference in mean throughput was tested with a paired t-test at a 5% significance level.

5. Results

Figure 8 shows the relationship between the effective index of difficulty and movement time measured for each participant. The graphs also overlay the line $MT = a \times ID_e$, fitted by the least-squares method for each condition, with and without UIA. As in previous studies,[6–8] a close proportional relationship exists between the effective index of difficulty and movement time. Figure 9 shows the mean and standard deviation of throughput. For Participant A, the throughput was 0.47 ± 0.17 bits/s (mean ± standard deviation) without UIA and 0.94 ± 0.21 bits/s with UIA; for Participant B, the throughput was 0.58 ± 0.13 bits/s without UIA and 0.87 ± 0.18 bits/s with UIA. Both participants showed significantly higher throughput when using UIA ($p < 0.0001$, paired t-test).

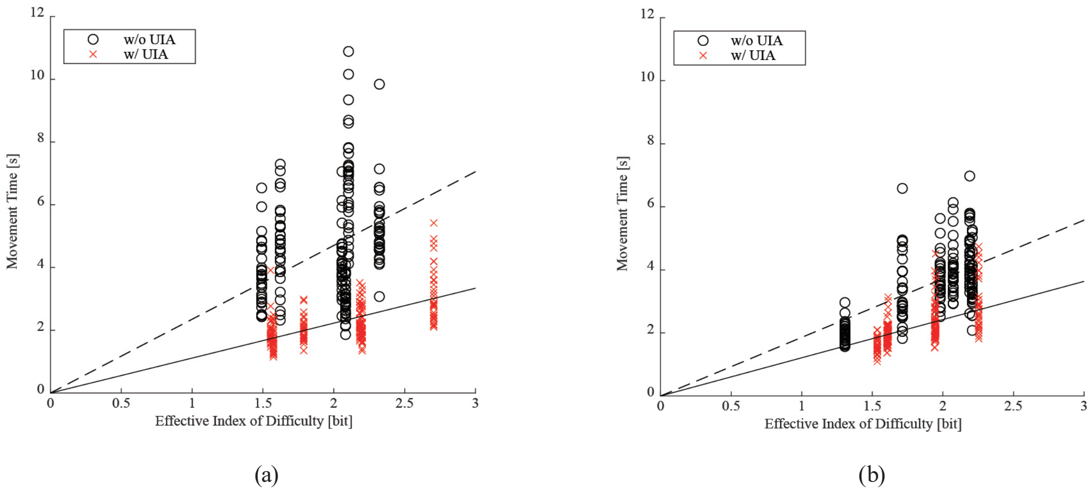


Fig. 8. (Color online) Relationship between the effective index of difficulty and movement time without (w/o) and with (w/) the use of the UIA. (a) Results for Participant A and (b) results for Participant B.

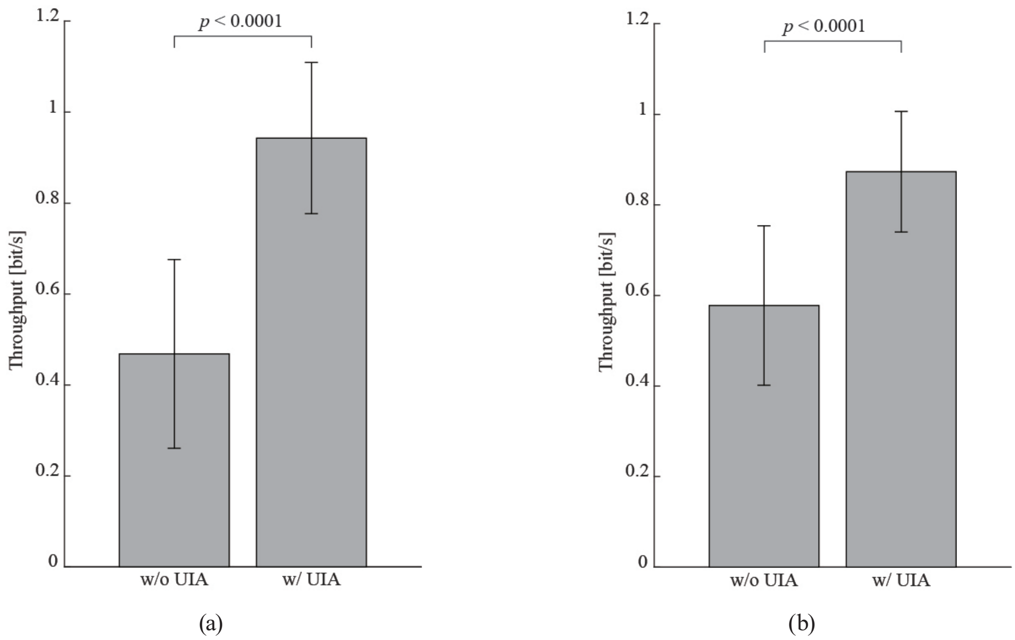


Fig. 9. Throughput in the cases without (w/o) and with (w/) the UIA. (a) Results for Participant A and (b) results for Participant B. Bars indicate the mean, and error bars indicate standard deviation.

6. Discussion and Conclusions

We developed a processing method (UIA) for force sensor-based input devices for hand-held robotic forceps to remove unintended input from operations involving tip direction due to gripper operation. In experiments with two subjects, UIA resulted in a 1.5- to 2-fold increase in the throughput of the input device. This means that the use of UIA reduces the operation time under the conditions of this experiment by about 2/3 to 1/2. We presume that the reason it takes longer when UIA is not used is that the gripper operation must be performed more slowly to reduce the effect of unintended input. Unintended input could cause cursor movement during the gripper operation, which could cause the cursor to move outside the goal at the end of the operation and cause the task to fail. Therefore, participants had to carefully operate the gripper so that the cursor would not go outside the circle during its operation. In contrast, when using UIA, the cursor command is frozen during the gripper operation, so if the cursor is placed inside the goal during the reaching motion, the cursor rarely moves out of the goal even if the gripper operation is performed quickly. Therefore, we infer that the task can be successfully completed with a fast-gripping motion. In addition, the fact that the UIA allows the gripper operation to be performed with less attention may influence the reaching movement immediately preceding it, but assessing the accuracy of this suggestion requires further study.

Note that this experiment did not use a foot pedal to operate the clutch. Operating the clutch would allow gripper operation without generating unintended operation input by fixing the joint after the reaching movement, even in the absence of UIA. However, we inferred that training is required to quickly step on the foot pedal while manipulating the forceps' tip. The proposed UIA may automate this clutch operation, hence the use of the term "soft clutch" in Sect. 3.2. Therefore, we infer that the proposed UIA can prevent unintended inputs caused by gripping operation more efficiently than the actual clutch operation. However, there is a possibility that the foot pedal may be more efficient due to the difference in reliability between the actual foot pedal and the soft clutch, and this point needs to be verified in the future.

We described a process for eliminating unintended force input associated with the gripper operation used in hand-held forceps that have a force sensor as an input device, and the impact of this process on operational performance was quantitatively demonstrated by a virtual grasp-and-reach task using the input device. In the future, it will be necessary to verify the effect of this interface improvement in a realistic surgical environment and to further improve the operability of the device by comparing it to other methods.

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