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Improved Integrated Robotic Intraocular Snake: Analyses of the Kinematics and Drive Mechanism of the Dexterous Distal Unit

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Abstract

Retinal surgery can be performed only by surgeons possessing advanced surgical skills because of the small, confined intraocular space, and the restricted free motion of the instruments in contact with the sclera. Snake-like robots may be essential for use in retinal surgery to overcome this problem. Such robots can approach the target site from suitable directions and operate on delicate tissues during retinal vein cannulation, epiretinal membrane peeling, and so on. We propose an improved integrated robotic intraocular snake (I²RIS), which is a new version of our previous IRIS. This study focused on the analyses of the kinematics and drive mechanism of the dexterous distal unit. This unit consists of small elements with reduced contact stress achieved by changing wire-hole positions. The kinematic analysis of the dexterous distal unit shows that it is possible to control the bending angle and direction of the unit by using two pairs of drive wires. The proposed drive mechanism includes a new pull-and-release wire mechanism in which the drive pulley is mounted at a right angle relative to the actuation direction (also, relative to the conventional direction). Analysis of the drive mechanism shows that compared to the previous drive mechanism, the proposed mechanism is simpler and easier to assemble and yields higher accuracy and resolution. Furthermore, considering clinical use, the instrument of the I²RIS is detachable from the motor unit easily for cleaning, sterilization, and attachment of various surgical tools. Analyses of the kinematics and drive mechanism and the basic functions of the proposed mechanism were verified experimentally on actual-size prototypes of the instrument and motor units.

Keywords

medical robotics; retinal surgery; microsurgery; mechanical design

1. Introduction

Retinal surgery is one of the most difficult surgical procedures that can be performed only by surgeons possessing advanced surgical skills. These surgeons must perform the operations within the small, confined intraocular space using instruments with restricted free

motion in the sclera. Many robotic systems that assist in retinal surgery and enhance surgical skills have been developed to overcome this problem [1]. These robots are teleoperated robotic systems controlled by means such as the trackball [2], joystick [3], or master arm [4]; cooperatively controlled robotic systems [5, 6]; handheld robots or devices [7–12], and untethered microrobots [13]. Steady-Hand Eye Robot (SHER) [5] developed by one of our research group enables smooth tool manipulation using a cooperative control scheme between the surgeon and robot arm. The SHER system enhances tool manipulation accuracy in various vitreoretinal surgery tasks. Some robot systems were applied to in vivo studies [14–16] or in-human studies [17, 18]. However, these systems implemented straight rigid tools.

Snake-like robots can be crucial for use in future retinal surgery. Such robots can approach a target from suitable directions and operate on delicate tissues when accessing its anterior portion for procedures such as vein cannulation or membrane peeling. Many snake-like robots have been developed for medical use [19–25]. In the conventional snake-like robots, bending functions are designed by mechanical hinges or elastic functions of structural members. Mechanical hinges are difficult to implement on a submillimeter scale because the hinge shaft and holes are so small that they cannot be designed and assembled with sufficient strength. The elastic functions of structural members are applied to microsurgical snake-like robots [26–28] because of their simple structure and capability for reduced diameter. However, the bending radii of the snake-like robots using the structural members are large. In such cases, the robot arms (e.g., SHER) that hold the snake-like robot should have large motion ranges to allow the end effector to approach a target from various directions (see Fig.1 (a)). In our earlier work, we presented the design of a dexterous handheld submillimeter intraocular robot called the Integrated Robotic Intraocular Snake (IRIS) [29]. The original dexterous distal unit (DDU) of the IRIS is based on the principle of the variable neutral-line mechanism [30]. Subsequently, a more compact actuation unit with better resolution for the IRIS, preliminary operational evaluation of the IRIS, and its integration with the SHER system were presented in [31]. However, from the perspective of clinical use, the previously developed IRISs [29, 31] and conventional system [28] are still large, heavy, and mechanically complex. A more compact and simpler IRIS is desired for integration in robotic systems for retinal surgery. Furthermore, the instrument should be detachable from the motor unit for cleaning, sterilization, and attachment of various types of surgical tools. As a continuation of our previous works [29, 31], we proposed an improved integrated robotic intraocular snake (I²RIS) [32].

This study is focused on the analyses of the kinematics and drive mechanism of the DDU. In this paper, first, a system overview of the SHER with the IRIS, small elements with reduced contact stress, and the kinematic analysis of the DDU are shown. In the kinematics analysis, the relationships between the bending angle and direction of the DDU and the pull-and-release wire displacement were derived. Next, a new drive unit was designed. This design includes a new wire drive mechanism wherein the drive pulley is mounted at a right angle relative to the actuation direction. During the drive mechanism analysis, the relation between the rotation angle of the drive pulley and the pull-and-release wire displacement was derived, and the position of the wire end point on the drive pulley was decided based on the analysis results. Finally, the kinematics and drive mechanism analyses and the basic

functions of the proposed mechanism were experimentally verified on actual-size prototypes of the instrument and motor units.

2. I²RIS Mechanism Analysis and Design

Medical robots for retinal microsurgery require many strict system design specifications. Figure 1 shows the SHER+IRIS system overview and the required specification of the DDU of the IRIS based on our previous work [29]. The IRIS is located at the distal end of the SHER. The SHER has 5 degrees-of-freedom (DOF) to help determine the tip position of the IRIS end effector within the intraocular space. The shaft diameter, which should be sufficiently small to make incisions into the sclera, is 0.9 mm, equivalent to a 20 gauge needle and is currently the maximum acceptable size in retinal surgery. For clinical procedures such as epiretinal membrane (ERM) peeling and retinal vein cannulation (RVC), an instrument should be able to deliver and maintain sufficient force. Since the forces exerted are mostly below 15 mN in both ERM peeling [33] and RVC [34, 35], the desired payload was set as 30 mN. The motion range of pitch and yaw directions required to approach tissue from a suitable direction were set as $\pm 45^\circ$. The wrist mechanism length was set to less than 10 mm, to enable large rotation within a small space within human eye inner diameter of 25 mm.

Since the IRIS system should be small and compact, both the DDU design and the drive unit design are vital. This section presents the designs of the DDU and drive unit of the I²RIS.

2.1. Dexterous distal unit

2.1.1. Conceptual design—Figure 2 shows the conceptual design of the DDU of the I²RIS. The DDU is composed of 13 disk-like elements that are connected and actuated by four wires to provide 2-DOF motion, i.e., bending around the pitch and yaw axes. Each element has cylindrical top and bottom surfaces and five holes, as shown in Fig. 2 (b). The disk center hole is used for passing the driving element or providing the end-effector energy, e.g., for microforceps, needles, or cannulae. The elements make contact with each other via cylindrical surfaces distributed alternatively in the orthogonal direction. In the case of bending around the pitch or yaw axes, relative to each other, each element bends by about 7.5° to achieve a total of 45° bending at the six cylindrical surfaces gaps. According to the Hertz theory, the contact length of the elements must be increased to reduce the contact stress [29].

Figure 3 shows the previous and current element designs and compares the bending motion of the two designs. As shown in Fig. 3 (a), the contact length of the cylindrical surfaces can be increased by changing the wire holes positions. Moreover, a cylindrical contact region of 7.5° ($= \pm 3.75^\circ$) is sufficient for a yaw and pitch motion range of $\pm 45^\circ$. Using this design, the elements thickness can be decreased from 0.25 mm to 0.15 mm, as shown in Fig. 3(b). The new design reduces the dead space and the DDU length to less than 2 mm.

2.1.2. Kinematic analysis—As shown in Fig. 3 (b), in the previous mechanisms, the bending motion of each element in the pitch (or yaw) direction is driven by a pair of independent wires 2 and 4 (or wires 1 and 3) and therefore, four actuators are

required. However, in the proposed mechanism, the bending motion is driven by two pairs of interconnected wires using two actuators. The kinematics analysis of the proposed mechanism is derived as follows.

Figure 4 shows the geometric model for the kinematic analysis between the first and second element from the proximal end in the initial and bending states. The snake first element is called “proximal end element”, and the 13th element is called “distal end element”. In this kinematic analysis, the coordinate system of the proximal end element is defined as Σ_0 on the bottom side flat surface of the element. As shown in Fig.4(b) and (c), the other coordinate systems of the elements are defined as $\Sigma_i (i = 1, 2, 3, \dots, 12)$ located at the intersection of the central axis of the (i+1)th element and the (i+2)th element, and the orientations are fixed at the (i+1)th element.

The pitch axis represents the rotation around the y axis, and the yaw axis, that around the x axis. Fig. 4 shows the bending in the pitch axis direction: ϕ_i is the angle between the center axis of the element and the center of the wire hole, and ϕ_p is the pitch angle between the center axis of the element and the contact point of each element pair. Therefore, each bending angle between adjoining elements is $2\phi_p$. In this kinematic analysis, it is assumed that the bending angles between every two consecutive elements are identical. Since the DDU has six gaps in each direction (see Fig.2), the total bending angle for each direction is $12\phi_p$.

In the case of bending in the pitch direction, the differences in length between the initial position (straight case, Fig. 4.a) and bent position with angle ϕ_p (Fig.4,b) of the wire of the release side, i.e., g_{pr} , the wire of the pull side, i.e., g_{pp} , and the central gap, i.e., g_{pc} are as follows:

$$\Delta g_{pr} = g_{pr} - g_i = r_e (\cos(\phi_i + \phi_p) - \cos\phi_i) \quad (1)$$

$$\Delta g_{pp} = g_{pp} - g_i = r_e (\cos(\phi_i - \phi_p) - \cos\phi_i) \quad (2)$$

$$\Delta g_{pc} = g_{pc} = r_e (1 - \cos\phi_p) \quad (3)$$

where suffixes i , r , p , and c mean the initial, release, pitch or pull, and center, respectively, and r_e is the radius of the cylindrical surface. Similarly, the differences in the wire length in the case of bending in the yaw direction are g_{yr} , g_{yp} and g_{yc} , and they are obtained using g_{yr} , g_{yp} , g_{yc} , g_i , r_e , ϕ_i and ϕ_y .

The displacements of wires 1, 2, 3 and 4 to bend the DDU in each direction, i.e., $W_i (i = 1, 2, 3, 4)$ and the total length of the central gap W_c are obtained using Eq. (1)–(8), by summing g_{pr} , g_{pp} , g_{pc} , g_{yr} , g_{yp} and g_{yc} . Wires 1 and 2 are two sets of wires positioned diagonally, respectively (see Fig. 2).

$$W_1 = 12\Delta g_{pp} + 12\Delta g_{yr} \quad (4)$$

$$W_2 = 12\Delta g_{pr} + 12\Delta g_{yr} \quad (5)$$

$$W_3 = 12\Delta g_{pr} + 12\Delta g_{yp} \quad (6)$$

$$W_4 = 12\Delta g_{pp} + 12\Delta g_{yp} \quad (7)$$

$$W_c = 12\Delta g_{pc} + 12\Delta g_{yc} \quad (8)$$

Next, the position and orientation of the coordinate system Σ_{12} of the distal end element are analyzed. Based on Fig. 4, the homogeneous transform relation of the coordinate systems Σ_0 and Σ_1 (rotation around the y axis), Σ_1 and Σ_2 (rotation around the x axis), Σ_2 and Σ_3 (rotation around the y axis), and Σ_{11} and Σ_{12} (rotation around the x axis) are as follows.

$$\begin{bmatrix} x_0 \\ y_0 \\ z_0 \\ 1 \end{bmatrix} = \begin{bmatrix} \cos 2\phi_p & 0 & \sin 2\phi_p & 0 \\ 0 & 1 & 0 & 0 \\ -\sin 2\phi_p & 0 & \cos 2\phi_p & h_e + h_p \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x_1 \\ y_1 \\ z_1 \\ 1 \end{bmatrix} = T_1 \begin{bmatrix} x_1 \\ y_1 \\ z_1 \\ 1 \end{bmatrix} \quad (9)$$

$$\begin{bmatrix} x_1 \\ y_1 \\ z_1 \\ 1 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos 2\phi_y & -\sin 2\phi_y & 0 \\ 0 & \sin 2\phi_y & \cos 2\phi_y & h_e + h_p + h_y \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x_2 \\ y_2 \\ z_2 \\ 1 \end{bmatrix} = T_2 \begin{bmatrix} x_2 \\ y_2 \\ z_2 \\ 1 \end{bmatrix} \quad (10)$$

$$\begin{bmatrix} x_2 \\ y_2 \\ z_2 \\ 1 \end{bmatrix} = \begin{bmatrix} \cos 2\phi_p & 0 & \sin 2\phi_p & 0 \\ 0 & 1 & 0 & 0 \\ -\sin 2\phi_p & 0 & \cos 2\phi_p & h_e + h_y + h_p \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x_3 \\ y_3 \\ z_3 \\ 1 \end{bmatrix} = T_3 \begin{bmatrix} x_3 \\ y_3 \\ z_3 \\ 1 \end{bmatrix} \quad (11)$$

where h_e is the height of the element, h_p (see Fig.4(c)) and h_y (in the case of bending in the yaw axis direction) are as follows:

$$h_p = g_{pc} / \cos \phi_p \quad (12)$$

$$h_y = g_{yc} / \cos \phi_y \quad (13)$$

Therefore, the position and orientation of the coordinate system Σ_{12} of the distal end element are obtained from Eq. (14).

$$\begin{bmatrix} x_0 \\ y_0 \\ z_0 \\ 1 \end{bmatrix} = T_1 \ T_2 \ T_3 \ T_4 \ T_5 \ T_6 \ T_7 \ T_8 \ T_9 \ T_{10} \ T_{11} \ T_{12} \begin{bmatrix} x_{12} \\ y_{12} \\ z_{12} \\ 1 \end{bmatrix} \quad (14)$$

where $T_2=T_4=T_6=T_8=T_{10}=T_{12}$ and $T_3=T_5=T_7=T_9=T_{11}$.

Figure 5 shows the relation between the bending angle and the pull-and-release wire displacement as calculated using Eq. (1)–(8) for the bending direction shown in Fig. 6. Of note, the pull-and-release wire refers to a set of wires positioned diagonally, i.e., wires 1 and 3, or wires 2 and 4. Fig. 5 (a) and Fig. 6 (a)(c) depict identical conditions, and Fig. 5 (b) and Fig. 6 (b) show identical conditions. The negative pull wire displacement calculated from the equations is shown as positive in Fig. 5. To bend the distal unit by 45° , the average of the maximum of the pull-and-release wire displacement is 0.216 mm, when the bending direction is 45° . The minimum is $0.153 (= 0.216/\sqrt{2})$, when the bending direction is 0° or 90° (pitch or yaw direction). The maximum difference in the pull-and-release wire displacement is 0.040 mm, regardless of the bending direction when the bending angle is 45° . The differences in the pull-and-release wire displacements are extremely small, and the drive wires have some elasticity. Therefore, these results suggest that it is possible to achieve bending of the DDU in one direction by using one actuator.

Figure 7 shows the bending angle and direction of the distal end element as calculated from the rotation matrix part of Eq. (9)–(14). The nominal bending angle and the nominal bending direction are the bending angle and bending direction based on the assumption that the DDU is a continuum, that the central axis is the neutral axis, and that the shape is continuously deformed into an arc. Figure 7 (a) shows the combinations of the bending angle of the pitch and the yaw direction for each element. Figure 7 (b) shows the difference from the nominal bending angle (45°) and the difference from the nominal bending direction shown in Fig. 7 (a). The maximum difference of bending angle is only 0.03° , and the maximum difference in bending direction is 0.78° . Although there are some differences from the nominal bending angle and direction, these results suggest that the bending angle and direction of the DDU can be controlled by using two pairs of drive wires.

2.2. Drive Mechanism Analysis

In a wire drive mechanism, the wires are generally actuated by the rotational motion of a pulley or the linear motion of a lead screw. As shown in Fig. 8, if the DDU is driven by one actuator using the conventional mechanism to bend in one direction, the pull-and-release wire displacements are equal to the drive wire displacement. However, for a device with $\phi 0.9$ mm diameter and 45° bending motion range, the maximum pull-and-release wire displacement is only 0.216 mm. Therefore, maintaining accurate bending angle control and assembling the parts of the drive mechanism are challenging. If the drive wire displacement is larger than the pull-and-release wire displacement, it will be easy to maintain the accuracy and resolution of the bending angle control and assemble the parts of the drive mechanism.

Figure 9 shows the concept of the proposed wire drive mechanism, including the coordinate systems. In this mechanism, a drive pulley is mounted at a right angle relative to the actuation direction, unlike that in the conventional pulley drive mechanism shown in Fig. 8(a). The direction of the drive wire displacement is almost perpendicular to the direction of the pull-and-release wire displacement. The drive pulley does not need to be a cylindrical surface. The end point of the wire is not wrapped around the drive pulley; it moves only in the pulley rotation x–y plane. The wire length between the origin (the wire entrance point) and the end point is changed by the pulley rotation. The relationship between the drive pulley rotation angle θ_{in} and the pull-and-release wires 1 and 3 lengths $l_i (i = 1, 3)$ can be obtained from the following equation:

$$l_i = \sqrt{l_x^2 + l_y^2 + l_z^2} = \sqrt{(r \cos(\theta_{in} - \theta_{offi}))^2 + (l_y + r \sin(\theta_{in} - \theta_{offi}))^2 + l_z^2} \quad (15)$$

where r is the drive pulley radius; θ_{offi} the offset angle of the wire end point on the pulley; l_y , the y-direction distance of the pulley center; and l_z , the z-direction distance from the origin to the end point of the wire on the pulley. Similarly, relationship for wires 2 and 4 can be calculated.

Figures 10 (a) and (b) shows the three-dimensional (3D) and two-dimensional (2D) drawings, respectively, of the drive wire and tension F . The relationship between the input torque T and the wire tension F is as follows:

$$T = F_r r = F \frac{l_{xy}}{l} r \sin \theta_A \quad (16)$$

where $F_r = F_{xy} \sin \theta_A$, $F_{xy} = F \frac{l_{xy}}{l}$, $\cos \theta_A = \frac{l_{xy}^2 + r^2 - l_y^2}{2l_{xy}r}$.

When $T = FR$, R is expressed as follows:

$$R = \frac{l_{xy}}{l} r \sin \theta_A \quad (17)$$

R can be defined as a “virtual radius.”

Figure 11 shows the two pull-and-release wire displacements $\Delta l_i = l_i - l_0$ ($i = 1, 3$), where l_0 is the initial wire length, and represents the difference between the pull-and-release wire displacements ($l_1 - l_3$). The wire bending angle at the wire entrance point (see Fig. 10) and the virtual radius for the case when the wire end point θ_{off1} is changed from -5° to 15° and θ_{off3} is changed from 185° to 165° at intervals of 5° are shown in Fig. 11. The parameters were determined by trial and error and the following design specifications and conditions were assumed: (a) the maximum displacement of the pull and release wire is about ± 0.4 mm considering the margin; (b) the maximum motion range of the drive pulley is about $\pm 20^\circ$; and (c) the drive pulley diameter is about 10 mm, considering a motor diameter of 8 mm, which is diameter of the motor used in the previous IRIS.

The required pull-and-release wire displacements $l_f=0.216$ mm to bend the DDU 45° is obtained from the drive pulley rotation angle $\theta_{in} \doteq 10^\circ$. The drive wire displacement $r\theta_{in}$ is 0.87 mm. Therefore, the drive wire displacement is four times the pull-and-release wire displacement l_f . Similarly, the virtual radius R is about 1.25 mm. This result means that the proposed mechanism is similar to the conventional pulley drive mechanism with a pulley radius of about 1.25 mm. The real radius of the drive pulley is 5 mm. Therefore, the proposed drive mechanism can enable easy assembly and higher accuracy comparatively to the conventional drive mechanism.

The pull-and-release wire displacement l_f is changed almost linearly. The results mean that the proposed wire drive mechanism can enable two-motor actuation with 2-DOFs. The previously developed IRISs [29, 31] performed four-motor actuation. Furthermore, this mechanism is suitable for wire drive mechanisms with a small displacement motion range, such as in the case of the DDU of the IRIS.

In the case of the conventional drive mechanisms, the pull-and-release wire displacements are equal. Therefore, the best value for the difference of the pull-and-release wire displacements ($l_1 - l_3$) is 0 mm. For $\theta_{off1}: 5^\circ$, $\theta_{off2}: 175^\circ$, the difference is the minimum and better than that compared to other positions (see Fig. 11(b)). On the other hand, in this drive mechanism, the pull-and-release wire are bent at the wire entrance point. Small bending angle of the wire at the wire entrance point is preferred because the large bending angles reduce the durability of the wire. In the case of $\theta_{off1}: 15^\circ$, $\theta_{off3}: 165^\circ$, the wire bending angle at the wire entrance point is smaller than that compared to other positions (see Fig. 11 (c)). Moreover, it is possible to cancel the wire displacement difference by means of the combination of the wire displacement difference caused by the bending motion as shown in Fig. 5.

In this research, the wire end points were selected as $\theta_{off1}: 10^\circ$, $\theta_{off2}: 170^\circ$ (the red line in Fig.11). The difference between the pull-and-release wire displacements, i.e., ($l_1 - l_3$) is larger than the optimum case: $\theta_{off1}: 5^\circ$, $\theta_{off2}: 175^\circ$. However, the wire bending angle at the wire entrance point is smaller in this research. Furthermore, the difference of the wire displacements has the effect of returning the drive pulley to the origin automatically because of the elongation elasticity of the wire, and this effect will allow “easy attach” when attaching the instrument unit to the motor unit.

2.3. Instrument and motor unit design

The instrument unit and a motor unit are designed according to the conceptual design presented above. Generally, the instruments for medical robots must be detachable from the robot body to enable the required cleaning, sterilization, and attachment of various surgical tools. Therefore, the I²RIS instrument was designed to be detachable. Figures 12 and 13 show the instrument and motor unit. The instrument unit can be easily attached and detached from the motor unit using handle levers and guiding pins and holes.

3. Experimental results and discussion

The effectiveness of the proposed mechanism was verified by using actual-size prototypes of the instrument and motor units.

3.1. Prototyping of the instrument unit and motor unit

Figure 14 shows the DDU prototype and the wire assembly method. The elements were made of SUS 303 and can be manufactured by machining using drills and end mills. The drive wires were $\phi 0.15$ mm (1×19) wires made of SUS 304. A preliminary experiment confirmed that a nitinol wire has lower stiffness, larger friction, and larger hysteresis than an SUS wire. The inner diameter of the tool shaft is 0.76 mm and the diameter of the hole at the wire entrance point is 0.5 mm, which provides sufficient space for the four drive wires from the wire end point on the drive pulley to pass smoothly without congestion. The assembly method by the wire root shown in Fig. 14 is very easy and simple and does not require the use of any glue, fixture parts, or knots at the distal end element. Note that the wire in a pull-and-release wire pair (namely, wires 1 and 3, and wires 2 and 4) are not the same wire. In fact, the wire pair 1 and 2 and the wire pair 3 and 4 are the same wires, respectively. The end points of wires 1 and 3 (and similarly, those of wires 2 and 4) are connected to the same drive pulley using super glue (cyanoacrylate).

Figure 15 shows an overview of the actual-size prototypes of the instrument and motor units. The mechanical parts were made of 3D-printed materials (printed by Formlabs Form 2 Photopolymer Resin Standard Grey built with 0.05-mm layers and Accura 60 High-Resolution Stereolithography built with 0.05-mm layers) and brass. The weights of the instrument and motor units were 6.4 and 25.9 g, respectively, and total weight was 32.3 g. The instrument unit could easily be attached and detached from the motor unit using handle levers and guiding pins and holes, as shown in Fig. 15. The instrument couplings returned to their original positions automatically because of the restitution force by the wire tension. Therefore, the instrument couplings could be easily aligned with the motor couplings when attaching the instrument. The instrument unit can be detachable from the motor unit for cleaning and sterilization. However, future investigations may be necessary to decide between a disposable solution versus a sterilizable and reusable one.

3.2. Manual drive bending experiment

Figure 16 shows an overview of the experimental setup for the manual drive experiment. The torque was input by the weight ($25 \text{ g} \times \text{four piece}$) using gravity at the coupling hole to only one instrument coupling. Therefore, the bending direction is 45° (the diagonal direction shown in Figs. 5 and 6). The rotation angle of the drive pulley and the bending angle of the DDU were measured from photographs captured from the perpendicular direction (see Fig. 16) and using the angle measurement function of 2D CAD software. The bending angle was measured from the images of a nitinol wire inserted into the center hole of the distal unit (see Fig. 18). The measurement error of this method using 2D CAD software is about 0.2° calculated using 10 different angle photographs.

Figure 17 shows two consecutive measurement results of the relation between the input torque of the drive pulley, rotation angle of the drive pulley, and bending angle of the DDU. This experiment was performed out under the no-load condition; therefore, the input torque originates from the restoring force of the elasticity of the wire because of the differences in the pull-and-release wire displacements. The required motion range of $\pm 45^\circ$ was obtained by the command angle of a drive pulley angle of $\pm 20^\circ$ or less. The rotation angle of the drive pulley was larger than the theoretical value. This may be caused by wire elongation and the gaps between the wire holes and the wires and so on. Although further experiments are required to clarify the cause, the bending angle can be controlled via the manipulation of the drive pulley angle by correcting the difference from the theoretical value by calibration.

The hysteresis between the input torque and bending angle of the DDU is larger than the hysteresis of the rotation angle of the drive pulley. However, the bending angle is controlled by the position control of the drive pulley, and therefore, it is not a serious problem. The maximum tension of the wire is about 3.2 N as calculated from Eq. (16) using the virtual radius (about 1.25 mm) and the input torque of the drive pulley (about 4 mNm). The wire maximum tension is within the safe range because the wire has a tensile strength of more than 10 N.

The drive pulley returned to the vicinity of the origin automatically when the input torque was zero. The hysteresis was less than $\pm 5^\circ$. Therefore, it is easy to align the coupling angle when attaching the instrument.

3.3. Motor drive bending experiments

The motor coupling was driven by a servo system (Maxon Motor Inc.) consisting of a DC servo motor (DCX8M) with a reduction gear (GPX8, gear ratio 64:1), an incremental encoder (ENX 8MAG 256 pulses/revolution), and a controller (EPOS2 24/2). In the experiments, the incremental encoder initialization is performed manually by visual inspection. In the future developments, for consistency and accuracy in system initialization, we may consider employing absolute encoders.

Figures 18 show the motor drive experiment results of the bending motion profile when there is no payload. The DDU is driven by one motor, and therefore, the bending angle is 45° . Figure 19 shows the motor drive experiment results of the relation between the command angle of drive pulley θ_{in} and the bending angle of the DDU driven by one motor for the case of a payload of 30.7 mN and that of no payload, and for twice measurement for each. The bending angle was measured from the pictures as done in the manual drive bending experiment. The pictures were captured from a direction perpendicular to the bending direction. The required motion range of $\pm 45^\circ$ was obtained by setting the command angle of the drive pulley angle of $\pm 20^\circ$ or less even when the payload was 30.7 mN. The command angle was larger than the theoretical value. This could be attributed to the backlash, torsional stiffness, wire elongation, and so on. Figure 20 shows the motor drive experiment results of the relation of the command angle of the drive pulley θ_{in} and the bending angle of the DDU driven by a combination of two motors. The bending direction is 0° (pitch direction) and -22.5° . The command angles of the two drive pulleys were decided according to the kinematics analysis results. The bending angles of the DDU were measured

by same method as mentioned above. The photographs were captured from a perpendicular direction determined using a digital tiltmeter. As shown in Fig. 19 and 20, bending by 45° , which is the required specification, was achieved in a predetermined direction for the following four basic types of motor drive cases: (cases 1, 2) each motor drives in bending direction of 45° or -45° ; (case 3) two motors drive by same motor angles in the bending direction 0° ; (case 4) two motors drive by different motor angles in the bending direction -22.5° . The experimental results show that it is possible to control the bending angle and direction of the DDU by a combination of two motors.

The specifications of the I^2 RIS based on the experimental results are listed in Table 1. The specifications of the developed I^2 RIS satisfy the requirements shown in Fig. 1. The integrated system (SHER + I^2 RIS) positioning precision and resolution will be examined in future work.

4. Conclusion

As a part of our ongoing efforts to improve our previous works on IRIS [29, 31], we proposed the I^2 RIS, a, simpler, and more compact system [32]. This paper focuses on the analyses of the kinematics and drive mechanism of the DDU. In the kinematics analysis, the relation between the bending angle and direction of the DDU and the pull-and-release wire displacement were derived. It was shown that the control of the bending angle and direction of the DDU is possible by means of two pairs of pull-and-release wires. In the drive mechanism analysis, the relation between the rotation angle of the drive pulley and the pull-and-release wire displacement was derived. The position of the wire end point on the drive pulley was fixed based on the analysis results. Finally, the kinematics and drive mechanism analyses and the basic functions of the proposed mechanism were experimentally verified using actual-size prototypes of the instrument and motor units. The developed I^2 RIS is a simpler and more compact system that is suitable for use in retinal surgery.

The following future works are planned as a step toward achieving a clinical-grade system: (1) implementation and evaluation of (a) an end effector, such as a needle, a grasper, an optical fiber, and an energy device, on the DDU and (b) a user interface for the bending motion on the motor unit.; (2) integration and evaluation of this mechanism with the SHER system or other remote center-of-motion mechanisms; (3) development of a handheld IRIS; (4) development of a 2-stage, 4-DOF drive mechanism using 8-holed elements at the proximal stage; and (5) development of small diameter DDUs comparable to current clinical practice devices such as 23G. We note that it may be possible to build 25G and 27G tools similar to the one presented in this paper but the technological limitations are tremendous.

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Fig. 1. Steady-Hand Eye Robot (SHER) and the required specifications of the dexterous distal unit (DDU) [21]: (a) system overview of SHER with Integrated Robotic Intraocular Snake; (b) required specifications of dimension and motion range of DDU.

Fig. 2. Conceptual design of the DDU of I²RIS: The unit is composed of 13 disk-like elements providing 2-DOF bending joints actuated by four wires. (a) Overview; (b) three-view drawing of the element (dimensions in millimeter).

Fig. 3.

Comparison of the previous and current element designs and bending motion: (a) The previous element; (b) the proposed element, in which the contact surface is increased (thereby reducing contact stress) by changing the hole position, and the bending motion of each element is driven by two pairs of interconnected wires.

Fig. 4.

Kinematic analysis of the first and second elements: (a) The initial state; (b) the bending state; (c) magnified view of the center of the bending state.

Fig. 5.

Relationship between the bending angle and the pull and release wire displacement: (a) Pitch or yaw direction (bending direction: 0° or 90°); (b) diagonal direction (bending direction: 45°).

Fig. 6.

Bending state and definition of bending angle and direction: (a) Pitch direction (bending direction: 0°); (b) diagonal direction (bending direction: 45°); (c) yaw direction (bending direction: 90°); (d) bending angle and direction definition.

Fig. 7.

Bending angle and direction of the distal end element; (a) combinations of the bending angle of the pitch and yaw directions for each element; (b) difference from the nominal bending angle (45°), and the difference from the nominal bending direction.

Fig. 8.

Conventional wire drive mechanism: (a) Rotation pulley type; (b) lead screw type. The push–pull wire displacements are equal to the drive wire displacements. In the case of IRIS, the push–pull wire displacement is 0.216 mm for a total bending of 45° for the DDU.

Fig. 9.

Concept of the proposed wire drive mechanism and coordinate systems (dimensions in millimeter): (a) three-dimensional (3D) drawing, (b) x-y plane two-dimensional (2D) drawing. The drive pulley is mounted perpendicular to the actuation direction, unlike that in a conventional pulley drive mechanism.

Fig. 10. 3D and 2D drawings of drive wire and tension: (a) The 3D drawing; (b) the 2D drawing on the x - y plane.

Fig. 11.

Proposed drive mechanism analysis: (a) Pull-and-release wire displacements; (b) difference of pull-and-release wire displacements; (c) bending angle of the wire at the entrance point; (d) virtual radius, shown by the red line, is the selected parameter.

Fig. 12.
Instrument unit: (a) overview, (b) cross section.

Fig. 13.

Design of instrument and motor units: (a) Attached state; (b) detached state.

Fig. 14.

Actual-size prototypes: (a) DDU; (b) element; (c) assembly method of wire root.

Fig. 15. Overview of actual-size prototypes of instrument and motor units: (a) attached state, (b) detached state.

Fig. 16.
Overview of the experimental setup for the manual drive experiment.

Fig. 17.

Manual drive experiment results: (a) Input torque of the drive pulley and bending angle of the DDU; (b) the rotation angle of the drive pulley and bending angle of the DDU.

Fig. 18.

Motor drive experiment: DDU is driven by one motor to bend; bending direction is 45° .

Fig. 19.

Command angle of the drive pulley θ_{in} and bending angle of DDU driven by one motor: (a) Bending direction is 45°; (b) bending direction is -45°. The payload is 30.3 mN.

Fig. 20.

Command angle of the drive pulley θ_{in} and bending angle of DDU driven by a combination of two motors. Bending direction is 0°(pitch direction) and -22.5°.

Table 1.Specifications of the developed improved integrated robotic intraocular snake (I²RIS)

Items		Specifications
<i>Dimensions of distal tip</i>	<i>Diameter</i>	0.9 mm
	<i>Bending length</i>	1.95 mm
<i>Range of motion</i>	<i>Pitch</i>	$> \pm 45^\circ$
	<i>Yaw</i>	$> \pm 45^\circ$
<i>Payload</i>		> 30 mN
<i>Instrument unit weight</i>		6.4 g
<i>Motor unit weight</i>		25.9 g
<i>Total volume without shaft and distal tip</i>		$20 \times 20 \times 75$ mm