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Intraocular Snake Integrated with the Steady-Hand Eye Robot for Assisted Retinal Microsurgery*

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Abstract

Due to the confined intraocular space and physical constraints in tool manipulation, snake-like robots have a significant potential for use in retinal microsurgery. By enhancing the dexterity at the tool tip, not only the operable space on the retina can be enlarged, but also the delicate target tissues can be reached at an optimal angle minimizing the damage and making the operation much easier. In this study, we present an improved version of our earlier integrated intraocular snake (IRIS) robot, and combine it with another robotic assistant: the cooperatively controlled Steady-Hand Eye Robot (SHER). SHER is used to drive IRIS close to the retina with precision, while IRIS makes omnidirectional bends by combining its yaw and pitch motions and provides a significantly enhanced intraocular dexterity while holding the sclerotomy port fixed. For precise control of IRIS, its snake-like tip actuation has been characterized through experiments considering both a free tool tip and external loading at the tool tip. The workspace analysis showed $\pm 45^{\circ}$ yaw and pitch with excellent repeatability ($\pm 1^{\circ}$) despite the highly miniaturized articulated segment length (3 mm) and very thin shaft (Ø 0.9 mm). Our preliminary experiments in an artificial eye model have shown feasibility in reaching targets requiring bends up to 55° accurately.

I. Introduction

Retinal microsurgery is one of the most technically demanding surgical disciplines, requiring dexterous manipulation of extremely delicate tissues in a confined workspace. During the operation, the surgeon uses a surgical microscope positioned above the patient's eye to get a magnified visualization of the retina. Then inserting thin-shafted instruments through a small incision on the sclera (\emptyset <1 mm), the surgeon tries to reach the surgical target and performs the procedure, which can be for instance, epiretinal membrane peeling,

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retinal vein cannulation or subretinal microinjection. During this phase, very fine and precise control of the instruments is crucial to avoid complications on the delicate retinal tissues. Though, due to the trocar constraint at the sclerotomy, moving the instruments may cause the eye, and therefore the surgical target on the retina, to move as well. This is in fact a beneficial feature that surgeons routinely use to easily adjust the eyeball orientation until getting a good view of the clinical target under the operating microscope. However, once the desired view is obtained and instruments begin interacting with the retina, the surgeon may want to avoid further movement of the eyeball. In this case, tool manipulation is confined to only three rotational degrees of freedom (DOF) about the sclerotomy and one translational DOF along the instrument axis. Manipulating the tool in other directions, such as translating laterally, will cause the eyeball to move, the microscope view to change, and will create a potentially risky relative motion between the surgical instrument tip and retinal tissue. This sets a strict limit on the tool orientation, and therefore angle of approach between the surgical tip and the retinal tissue, for the reachable positions inside the eye. A similar problem exists in other surgical domains, where the required dexterity was provided by robotic systems integrating additional DOFs at the distal end of the surgical instruments [1– 3], e.g., the EndoWrist instruments from Intuitive Surgical and snake-like robots. Following a similar strategy and enhancing tool tip dexterity on ophthalmic instruments can potentially provide significant benefits to several procedures in retinal microsurgery.

A prototypical retinal microsurgery task is membrane peeling, where the surgeon delaminates a very thin fibrous membrane (micron scale) adherent to the retinal surface, using either a pick or micro-forceps. Excessive delamination forces during this procedure may lead to serious complications and even loss of vision [4]. Studies have shown significant dependence of delamination forces on the peeling angle [5], which is hard to control with the conventional tools. To achieve better dexterity inside the eye, an articulated micro-forceps was designed and shown to enlarge the operable area on the retina [6]. Yet, the swing-joint in this design required adjustment and locking right after insertion into the eye and before the actual operation, thus could not provide active bending during membrane delamination.

Injection of therapeutic and diagnostic agents into the retina is another challenging field, which can benefit from dexterous instruments. To cure degenerative retinal diseases ocular gene therapy has emerged as a promising method [7, 8], where various vectors are delivered to target areas by subretinal microinjections. Though, with the conventional tools, the operable area on the retina remains limited. Another difficult procedure is retinal vein cannulation (RVC), which aims to treat retinal vein occlusion by direct therapeutic agent delivery methods [9]. This requires direct injection into the occluded retinal veins, which are typically less than 100 μ m in diameter [10]. Due to small size and fragility of retinal vasculature, using an angled cannula, e.g., 30° [11], or aiming a straight cannula into the vessel at an angle, e.g., 45° [12], can enable a more gradual and therefore safer approach to the vein. In addition, the use of prebent microneedles has been explored [13] and a stent deployment unit with adjustable approach angle via concentric tubes has been devised [14]; yet in these approaches, the range of bending that can be achieved within the confined intraocular space was limited.

In order to assist retinal microsurgery, several teleoperated [15–17], cooperatively controlled [18, 19], handheld robots [18–22], and untethered micro-robots [25] were developed. Among these systems is the Steady-Hand Eye Robot (SHER), which provides smooth tool manipulation based on a cooperative control scheme between the surgeon and a stiff non-backdrivable robot arm. SHER system was shown to enhance tool manipulation accuracy in various vitreoretinal surgery tasks. In our earlier work, we presented the design of a sub-millimeter intraocular dexterous handheld robot, the Integrated Robotic Intraocular Snake (IRIS) [26]. Based on a variable neutral-line mechanism, this robot had a snake-like dexterous distal unit (only 3 mm long) providing sharp bends $(\pm 45^{\circ})$ right at the tool tip in a very compact form factor (0.9 mm in diameter) for retinal applications. However, the initial prototype suffered from poor motor resolution and suboptimal wire pretension limiting the overall performance significantly.

This study builds on our previous work [26] and presents 3 major steps taken toward its use in robot-assisted retinal microsurgery: (1) a new more compact actuation unit with better resolution for IRIS, (2) development of a model based control procedure, and (3) preliminary operational evaluation of IRIS and its integration with the SHER system.

II. Design

A. System Overview

The previous version of our snake-like robot, IRIS [26], was designed to be held in hand throughout the operation. One of the major goals in this work is to enable its use not only handheld but also in combination with a robotic microsurgery assistant, namely SHER [18, 27]. This approach aims at (1) providing better accuracy in tool positioning by eliminating the detrimental effects of physiological hand tremor of the operator, and (2) enabling the surgeon to better focus on and more easily control the articulated tip of IRIS. The integrated system is shown in Fig. 1. While the gross tool manipulation until reaching the vicinity of the retina is realized with the SHER system holding the IRIS, fine targeting is achieved and surgical maneuvers are performed by telemanipulating the dexterous tip of IRIS via a Phantom Omni.

B. IRIS: New Actuation System

The IRIS employed in this study is an improvement on its ancestor [26], with a more compact and lighter form factor and better resolution in tip articulation which is provided via a new actuation system (Fig. 2). The distal dexterous unit of the new IRIS has an outer diameter that is equivalent to a 20 Gauge ophthalmic instrument (\emptyset 0.9 mm), which requires a small enough incision on the sclera, and is 3 mm in length. It has two actuated DOFs, yaw and pitch (Fig. 3a), each with a ±45° motion range, and 30 mN of force capability at the tip. The dexterous unit is composed of 12 identical disk-like elements, each 0.25 mm in length and with a curved top surface (radius of curvature: 0.8 mm). Each disk-like element (Fig. 3b,c) has five holes (\emptyset 0.2 mm). The center hole can be used to pass through proper surgical tools, such as a microneedle in case of injection or a micro-forceps for membrane peeling. The other four holes carry nitinol wires (\emptyset 0.125 mm) providing the articulation of the snake-like unit (Fig. 3d).

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The new IRIS adopts a simpler structure with more powerful motors and finer angular resolution (Fig. 4). The dexterous tip is actuated by pulling or releasing the pretensioned nitinol wires via four DC motors (RE8, Maxon Motor Inc.), each with a spindle drive (gear ratio 64:1, GP8S, Maxon Motor, Inc.), a high precision encoder (100 counts/turn) and a digital positioning controller (EPOS2 24/2, Maxon Motor Inc.). The nitinol wires are symmetrically routed by two pulleys and pretensioned by four modules, which consist of springs, IKO linear bushings, nuts and guide screws. Each module can adjust the pretension by screwing the nut to push the linear bushing along the IKO miniature linear guide way. Each bushing is connected to its spindle nut via a wire driving connector. When a motor spins its lead screw, the spindle nut pulls the wire driving connector linearly backward/ forward tensioning/releasing the nitinol wire on that line causing the snake-like distal to bend/straighten. In order to bend the tip in a plane (pitch or yaw in Fig. 3a), two wires need to be actuated synchronously: when a wire is pulled, the wire on the opposite side should be loosened. Pulling both of the wires at same time can be used to increase the stiffness of the tip while interacting with the tissues after the desired orientation is reached.

The nitinol wires in this design have to be properly pretensioned to keep all the disc-like elements together. According to the contact mechanics computation based on Hertz theory in [1], the maximum allowable pretension on each wire is $F_{\text{pretension}} = 0.2 \text{ N}$. The corresponding torque on the each lead screw ($T_{\text{lead screw}}$) can then be computed using

$$T_{\text{lead screw}} = \frac{F_{\text{pretension}} * p}{2 * \pi * \eta_{\text{lead screw}}} \quad (1)$$

where p = 0.5 mm is the pitch and $\eta_{lead screw}$ is the efficiency of the lead screw. The torque required at each motor can be obtained using

$$T_{motor} = \frac{T_{lead \, screw}}{i * \eta_{gearhead}} \quad (2)$$

where i = 64 is the reduction ratio and $\eta_{gearhead}$ is the efficiency of the gearhead. The relationship between the rotary speed of motor (s_m) and the translational speed of the nitinol wire (s_{wire}) is given by

$$s_{\text{wire}} = \frac{s_{\text{m}} * p}{60 * i} \quad (3)$$

The selected motors provide a nominal rotational speed of 3500 rev/min, which propagates to a wire translation speed of 0.46 mm/s and provides a 45° bend at the tip in approximately 8–9 seconds, which is sufficiently fast for the targeted applications. During the operation, the

position of each motor is independently controlled by a custom C++ interface using the provided libraries by Maxon while communicating over a single mini-USB cable.

C. Integrated Control Scheme with the SHER System

SHER is a cooperatively-controlled device where the operator and the actively controlled robot arm simultaneously hold and move the surgical tool with a speed proportional to the forces applied by the operator [18, 27]. The robot has 5 DOF, including XYZ linear stages for translational motion, a rotary stage for rolling and a tilting mechanism. We attached IRIS in the tool mount of SHER and adopted the control scheme shown in Fig. 5. Accordingly, the operator performs gross tool manipulation cooperatively with the SHER system, providing a tremor free approach to the retina. During this phase the tool is moved with a velocity proportional to the force operator is applying. Upon reaching the retina, the operator releases SHER handle and uses a Phantom Omni device to teleoperate the snake-like tip and finely adjust the tool tip orientation. During this phase, the motion of the user's hand is scaled down by 1/3 and the corresponding bending angle is translated into wire pulling distance—and therefore motor command input—based upon the deflection characteristics of IRIS tip, which is to be identified in Section III. Upon completion of the surgical task, the tip is first straightened again using Phantom Omni, and the tool is pulled out of the eye using SHER (see the video attachment).

III. Experimental Characterization of IRIS Actuation

In order to accurately manipulate the snake-like tip of IRIS, the relation between the bending angle of IRIS and the displacement of each nitinol wire needs to be identified. Following an experimental characterization approach, we built the setup shown in Fig. 6a. IRIS was mounted on a Cartesian stage to position the tool tip in the center of an angular coordinate board. Then, by incrementing the position of each motor separately, each nitinol wire was gradually pulled/released (up to 2.5 mm of wire displacement in increments of 0.5 mm) 10 times and the resulting bending angle at the tip was recorded by capturing images of the angular coordinate board via the camera located above. A sample image from this experiment is shown in Fig. 6b.

We explored the relationship between the tip bending angle and wire translation distance considering two different conditions: without any tip load and with tip load (see the video attachment). Results for the first condition (no external forcing at the tool tip) are shown in Fig. 7. The maximum bending angle that could be achieved was about 45° for both pitch and yaw. It was observed that the bending angle varied almost linearly with wire displacement within the 5° – 40° range, for which the mean sensitivity of each wire is reported in Table I. While approaching a 5° bend from the straight configuration, the rate of increase in bending angle got higher. Inversely, after the bending angle exceeded about 40° , the rate of bending gradually declined. This nonlinear behavior around the extremes (0° – 5° and 40° – 45°) is attributed to the inherent elasticity of and frictional effects between the nitinol wires and 3D printed plastic structural components. There is some discrepancy in the sensitivity of all wires observed during the releasing and pulling cycles (for instance for wire 1, 26° /mm while pulling in comparison to 34° /mm while releasing), which indicates a slightly

hysteretic response. Nevertheless, the variation in the observed bending angles at each wire translation value between the 10 pulling/releasing cycles is very low, leading to very small error bars in Fig. 7 (max value is 1.01°) and showing good repeatability of the observed bending behavior. When the experiment was repeated with a tip load of 3.5 grams (by hanging a nut at the tool tip as shown in Fig. 8), similar repeatability was observed (Fig. 9). The applied load was chosen to reflect an upper bound for most tool-to-tissue interaction forces in retinal microsurgery, which typically remain under 10 mN [4]. Though the computed sensitivities (Table I) were slightly different than the values reported for the no load case, indicating some dependence of response to the tool tip forcing. The observed behavior was similarly highly repeatable during the 10 repeated pull/release cycles.

IV. Actuation Control

We used a Phantom Omni to control the bending angle of the IRIS tip in an intuitive and easy way. Since the range of Omni motion (δ_{Omni}) and IRIS bending angle ($\theta_{r,p}$) are not identical, a scaling factor (k') can be used for mapping:

$$\theta_{\rm r,\,p} = \frac{\delta_{\rm Omni}}{k'} \quad (4)$$

where $\theta_{r,p}$ denotes either yaw or pitch angle at the tip. Based upon the identified linear relationship between the bending angle and wire translation in section III, $\theta_{r,p}$ can be computed:

$$\theta_{\rm r,p} = d_{\rm w} \cdot k \quad (5)$$

where k is bending angle per wire displacement given in Table I, d_w denotes the wire translation needed to bend IRIS. Here d_w can be calculated from

$$d_{w} = t \cdot s_{wire} \quad (6)$$

where t is the sampling time. The s_{wire} can be calculated by equation (3). Then plugging equations (5) and (6) into equation (4) reveals:

$$\delta_{\text{Omni}} = \mathbf{k}' \cdot \mathbf{k} \cdot \mathbf{t} \cdot \frac{\mathbf{s}_{\text{m}} * \mathbf{p}}{60 * \mathbf{i}} \quad (7)$$

Using (7), the motor speed (s_m) can be controlled proportionally to the movement of the Omni handle (δ_{Omni}).

V. Preliminary Evaluation Experiment

For a preliminary evaluation of IRIS, the experimental setup shown in Fig. 10a was used. IRIS was fixed on a 3-DOF support platform. A camera with an integrated light source provided a magnified view of the operating area to the operator on a monitor. An artificial eye model was used, which consisted of a rubber sclerotomy and a curved bottom layer (Oslash; 25 mm), closely replicating the dimensional constraints during retinal microsurgery in human eyes (Fig 11a). We placed six small plastic balls on the curved bottom layer of the eye phantom, representing retinal targets (Fig. 10b and 11b). The targets were arranged in two rows and 10 mm apart from each other. The insertion point on the simulated sclera was elevated approximately 9.5 mm above the center of the eye model. A piece of optical fiber was passed through the center hole of the IRIS, and fixed such that a 17 mm segment (between points P and S in Fig. 11a) of it was protruding from the IRIS tip. After the IRIS is inserted through the simulated sclera, the experimental task was to use Phantom Omni, move the fiber tip inside the eye ball by bending the dexterous unit, and touch each of the six targets.

Line segment PQ in Fig. 11a represents the distal dexterous unit of IRIS which is 3 mm length. In order to touch points 1 and 4 in Fig 11b, the snake-like tip needs to be bent approximately 17°. Reaching the other end, i.e. points 3 and 6, requires about 55° of bending, which is slightly above the range we used while characterizing IRIS actuation (0°– 45°). Nevertheless, the results in Fig 12 show that still this is within the tool capabilities. All the points could be reached successfully using only the yaw and pitch DOFs of IRIS while maintaining the sclerotomy point fixed, which demonstrates a significantly improved intraocular dexterity.

VI. Discussion and Conclusions

The developed snake-like robot (IRIS) makes omnidirectional bends by combining its yaw and pitch DOFs, and provides a significantly enhanced intraocular dexterity while holding the sclerotomy port fixed. Employing a miniaturized articulated segment as small as 3 mm, the tool tip can be bent more than 45° with excellent repeatability ($\pm 1^{\circ}$). The tool is actuated driving four nitinol wires. Characterization experiments with free tool tip and externally loaded tool tip conditions both revealed a linear response within $5^{\circ}-35^{\circ}$ of bending. For bends greater than about 35°, the relation between bending angle and wire translation turns non-linear due to increased friction inside the articulated segment as well as the inherent elasticity of nitinol wires and 3D printed plastic components. The issue can potentially be alleviated by replacing nitinol wires with tungsten wires, which exhibit less elastic behavior. Nevertheless, our preliminary experiments in an artificial eye phantom have shown feasibility in precise targeting even for this range (up to 55°). In our future work, we will explore more agile and transparent control methods, such as adding force sensing to the IRIS and using the tension force information to estimate tool stiffness and tool tip loading. This will ensure accurate manipulation of the tool even in the presence of tool-to-tissue interaction forces. Upon integration of this feature, tool evaluation will continue targeting micron scale features on more realistic phantoms such as chorioallantoic membrane models,

and considering surgical tasks including epiretinal membrane peeling and retinal vein cannulation.

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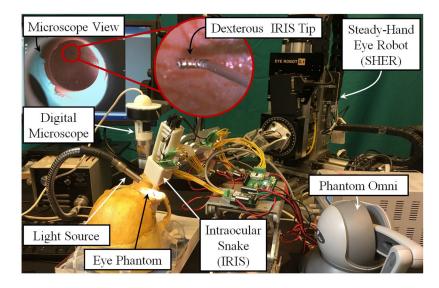


Figure 1.

System overview: a new intraocular snake (IRIS) was integrated with the Steady-Hand Eye Robot (SHER). Cooperatively controlled SHER is used to manipulate IRIS and bring the tool tip close to the retina without hand tremor. The dexterous snake-like tip of IRIS is then actuated using Phantom Omni to adjust tool tip orientation for accurate targerting inside the eye.

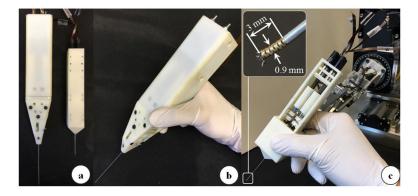


Figure 2.

(a) Earlier IRIS prototype (left) [26] versus the new design (right): new IRIS has a more compact and lightweight design with a new actuation system. (b) Previous version of IRIS was designed as a handheld instrument. (c) New IRIS can also work in combination with SHER for hand tremor canceling and easier control of the snake-like tool tip, which is 3mm in length and only 0.9 mm in diameter.

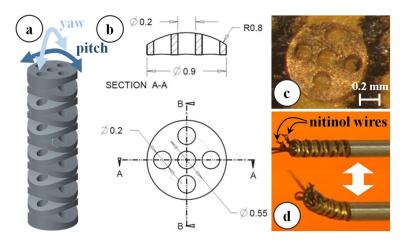


Figure 3.

(a) The dexterous tip of IRIS is composed of 12 disk-like elements, providing 2-DOF actuation: pitch and yaw. (b) Dimensions of each disk-like element. (c) Fabricated disk-like element. (d) 4 nitinol wires passing through the holes on the disk-like elements are tensioned or released to bend the snake-like tip.

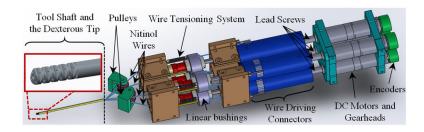


Figure 4.

Inner structure of the new IRIS: four DC motors are used to pull or release nitinol wires of the dextereous tip independently.

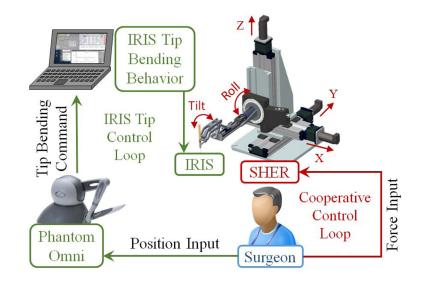


Figure 5.

Control scheme of the integratd system: SHER provides gross tool manipulation via cooperative control until reaching the vicinity of the retina while tool tip orientation is adjusted by bending the IRIS tip via a Phantom Omni.

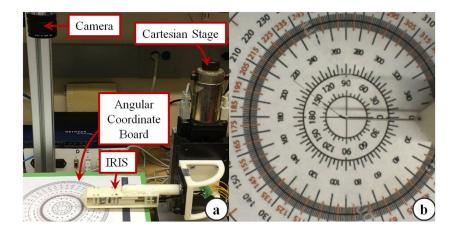


Figure 6.

(a) Experimental setup for charactering the bending angle of IRIS tip with respect to the linear displacement of each nitinol wire. (b) A camera image of the angular coordinate board and the bent IRIS tip.

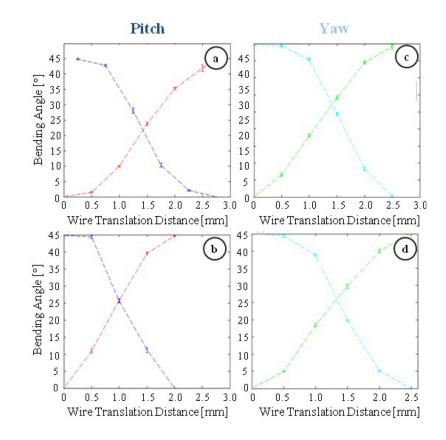


Figure 7.

Bending response of IRIS tip to nitinol wire displacement without any loading: pitch motion while wire 1 (a) and wire 3 (b) are being pulled (red) and released (blue), yaw motion while wire 2 (c) and wire 4 (d) are being pulled (green) and released (cyan).

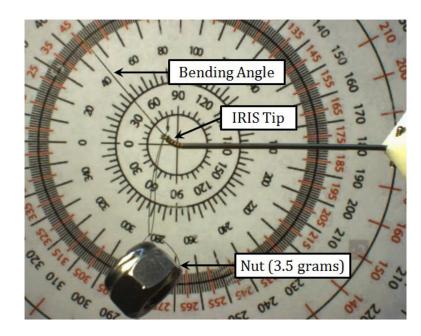


Figure 8.

Experimental characterization of IRIS actuation with external loading at the tool tip. The angular coordinate board was held vertically behind IRIS and a nut weighing 3.5 grams was hung at the tool tip.

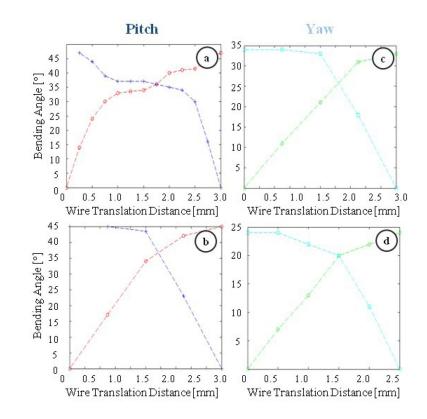


Figure 9.

Bending response of IRIS tip to nitinol wire displacement with 3.5 grams of loading at the tip: pitch motion while wire 1 (a) and wire 3 (b) are being pulled (red) and released (blue), yaw motion while wire 2 (c) and wire 4 (d) are being pulled (green) and released (cyan).

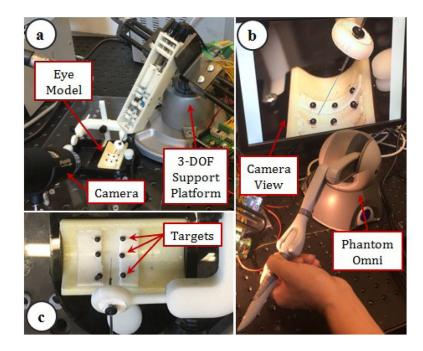


Figure 10.

Experimental setup for a preliminary evaluation of IRIS: (a) IRIS was fixed on a 3-DOF support platform; (b) after inserting the tool tip through the simulated sclera, the dexterous distal was bent using Phantom Omni; (c) the challenge was to touch 6 targets (black plastic balls) on the simulated retina surface (curved with Oslash; 25 mm).

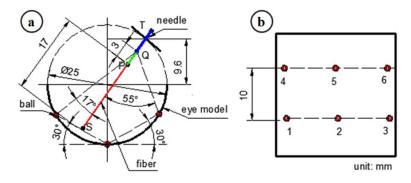
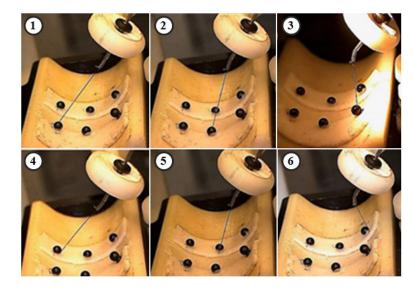


Figure 11.

Dimensions of the artificial eye model used in evaluating IRIS operation: (a) side view showing dimensions relative to an average human eyeball, (b) top view showing the location of six targets on the simulated retina surface.



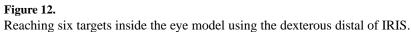


TABLE I

Bending Angle per Wire Displacement

Wire #	Pulling		Releasing	
	No tip load	With tip load	No tip load	With tip load
Wire 1	26°/mm	24°/mm	34°/mm	30°/mm
Wire 2	21°/mm	21°/mm	31°/mm	33°/mm
Wire 3	30°/mm	34°/mm	35°/mm	46°/mm
Wire 4	23°/mm	14°/mm	34°/mm	22°/mm