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Two-finger Multi-DOF Folding Robot Grippers ⋆

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Abstract: Two-finger robot grippers are widely used in various applications. Most conventional designs have a single degree of freedom (DOF). Other than open-and-close, they do not offer additional manipulation ability. Meanwhile, multi-finger high-DOF hands face cost and reliability issues. This paper presents three- and four-DOF linkage mechanisms to design robot grippers that can conduct two-finger twisting and rolling. Kinematics of the linkage mechanisms is studied. Tendon drives are designed so that the robot grippers can be used on tubular robots. A folding mechanism is proposed to help the gripper go through small entrances and narrow passages. Measures that help with miniaturization are discussed, providing opportunities in certain applications such as minimally invasive surgeries. Several advanced design concepts are also discussed for increasing the potentials of the robot grippers.

Keywords: Robot Hands, Robot Grippers, Object Manipulation, Mechanisms, Tubular Robots

1. INTRODUCTION

Tubular robots carrying grippers are considered an effective solution for manipulation tasks that involve small entrances and narrow passages. One of the most important applications of such kind is minimally invasive surgery (Fig. 1), where miniature grippers are carried by either straight or curved tubes to reach locations inside human bodies and conduct surgical treatment [Li et al. (2017), Cepolina and Michelini (2004), Chen et al. (2020), Peters et al. (2018)]. The robot grippers are a key element in such systems. The grippers are usually designed to be of a scissors-like topology with co-located pivot joints (Fig. 2). When the two fingers close, the gripper is of a minimal outer profile and can go through small entrances and narrow passages.

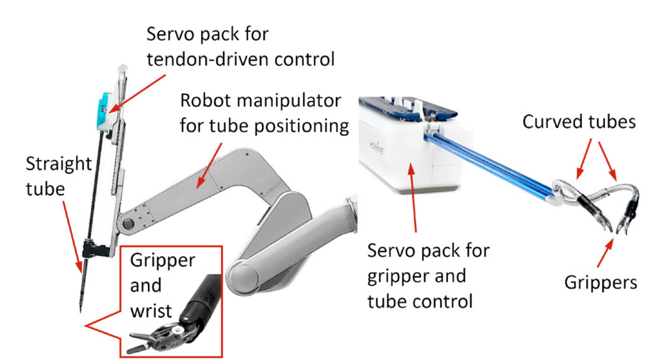

Fig. 1. Tubular robots by Intuitive Surgical (left) and Memic (right)

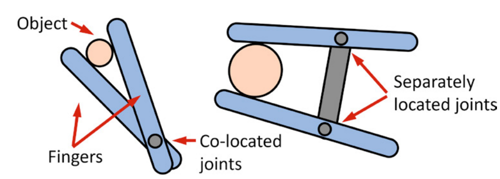

Fig. 2. Two-finger grippers with co-located and separately located joints

A wrist module of two DOFs usually connects the gripper to the carrying tube, providing certain ability of fine manipulation. The co-located pivot joints of the fingers often double as one of the wrist joints [Cepolina and Michelini (2004)]. However, using the wrist to re-orient an object carried by the gripper, even to the smallest extent often requires nontrivial motion of the carrying tube. Such motion is not always applicable, especially for tasks requiring curved tubes. With no additional DOFs on the gripper itself, no in-hand manipulation is possible. In-hand manipulation is the ability to move an object with fingers while holding it in hand. It has been commonly believed that in-hand manipulation is a key to realize subtle (yet important) maneuvers in object manipulation [Ma and Dollar (2011), Edwards et al. (2018), Shumway-Cook and Woollacott (2007)].

Other than the lack of in-hand manipulation ability, a two-finger gripper with co-located joints can only handle relatively small objects. Due to basic mechanics, when holding an object, the fingers tend to force the object out of grasp. The use of more abrasive textures on the inner surfaces of the fingers can help with grasping [Cepolina and Michelini (2004)] but at the cost of potentially damaging the object being held (e.g., soft tissues). The use of multiple grippers to handle an object together [Chen et al.

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(2020), Peters et al. (2018)] improves manipulation ability but brings much additional spacial burden.

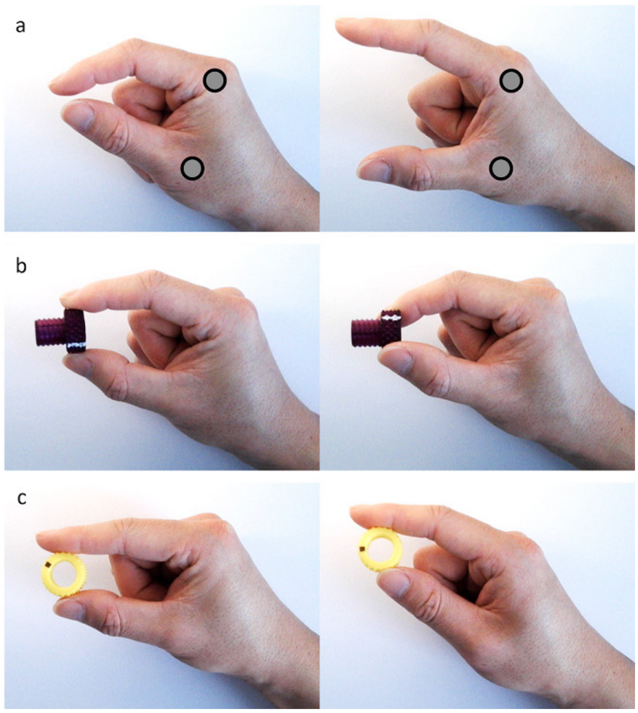

Fig. 3. Two-finger manipulation of human hands - a. separately located joints, b. twisting, c. rolling

Many human in-hand manipulation skills are actually realized using just two fingers - the index finger and thumb. The nontrivial distance between the joints at the roots of the index finger and thumb helps handle objects of a wide range of sizes. Two major in-hand manipulation skills of human hands are twisting and rolling using the index finger and thumb (Fig. 3). Note that terms used to refer to these moves vary from study to study. Detailed theories can be found in the studies of human hand anatomy, prehensile manipulation, and oppositions [Bullock (2016), Bullock and Dollar (2011), Bullock et al. (2012), Iberall (1997)]. It would be much beneficial if a two-finger robot gripper has more than one DOF and offers some in-hand manipulation ability. [Ejima et al. (2011)] is one of a series of work presenting multi-DOF two-finger grippers using micro Stewart platforms. [Bicchi and Marigo (2002), Chen et al. (2014), and Tincani et al. (2013)] give two-finger robot grippers additional DOFs with actuated moving surfaces on the fingertips. The mechanisms, however, have little chance to be implemented on tubular robots for miniature applications such as minially invasive surgeries. [Rojas et al. (2016)] presents a two-finger robot gripper that uses a four-bar mechanism on each finger to provide a total of two DOFs. The motion of the two fingers are limited to be on a plane and for in-hand rolling only, without the ability to twist.

This work develops multi-DOF two-finger robot grippers that can handle larger objects and conduct in-hand twisting and rolling. The designs can be tendon-driven and come with a folding mechanism that helps the gripper go through small entrances and narrow passages, allowing them to be used on tubular robots. In addition, the entire gripper with all of its DOFs can be actuated through a single handle, allowing easier miniaturization. Other than minimally invasive surgeries, the proposed robot grippers also have potential to be used on industrial robot manipulators for material handling in manufacturing and so on, providing a good balance between the conventional two-finger grippers with only one open-and-close DOF (very affordable, reliable but not capable) and multi-finger hands with a high number of DOFs (very capable but costly and not reliable).

2. BASIC DESIGN

2.1 The Linkage Mechanism

We first introduce a linkage mechanism (Fig. 4) to build robot grippers that provide three DOFs. Linkage L_0 is grounded to the base. (Extensions of) linkage L_3 and L_4 serve as the two fingers. All DOFs are driven by the motion of a single body - the actuating handle. Joint j_0 is a pivot joint, while joint j_1, j_2, j_3, and j_4 are ball-joints, enabling space motion (as opposed to planar motion) of the fingers. In addition to open-and-close, two-finger twisting and rolling can be realized, mimicking the two-finger manipulation skills of human hands using the index finger and thumb. Other than the three DOFs shown in Fig. 4, the actuating handle is constrained. The other three DOFs of the actuating handle would induce either no finger motion or motion that is not as useful. Depending on the application, additional constraints can be applied to the motion of the actuating handle if only one of the twisting and rolling motion is needed.

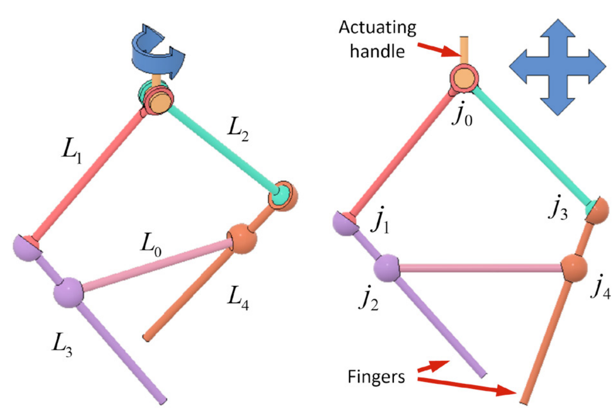

Fig. 4. Schematic of the linkage mechanism

The distance between joint j_2 and j_4 allows the two fingers to handle larger objects. However, the width of the gripper will likely exceed the thickness of the carrying tube, making it problematic to go through small entrances and narrow passages. A folding mechanism is designed as shown in Fig. 5. The design allows the proposed robot gripper to be folded into a compact and slim profile, so as to go through narrow places before it reaches the workplace. When the folding joint j_f is forced as shown in Fig. 5, the whole linkage mechanism is unfolded. L_{01} and L_{02} are then grounded to the base of the gripper.

Instead of using conventional ball and pivot joints, the joints in the linkage mechanism can be replaced by flexible structures, allowing the gripper to be fabricated in one

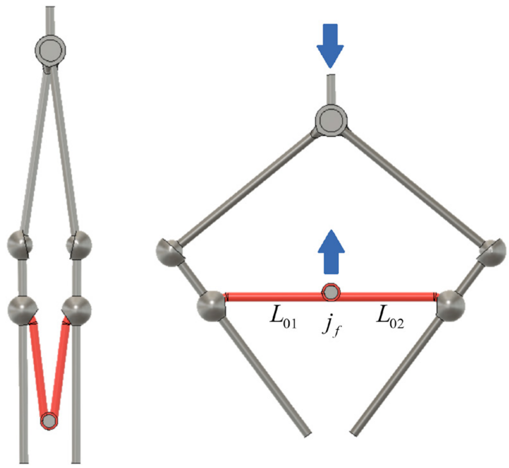

Fig. 5. Schematic of the folding mechanism

piece (Fig. 6). This is especially beneficial if it needs to be made at a miniature scale for applications such as minimally invasive surgeries. The flexible structures also offer larger ranges of motion than conventional ball joints. The stabilizers shown in the figure are additional flexible structures that help constrain and stabilize the folding and unfolding process. The stiffness of the flexible structures, including the joints and the stabilizers serves to keep the gripper naturally folded unless the folding pivot (joint j_f) is pulled by a tendon. This much simplifies controlling the folding/unfolding actions.

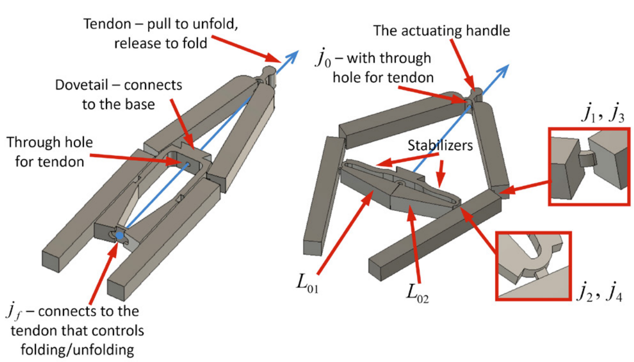

Fig. 6. One-piece design with flexible structures as joints

2.2 Motion Converter and Tendon Drive

In order to be mounted on tubular robots, especially ones that use curved tubes, the robot gripper needs to be driven by tendons, which can only provide pulling forces. A mechanism is needed to convert the motion of the actuating handle on the gripper to the pulling actions of the tendons. Figure 7 shows a basic design of a motion converter that allows tendon-driven control of the open-and-close and the twisting moves of the gripper. The design features a sleeve and a core piece that sit co-axially. When pulled by the tendon, the core piece moves linearly with respect to the sleeve as guided by the pins on it and the straight slots on the sleeve. The sleeve rotates as guided by the spiral slots on it and the pins on the outer shell, carrying the core piece to rotate with it together. The tip of the core piece is connected to the actuating handle on the hand piece. The core piece has a through tunnel in the center to accommodate the tendon(s) for controlling the unfolding of the hand piece and additional functions. In addition to the open-and-close and the twisting moves, the rolling move of the fingers could be realized by adding a linkage between the motion converter and the actuating handle (Fig. 8). The linkage shall be controlled by two additional tendons, which reach the linkage via the through holes on the core piece of the motion converter. All tendons are pulled by pulleys and servos at the other end of the tube.

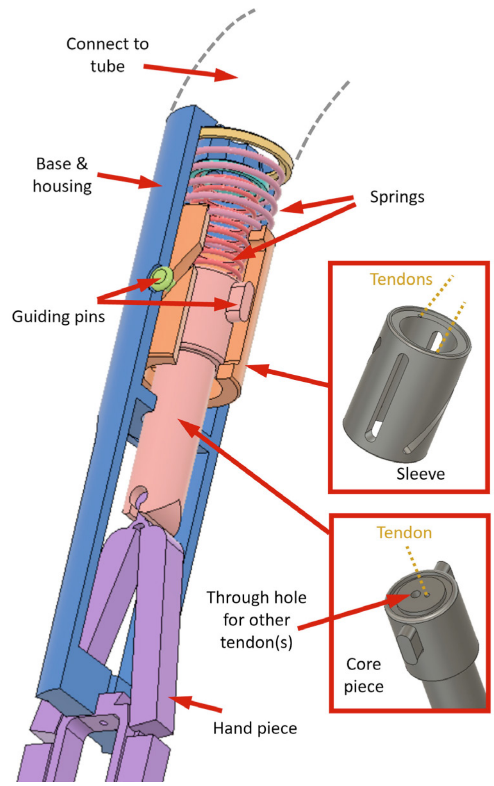

Fig. 7. A basic 2-DOF motion converter for tendon drives

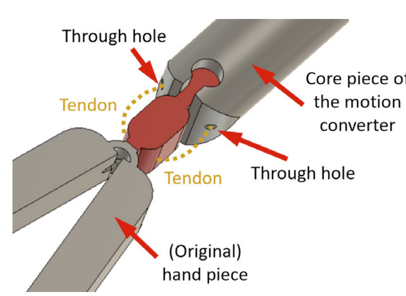

Fig. 8. The additional linkage for tendon-driven two-finger rolling

3. KINEMATICS

The motion of the actuating handle can be divided into two groups (Fig. 9):

(1) Rotation θ around the gripper's center axis a, and
(2) Displacement (x, y) in the plane A that is attached to the handle and goes through axis a.

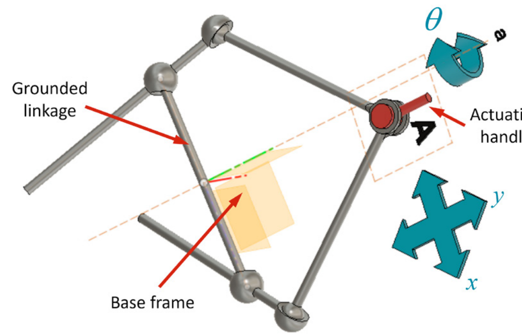

Fig. 9. Motion of the actuating handle

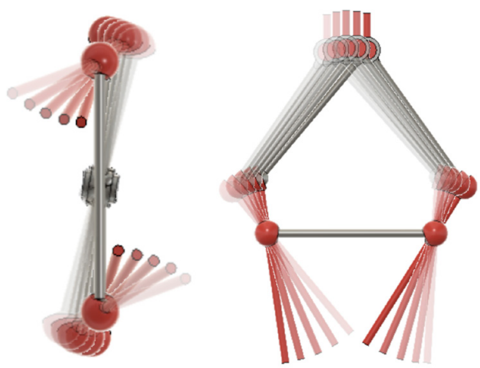

Fig. 10. Finger trajectories when only θ or (x, y) changes

When moved separately, the moves of the fingers caused by θ and (x, y) are illustrated in Fig. 10.

Note that Fig. 10 only shows the twisting move when there is no rolling and the rolling move when there is no twisting. It gives an impression that the twisting and rolling moves of the fingers are controlled separately by the two groups of motion of the actuating handle. In fact, the coupling between the two groups becomes increasingly severe when the fingers reach larger twisting angles (i.e., when θ is larger). Figure 11 demonstrates the coupling by showing the finger trajectory caused by the actuating handle's motion in the x direction when θ is nontrivial. Other than rolling, it can be seen that substantial twisting also occurs. In order to realize strictly planar rolling or twisting trajectories in general, the actuating handle has to move coordinately along both θ and (x, y).

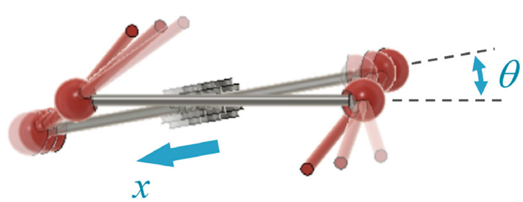

Fig. 11. Finger trajectory caused by actuation in the x direction at a nontrivial θ angle

The illustrations above use a benchmark set of linkage lengths. In order to increase the gripping force of the fingers, the lengths can be adjusted as shown in Fig. 12. The change, however, reduces the motion range of the fingers. It also affects which joints are more prone to reaching singularity.

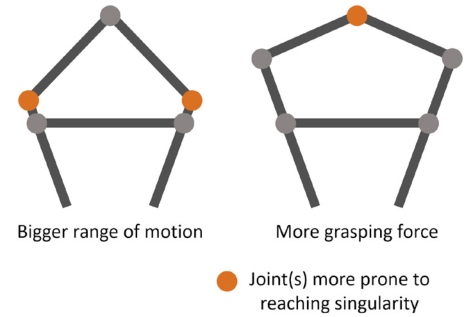

Fig. 12. Change of linkage lengths

4. PROTOTYPE AND MINIATURIZATION

Figure 13 shows a preliminary prototype of the proposed robot gripper with a basic 2-DOF motion converter, mounted on a tubular setup with a servo-pulled tendon drive. The open-and-close and twisting moves, together with the folding/unfolding function of the gripper are demonstrated. Note that the setup is not mean to validate any wrist function or tube bending maneuver, and no corresponding mechanisms are installed.

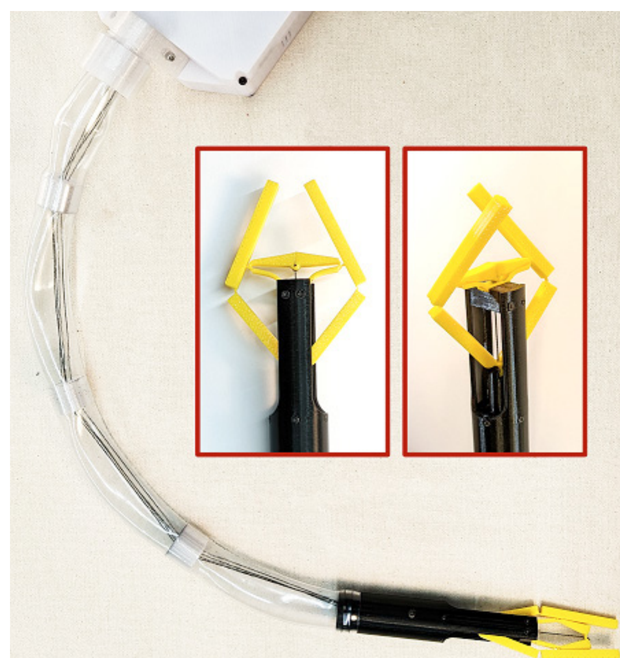

Fig. 13. A prototype of the proposed designs

The prototype is fabricated mostly with FFF 3D printing at a larger scale for proof of concept. Miniaturization to a scale small enough for applications such as minimally invasive surgeries should be feasible since commercial laparoscopic tools have long been featuring designs of complexities at similar or higher levels [Arkenbout et al. (2015), Ferhatoglu (2018)]. In addition, for the hand piece, other than injection moulding and 3D-printing, a miniature make of the one-piece design can be fabricated using a shrinking technique and polystyrene materials. As shown in Fig. 14, a larger profile can be first cut from a polystyrene sheet. After a controlled baking procedure, the piece shrinks to a much smaller size with increased thickness. The technique is widely known for its usage in popular child toys branded as Shrinky Dinks, as well as used in novel research in micro and nano fabrication [Oran et al. (2018), Lee et al. (2011)].

Fig. 14. A shrinking technique with polystyrene materials

5. ADVANCED DESIGNS

In addition to the basic design introduced earlier, this section discusses several advanced design ideas that could substantially increase the potential of the robot gripper. The linkage mechanism shown earlier in Fig. 4 is a (constrained) space five-bar mechanism that gives three DOFs to mimic the twisting and rolling moves of human index finger and thumb. The actuating handle can be designed differently as shown in Fig. 15. The resulting six-bar mechanism (with constraints) gives an additional DOF, which helps improve the agility of the fingers' rolling move. However, in order to be tendon-driven, the six-bar mechanism would require a motion converter with much increased complexity, which remains an open challenge for design and fabrication. Nevertheless, as mentioned earlier, the linkage mechanism can also be used in applications that are not tendon-driven and do not require a motion converter - e.g., carried by a robot arm for material handling in manufacturing.

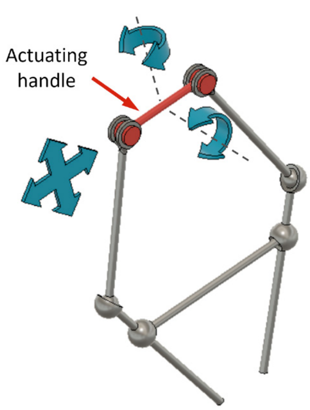

Fig. 15. A six-bar mechanism

The two fingers featured in the designs are identical. Their respective linkages are connected in a symmetric manner. Additional fingers can be added with the same linkages and a symmetric connection. Figure 16 shows a design with three fingers, which can provide additional stability for grasping and manipulation. The arrangement can accommodate as many fingers as an application needs.

The design of the motion converter presented earlier bears a nontrivial axial length, which is mainly needed to accommodate the rotating sleeve (and its spring). Such a design limits the ability to go through curved passages.

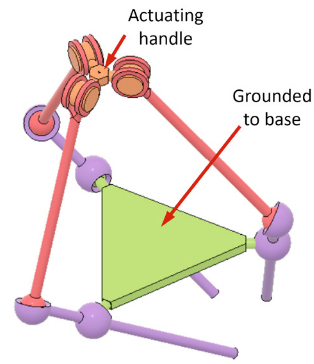

Fig. 16. A three-finger design

Figure 17 presents an alternative design. When one of the tendons is pulled, the through hole it goes through forces the sleeve to rotate. The motion converter using this design can be significantly shorter than the basic design introduced earlier.

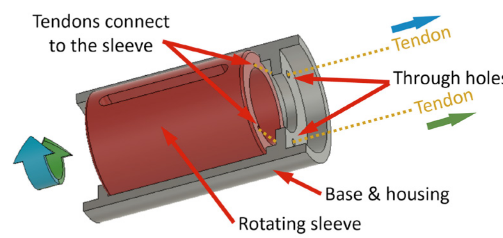

Fig. 17. An alternative design of the rotating sleeve in the motion converter

As discussed earlier, the one-piece design (Fig. 6) of the linkage mechanism greatly helps with fabrication at a miniature scale, especially with the shrinking technique (Fig. 14). The motion converter can benefit in the same way if it can be designed in one-piece with mostly planar features. Figure 18 illustrates an one-piece design that includes both the finger mechanism and the motion con-

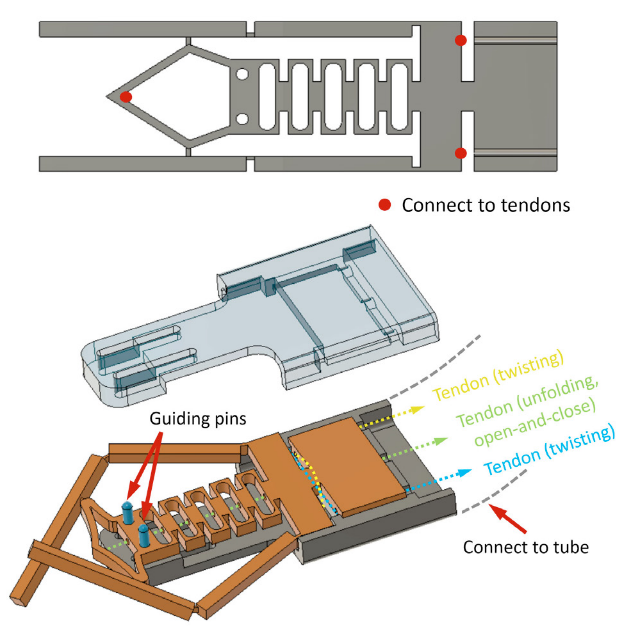

Fig. 18. Gripper and motion converter in one piece

verter. With an one-piece and planar topology, such a design has the potential to be fabricated at a scale even smaller than the needs of minimally invasive surgeries.

6. CONCLUSIONS AND FUTURE WORK

This paper presents designs of multi-DOF two-finger robot grippers. Space five- and six-bar linkage mechanisms are used to provide three and four DOFs respectively to realize twisting and rolling moves of two fingers. With more than just open-and-close motion, the designs provide certain in-hand manipulation capability for advanced object handling. The mechanisms can be tendon-driven and used on tubular robots. A one-piece design of the linkage mechanisms and a shrinking technique are introduced for fabrication at miniature scales, which is desirable for applications such as minimally invasive surgeries. For applications where tendon drives and miniaturization are not needed, such as robotic manufacturing, the simplicity of the linkage mechanisms also makes the designs appealing with a good balance between capability and reliability. Kinematics of the finger motion, including the coupling between the twisting and rolling moves is examined. In addition, several advanced design ideas are discussed for increasing the potentials of the robot grippers. Future work of this project includes fabricating prototypes at a miniature scale with tube bending mechanisms and a wrist, maturing the advanced designs, as well as extending the study on kinematics and control.

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