Preliminary Development of a Continuum Dual-Arm Surgical Robotic System for Transurethral Procedures

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Abstract. Bladder cancer, with the leading number of new cases in all urinary system cancers and a high recurrence rate, poses a substantial threat to human health. Even with the transurethral accessibility, current surgical tools have not fully allowed convenient resection of the bladder tumors. This paper presents the design and the preliminary development of a continuum dual-arm surgical robotic system for transurethral procedures. This development aims at improving the current surgical treatments by providing intravesicular imaging with enhanced distal dexterity. With the proposed system, new surgical techniques for bladder tumor resection could be explored. The clinical motivation, design overview, system descriptions and preliminary developments of this transurethral surgical robot are presented. With the system constructed in the near future, a series of ex-vivo and in-vivo experimentations would be carried out to verify the proposed functionalities.

Keywords: Continuum arm · Surgical robot · Transurethral procedures

1 Introduction

BLADDER cancer has the leading number of newly diagnosed cases in all urinary system cancers: about 74,000 new cases with 16,000 cancer-related deaths in US in 2015 [1]. About seventy percent of the bladder tumors are superficial when they are initially discovered. The primary treatment is transurethral resection (TUR) but the problem lies on the 3-month recurrence rate that could be as high as 75% [2]. Risk factors of the tumor recurrence include the number and size of the tumors: more and

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bigger tumors lead to a higher recurrence rate [3]. Chemotherapy, immunotherapy [2] or a repeat TUR (ReTUR) [4] could be carried out after the initial TUR to lower the tumor reoccurrence rate.

Even with the transurethral accessibility, current surgical tools have not fully allowed convenient resection of the bladder tumors so as to ensure a consistent treatment [2]. What's more, bigger bladder tumors are usually removed via multiple cuts. There is evidence that the floating tumor cells after electro-resection may also contribute to the tumor recurrence [2]. Clearly the clinical needs yearn for a surgical system with intravesicular dexterity and functionalities so that it could conveniently remove multiple bladder tumors unbrokenly even when the tumors are relatively big (e.g., bigger than 25 mm in diameter).

Contrast to the keen clinical needs, only incremental changes have been made to the surgical tools until recently Goldman *et al.* developed a continuum transurethral manipulator with integrated fiberscope, laser cautery and biopsy forceps for bladder tumor resection [5, 6]. On the related subjects, Hendrick *et al.* developed a dual-arm endoscopic robot for prostate surgery [7–9], while Russo *et al.* developed the ASTRO system for transurethral laser surgery of benign prostatic hyperplasia [10]. Several other systems were also developed for percutaneous brachytherapy [11, 12] and bladder urothelium examination [13]. As the main contribution, this paper proposes a dual-arm surgical system for transurethral procedures (DASSTUP) with enhanced intravesicular dexterity and imaging, as shown in Fig. 1, aiming at removing multiple superficial bladder tumors unbrokenly from their roots in the submucosa layer, even when the tumors are relatively large. The system consists of a customized multi-channel cystoscope, two exchangeable continuum arms for surgical interventions, and a lockable multi-joint system stand.

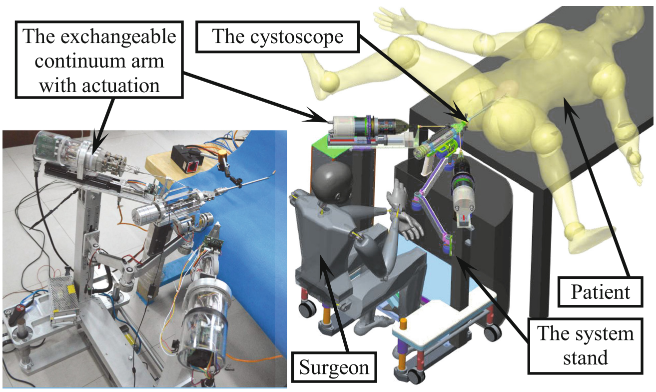

Fig. 1. Design and the partially constructed DASSTUP system

The paper is organized as follows. Section 2 presents the clinical motivations and the design overview. Section 3 presents the system descriptions while preliminary system fabrications and experimentations are reported in Sect. 4. The conclusions and the future work are summarized in Sect. 5.

2 Clinical Motivation and System Overview

A surgeon performing TUR should remove all visible tumors for the surgical treatment of bladder cancer, using a urologic resectoscope. The transurethral portion of a current resectoscope is a rigid tube with multiple telescoping components. A monopolar wire loop (or a laser fiber) is used to perform the tumor resection. Two critical hurdles are identified.

- Because of the rigidity of the resectoscope tube, it is quite difficult to pry the resectoscope to access the tumors on the side wall or near the entrance of the bladder. In some cases, the pubic bone prevents the resectoscope from being tilted to reach a bladder tumor.
- Large tumors have to be removed through multiple cuts and the floating cancer cells could potentially increase the tumor recurrence [2].

Despite the keen clinical needs, only incremental changes have been made to the resectoscope. For example, a flexible bending tip was integrated to enhance the intravesicular dexterity with laser resection [14], whereas the monopolar wire loop was made rotatable to facilitate tissue cutting [15].

Inspired by the recent advances in robotic systems for SPL (Single Port Laparoscopy) [16–20], The DASSTUP system with enhanced intravesicular dexterity and imaging is proposed in this paper, as shown in Figs. 1 and 2.

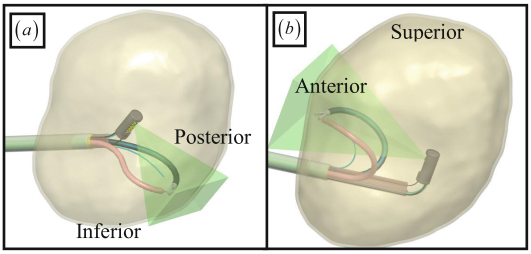

Fig. 2. Proposed uses of the DASSTUP system inside a bladder: (a) the forward-looking pose and (b) the backward-looking pose

A completely-redesigned cystoscope is firstly inserted into the bladder. With the vision unit extended and bent upwards, two miniature continuum arms could be inserted to form the forward-looking pose, as shown in Fig. 2(a). This working configuration primarily treats tumors in the posterior and inferior areas of the bladder.

The cystoscope could be flipped and inserted with the camera facing up. Then the vision unit could be extended and bent backwards. With the two continuum arms inserted, a backward-looking pose as shown in Fig. 2(b) is formed to treat tumors in the anterior and superior areas of the bladder. To be noted, the right arm in the DASSTUP system will appear as the left arm in the camera view under the backward-looking configuration. Proper mapping for the teleoperation should be implemented.

In either the forward-looking or the backward-looking poses, two manipulation arms could help to achieve complete resection of a large bladder tumor as a whole. For example, one arm could be used to push or grasp a large bladder tumor so as to expose its root. Then the other arm performs resection to separate the tumor from the (sub)-mucosa layer. The tumor could be placed into a pre-deployed bag for final extraction. In this way, possible floating tumors cells could be kept to a minimal level.

In order to lower the system complexity, the cystoscope is made manual, while the two continuum arms are motorized and controlled via a paradigm of teleoperation. As shown in Fig. 1, one surgeon will sit at the patient side to manipulate the cystoscope. Another surgeon will sit at a surgeon console (not shown) to tele-operate the continuum arms. The results presented in this paper focus on the patient-side development. Complete descriptions of the entire system would be introduced in a future publication.

3 System Description

The presented DASSTUP system consists of the following major components on the patient side: (i) one customized multi-channel cystoscope, (ii) two exchangeable continuum arms with actuation units, and (iii) a lockable multi-joint system stand. As mentioned above, the cystoscope is made manual, while the two continuum arms are motorized. These components are described in detail in this section.

3.1 Design of the Multi-channel Cystoscope

The customized multi-channel cystoscope is shown in Fig. 3. Its form was determined by carefully considering the intended use.

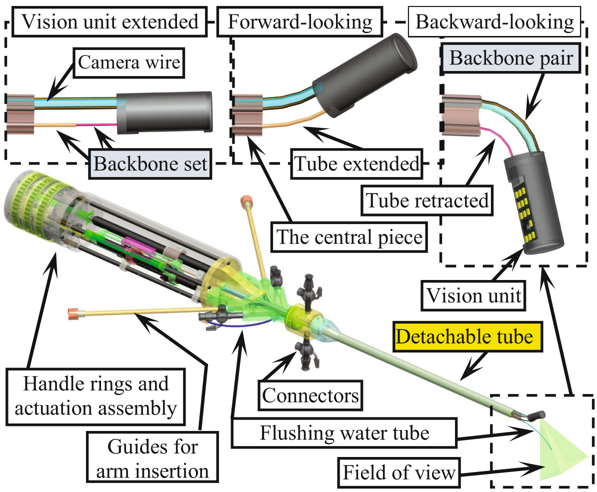

Fig. 3. (a) Cystoscope design of the DASSTUP system and (b) the cross section of the cystoscope

The primary function provided by a cystoscope is the illumination and visualization of the bladder. In the presented design in Fig. 3, the vision unit has a camera chip installed on the side wall (instead of on the end face like an ordinary cystoscope). The camera chip is surrounded by multiple LEDs (light-emitting diodes) for illumination. The vision unit is oriented by pushing and pulling three backbones that are made from super-elastic nitinol.

Since the DASSTUP system attempts to cover the entire bladder, ideally the camera chip could be oriented to look in any directions. If the camera chip is installed on the end face of the vision unit, the vision unit has to be rotated for nearly 180° to visualize the entrance area of the bladder. This could be hardly achieved by three backbones without any additional components to prevent the backbones from buckling.

With the camera chip installed on the side wall, the vision unit only needs to be re-oriented for about 90°. The actuation feasibility is demonstrated by the experiments that are presented in Sect. 4.1. Together with the rolling motion (rotation about the outer tube's axis) of the cystoscope, the entire bladder could be visualized.

This vision unit is oriented by pushing and pulling the backbones. These nitinol backbones and the vision unit essentially form a continuum parallel mechanism. Another continuum parallel robot could be seen in [21]. It is also similar to the DDU (Distal Dexterity Unit) firstly proposed in [22]. Since the vision unit is only subject to limited external loads, the use of a continuum structure is suitable.

Three adjustments could be realized for the vision unit, with respect to the cystoscope, by telescoping the elements inside the detachable outer tube: (i) extend the central piece together with the vision unit; (ii) extend the backbones with respect to the central piece to change the distance between the vision unit and the central piece; and (iii) orient the vision unit upwards and downwards to form the forward-looking and the backward-looking poses, respectively.

Even though the vision unit only needs to be re-oriented within a plane, three backbones are used for better structural stability. Their arrangement is shown in the cross section in Fig. 4. Two backbones, forming the backbone pair, are arranged next to the camera wire and connected to the vision unit. In order to reduce possible tear to the camera wire, the backbone pair always has the same amount of translation as the camera wire. This feature is realized by the actuation assembly. The backbone set is arranged in the lower half of the cross section, formed by a nitinol rod inside a nitinol tube. The nitinol rod is attached to the vision unit, while the tube could slide with respect to the rod. To orient the vision unit upwards, the tube will be extended, sliding over the nitinol rod, to push the vision unit. To orient the vision unit downwards, the tube will be retracted first and the nitinol rod will then be pulled as shown in Fig. 3.

The reason for this particular design is to prevent backbone buckling while orienting the vision unit. While orienting the vision unit upwards, the backbone set would be strong enough to undertake the compressive load. Then the bending stiffness of the backbone set should be higher than the bending stiffness of the backbone pair plus the camera wire. While orienting the vision unit downwards, the bending stiffness of the backbone pair plus the camera wire should be higher than that of the backbone set. The retractable concentric tube-rod configuration could introduce such a desired change in the bending stiffness.

The cross section of the cystoscope is shown in Fig. 4. An inner tube is arranged inside the detachable ∅8 mm outer tube. This outer diameter is set equal to the French gauge number of 24 (instead of 26) to fit a greater group of patients.

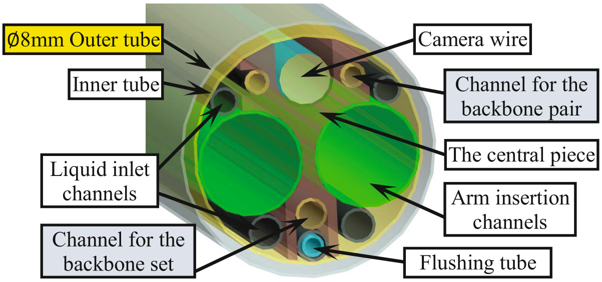

Fig. 4. Cross section of the DASSTUP's cystoscope

Besides the channels for the camera wire, the backbone pair and the backbone set, two channels are arranged next to the central piece for the two ∅3 mm exchangeable continuum arms. Four liquid inlet channels are used to circulate sterile liquid (e.g., water, saline, or glycine solution) during an operation. The gaps between the channels and between the outer and the inner tubes serve as the water outlets. There are four liquid circulation connectors in the cystoscope as shown in Fig. 3. The horizontal two are for inlets, while the vertical two are for liquid outlets.

One additional channel is reserved for the flushing tube. It will be used to flush the blood to clean the camera view at a surgical site.

The actuation assembly showed in Figs. 3 and 5 realizes the aforementioned three adjustments of the vision unit with respect to the cystoscope. There are three lead screws (A, B and C as shown in Fig. 5) in the actuation assembly. They are actuated by the three handle rings, via extensible shaft couplings.

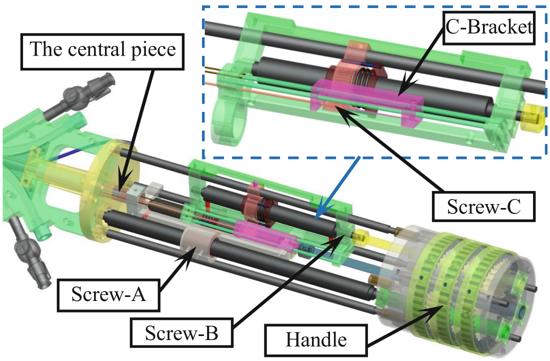

Fig. 5. Actuation scheme of the DASSTUP's cystoscope

For the deployment of the customized cystoscope, the detachable ∅8 mm outer tube would be firstly delivered into the bladder with the help of an obturator. Then the cystoscope is inserted into the outer tube with the vision unit at its initial pose. Under the initial pose, the backbones are completely retracted such that the vision unit axially pushes against the central piece.

After insertion, all the backbones are firstly extended from the central piece. Then the backbone set could be actuated to orient the vision unit, upwards or downwards, for a desired field of view.

3.2 Design of the Continuum Arm

Two ∅3 mm exchangeable continuum arms could be inserted through the channels in the cystoscope for surgical interventions.

The arm's DoF (Degree of Freedom) configuration is shown in Fig. 6(a). The arm consists of two continuum segments. Each segment possesses two bending DoFs. The arm is extended from the arm channel in the cystoscope. This is equivalent to actively change the length of the segment-I, giving the segment-I the third DoF. Moreover, the arm could be rotated about its axis to achieve a rolling motion. Thus in total, the arm possesses six DoFs plus one more actuation for the gripper. This DoF configuration is determined combining the advantages from previous developments [19, 23].

The arm has an outer diameter of 3 mm. Its structure is similar to the ones presented in [16, 19]. The arm cross section is shown in Fig. 6(b). Eight ∅0.5 mm holes are used for the arm backbones: four for each continuum segment.

The arm is connected to a transmission assembly as shown in Fig. 6(c). The arm backbones are routed by a set of guiding cannulae and connected to the nuts of the twin lead screws. The backbones arranged opposite to each other are connected to the nuts on a single twin lead screw so as to achieve the same amount of push-and-pull actuation to bend the corresponding segments.

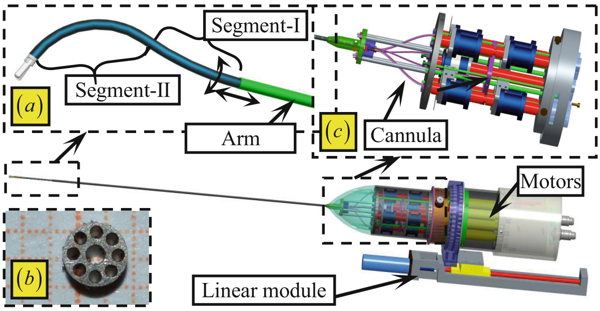

Fig. 6. Continuum arm of the DASSTUP system: (a) the DoF configuration, (b) the arm cross section, and (c) the transmission assembly

The arm rolling motion is actuated by a motorized gear ring in the actuation unit, whereas the translational motion of the Segment-I is actuated by a linear module that carries the motors and the arm.

The arm kinematics could refer to the kinematics presented in [23]. The kinematics is based on the modeling assumption that the segments bend into circular arcs. The details are not reported here for sake of brevity. Using the kinematics model, motions of the continuum arms could be simulated under teleoperation as shown in Fig. 7. It is shown that the arm tip could be controlled to trace the root area of a large bladder tumor in different locations of the bladder.

The root area assumes a diameter of 10 mm, while the bladder tumor assumes a diameter of 25 mm in the simulations in Fig. 7. The simulated tumors are located in the posterior and inferior areas of the bladder, while the DASSTUP system is assumed to be in its forward-looking pose.

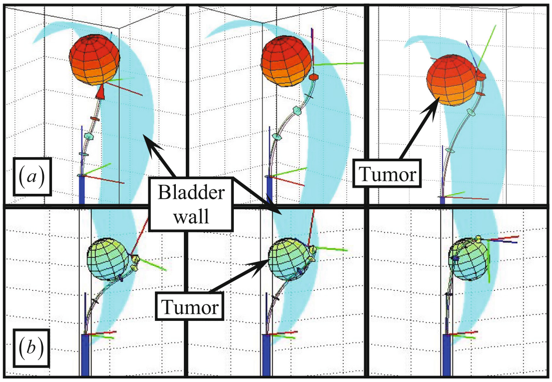

Fig. 7. Simulated movements of the continuum arm under teleoperation with the tumor in the (a) posterior and (b) inferior areas of the bladder.

3.3 Design of the System Stand

The lockable system stand is shown in Fig. 8. The wheels could be lifted by a lifting jack after the stand is moved to the suitable position. Two arm stands are located on the two sides of the system stand supporting the actuation units of the arms. A multi-joint lockable cystoscope holder is attached to the left arm stand. A cystoscope holder frame secures the cystoscope. One could position and orient the cystoscope by manipulating the handle.

The cystoscope holder possesses one prismatic joint and five rotary joints. A weight is connected to the base of the cystoscope holder via a pulley to balance the gravity of the cystoscope and the holder. Brakes are integrated to the pulley axis and to each rotary joint to lock the cystoscope holder, when the brakes are powered off. Once powered on, all the joints in the cystoscope holder could move freely. The brakes are switched on/off by a trigger in the handle.

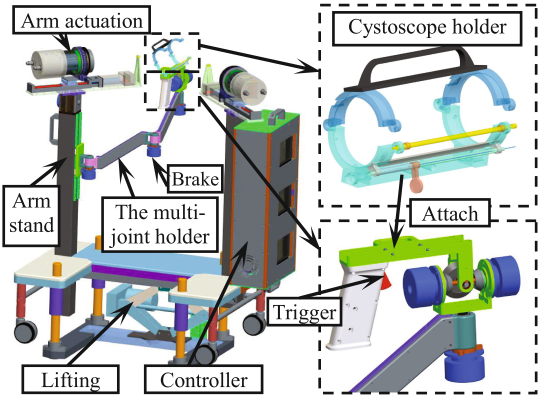

Fig. 8. Stand of the DASSTUP system

4 Preliminary Fabrications and Experimentations

With the DASSTUP system partially constructed, a series of experiments were carried out to verify the consistence between the actual system and the design expectation.

4.1 Verification of the Vision Unit

Before the cystoscope is fabricated, a series of experiments were firstly performed to verify the motion capability of the vision unit under the actuation by the backbones.

The experimental setup is shown in Fig. 9(a). The backbone arrangements are identical to the design as presented in Sect. 3.1. The camera wire and the backbone pair

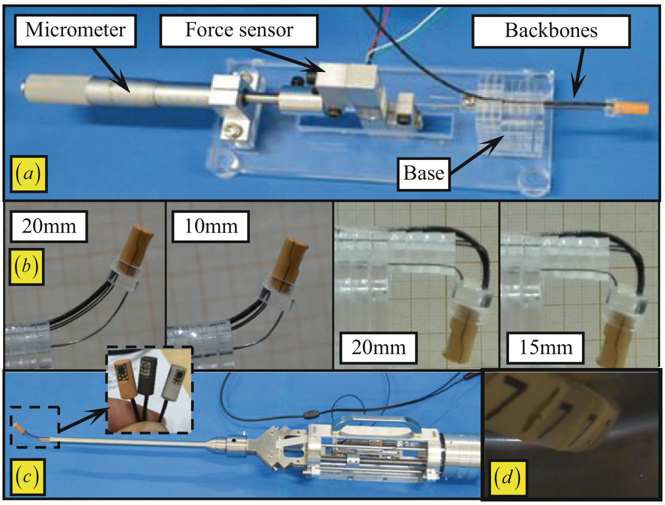

Fig. 9. Experimental verifications for the cystoscope: (a) the setup, (b) the forward-looking and backward-looking poses, (c) the fabricated cystoscope, and (d) a underwater view inside a coca can

(two ∅0.5 mm nitinol rods) is clamped to a base. The length of the backbone pair could be adjusted.

The backbone set is connected to a force sensor. The force sensor could slide along a slot in the base and actuated by a micrometer. Then the relationship between actuation lengths, actuation forces and the orienting angles could be measured. The results are shown in Fig. 9(b), when the length of the backbone pair is set to 20 mm, 15 mm, 10 mm, etc. With the positive results from the experiments, the cystoscope was fabricated and assembled as in Fig. 9(c). A camera view is shown in Fig. 9(d) when the vision unit was inserted into a coca can filled with water.

4.2 Bending Experiments of the Continuum Arm

In the kinematics model, shapes of the bending segments in the continuum arm are assumed to be circular. It is desired to verify this assumption for this particular development since the arm size is quite small. With the assumption verified, the teleoperation motions as shown in Fig. 7 could be expected.

The continuum arm in a short version was firstly assembled as shown in Fig. 10(a). Then the 25 mm long segment was bent up to 90° as shown in Fig. 10(b). The bending of the two-segment continuum arm was also tested as shown in Fig. 10(c). The bent shapes are close to circular arcs.

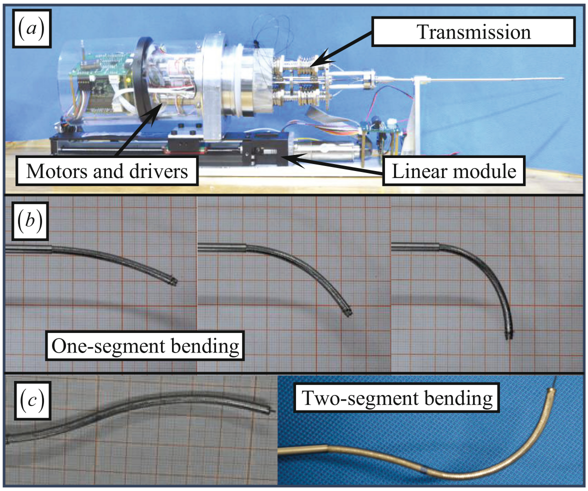

Fig. 10. Bending experiments of a continuum arm in a short version for modeling validation: (a) the assembly, (b) one-segment bending results and (c) two-segment bending results

5 Conclusions and Future Work

This paper presents the design and the preliminary results of the DASSTUP system, a continuum dual-arm surgical system for transurethral procedures. This development aims at improving the current surgical treatments of bladder cancer by providing intravesicular dexterity and imaging. With the proposed system, new surgical techniques for bladder tumor resection could be explored. The clinical motivation, design overview, component descriptions and system constructions are presented.

The immediate future work is to complete the system construction. Although most of the individual component have fabricated and tested, the integration could still be challenging. Fabrication of the long continuum arm could also become tricky. Arm actuation compensation would be expected. Eventually ex-vivo and in-vivo experimentations would be carried out to verify the proposed functionalities.

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