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Design of the SJTU Unfoldable Robotic System (SURS) for Single Port Laparoscopy

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***Abstract*—SPL (Single Port Laparoscopy) might generate better surgical outcomes than multi-port laparoscopy. Hence it draws continuous attentions in the past several years. Due to its operative difficulties, several robotic systems were constructed to help surgeons with the surgical manipulation tasks. The SURS (SJTU Unfoldable Robotic System) for SPL is then proposed, aiming at introducing several improvements over the existing systems. The SURS can now be inserted into abdomen through a Ø12mm incision in its folded configuration and can unfold itself into a dual-arm configuration for surgical interventions. 3D visual guidance is provided with integrated illumination. The design overview, component descriptions, and preliminary experimental characterizations are elaborated to demonstrate the SURS's potentials.**

I. Introduction

SPL (Single Port Laparoscopy) might generate better surgical outcomes than multi-port laparoscopy [1] and it draws continuous attentions in the past several years. Although emerging manual instruments have enabled SPL operations, it is still very difficult for surgeons to operate due to the crossed and mirrored hand-eye coordination. Surgeons might have to undergo substantial new trainings to be able to use these new tools, such as the RealHand™ instruments (Novare Inc.), the Laparo-Angle™ tools (CambridgeEndo Inc.), the SPIDER device, the SILS™ port (Covidien Inc.), the TriPort™ and QuadPort™ (Advanced Surgical Concepts Inc.), etc.

In order to allow surgeons to perform SPL procedures in an intuitive way, several robotic systems were developed. Key specifications of these SPL robots include i) the diameter of the access port, and ii) payload and the number of DoFs (Degrees of Freedom) of the SPL robots' manipulator arms. Sekiguchi *et al.* developed a SPL robot with two 5-DoF arms using a Ø30mm incision [2]. An updated version has two 6-DoF arms and uses a Ø25mm incision [3, 4]. Lee *et al.* and Cheon *et al.* developed SPL robots both use Ø25mm incisions [5, 6]. The latter has a payload capability of 14N. Titan Medical Inc. announced its SPORT™ (Single Port Orifice Robotic Technology) Surgical System with two 8-DoF arms and 3.25N payloads using a Ø25mm incision [7]. Picciagallo *et al.* constructed the SPRINT robot for SPL with two 6-DoF arms and 5N payload, using a Ø23mm incision [8]. Ding *et al.* developed the IREP robot for SPL [9, 10]. It possesses two 7-DoF arms and can be deployed through a Ø15mm port. Intuitive Surgical Inc. also introduced the VeSPA tool to be used with the da Vinci robot [11]. The tool uses a Ø35mm incision. Besides the SPL robots, several imaging systems for SPL were also developed [12-15].

Examining the existing state-of-the-art SPL robots, a few improvements could still be targeted: i) the diameter of the access port could be further reduced to minimize the surgical invasiveness; ii) the workspace and the payload capabilities of the manipulation arms could be further optimized; iii) system modularity and maintainability could be improved. Aiming to accomplish these improvements, the SURS (SJTU Unfoldable Robotic System) is developed as Fig. 1. It can be inserted into abdomen through a Ø12mm trocar in its folded configuration and can then be unfolded to form a dual-arm configuration for surgical interventions. It possesses 15 DoFs (two 6-DoF manipulation arms plus one 3-DoF vision unit).

Main contributions of this paper include the system design, integration and preliminary experiments of the SURS robot.

This paper is organized as follows. Section II presents the design objectives and overview of the SURS robot, whereas Section III describes various system components in detail. Preliminary experimental characterizations are reported in Section IV, with conclusions summarized in Section V.

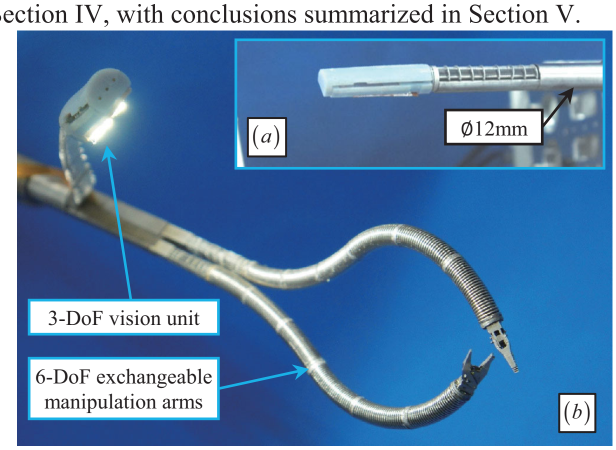

Fig. 1. The constructed SURS robot: (a) the folded configuration deployable through a Ø12mm incision, (b) the unfolded working configuration

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II. Objectives and Design Overview

Using the state-of-the-art SPL robots as benchmarks and aiming at achieving improved specifications, the design objectives of this effort to design a new SPL robot were hence determined as follows.

- ✧ The SURS robot should only use a Ø12mm incision for access. Since the IREP robot needs a Ø15 access port [9, 10], this work aims at a smaller diameter.
- ✧ It should possess two 6-DoF manipulation arms to ensure fair distal dexterity and adequate workspace.
- ✧ Each arm shall have a rated payload of 2N. The threshold forces to maintain functional states of the RealHand™ tools and the Laparo-Angle™ tools are 1.6N and 1.8N respectively [16]. Although this goal is lower than the specifications of some existing SPL robots, it is considered enough since the aforementioned manual tools with comparable specifications are used clinically.
- ✧ System modularity shall be enhanced. Manipulation arms with different end effectors (e.g. grippers, needle drivers, ablation tips) could be easily replaced during a surgery. Sterilization should be considered.
- ✧ A stereo vision unit with illumination shall be included.

The SURS robot was then designed as in Fig. 1 and Fig. 2, following the aforementioned design objectives. Its base plate could be attached to a standard 6R industrial robot. The 6R industrial robot acts as the RCM (Remote Center of Motion) mechanism and roughly positions the SURS robot around the incision point.

As in Fig. 1(a), the SURS robot could be folded into a Ø12mm cylindrical stem, and inserted into the abdomen by the industrial robot through a skin incision. It then unfolds itself to form a dual-arm configuration for surgical tasks.

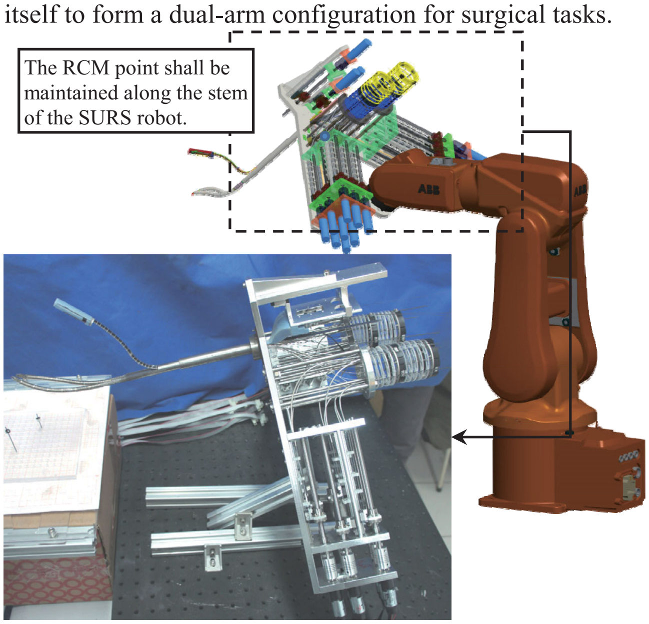

Fig. 2. Design overview of the SURS robot attached to an industrial robot

III. System Components Descriptions

Within the SURS robot, there are three key design aspects: the manipulation arm, the vision unit and the design of the cross section layout. Detailed components descriptions are presented in this section.

A. *Exchangeable Manipulation Arms with Gripper*

The SURS's capability largely depends on those of the manipulation arms. The topological structure of the SURS's arms was carefully selected in order to not only achieve satisfactory kinematic performance but also ensure the design compactness. According to the comparison of the kinematic performances of three continuum manipulators [17, 18], a 2-segment 6-DoF structure was used as the manipulation arm shown in Fig. 3.

The manipulation arm consists of a gripper, the DS-2 (Distal Segment #2), the DS-1 (Distal Segment #1), the PS-1 (Proximal Segment #1), the PS-2 (Proximal Segment #2), and the guiding cannulae, as in Fig. 3.

The DS-1 is similar to the DS-2. Each segment consists of three FC-4 nickel bellows (Servometer LLC.). The bellows are serially connected and all are 6.35mm in diameter and 18.8mm long. The bellow can be easily bent, compressed and stretched. Eighteen Ø0.5mm holes were drilled in the bellows' convolutions by wire EDM as shown in the inset of Fig. 3.

Nine Ø0.40mm nitinol rods as the DS-1's backbones are attached to one end marked by ER-1 (End Ring 1). The backbones are routed through the DS-1, the guiding cannulae, the PS-1, and attached to the other end of the PS-1. Nine more Ø0.40mm nitinol rods as the DS-2's backbones are attached to the bellow end marked by ER-2, routed through the DS-2, the DS-1, the guiding cannulae, the PS-1, and the PS-2, and attached to the end of the PS-2.

The DS-1 and the DS-2 both have 3 DoFs: a 2-DoF bending and a 1-DoF compression/stretching. These DoFs are actuated by the corresponding motions (bending, compression and/or stretching) of the PS-1 and the PS-2. Namely, the PS-1's bending would bend the DS-1 in the opposite direction; stretching the PS-1 would shorten the DS-1 and vice versa. Actuation of the PS-2 would drive the DS-2 similarly. This actuation duality results from the fact that the arrangement of the backbones in the DS-1 and the DS-2 is similar and scaled to that in the PS-1 and the PS-2.

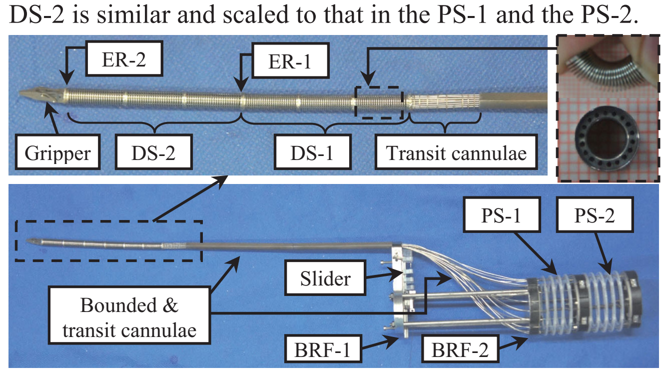

Fig. 3. The constructed exchangeable manipulation arm with gripper

The manipulation arm doesn't have a distal rotary wrist.

The reasons are explained below.

- ✧ A high payload capability is preferred for the SURS robot. A weak distal wrist would affect the overall loading capabilities. Without an effective way to ensure powerful actuation to the distal wrist, the wrist was excluded.
- ✧ A distal rotary wrist is helpful while driving a circular suture to penetrate tissues. As shown in [19, 20], a pre-curved nitinol suture could ease the tissue penetration motion. Without using a rotary wrist, such a suture could be pushed to penetrate the tissues to pass the threads for knot tying.
- ✧ The 6-DoF arm in this design could position its gripper fairly freely within the translational workspace. When a conventional suture has to be used, it is still possible to drive the suture incrementally without using a distal wrist.

The guiding cannulae are tightly bounded into a shape which is shown in the left portion of Fig. 5(a). In Fig. 3, transit cannulae are integrated to ensure the cannulae's smoothness.

The manipulation arms can be inserted into the actuation assembly one by one at the positions indicated in Fig. 4. The arms are fixed at the BRF-1 and the BRF-2 (Base Ring Fixtures 1 and 2) positions as indicated in Fig. 3 and Fig. 4. The BRF-2 in Fig. 4 was a C shape to allow the insertion of the BRF-1 and the cannulae of the arm. After the arm is inserted and fixed, the telescoping rod in Fig. 4 is connected to the slider in Fig. 3 such that a motorized ball screw drives the gripper.

Eight backbones indicated in Fig. 4 are connected to the end ring of the PS-1 and the PS-2. These backbones would be pulled and/or pushed to bend and/or stretch/shorten the PS-1 and the PS-2 so as to drive the DS-1 and the DS-2. These backbones are driven by the motorized ball screws through the guiding channels indicated in Fig. 4.

An arm with a different gripper could be easily replaced during surgery. Since the arm is purely mechanical, it can be sterilized by placing the arm into liquid agents (e.g. glutaraldehyde or ortho-phthalaldehyde).

The DS-1 and DS-2 in each arm both have a free length of 55mm. Their lengths can be varied between 45mm and 65mm. The length of the gripper is 15mm. Hence each arm has a free length of 125mm and the arm's length varies between 105mm and 145mm. The arm has a workspace that can envelope a cubic volume of 50mm × 50mm × 50mm, which is enough for a typical cholecystectomy.

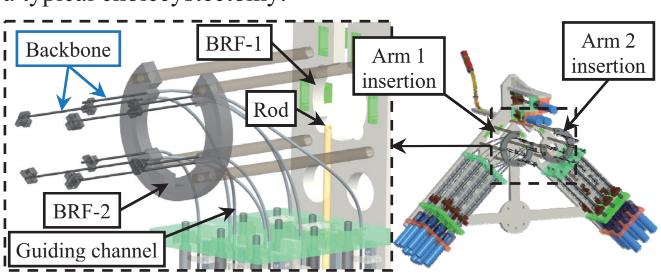

Fig. 4. Actuation assembly of the manipulation arms

B. Layout of the Stem Cross Section

The manipulation arms and the 3D vision unit of the SURS robot are deployed through a Ø12mm skin incision into abdomen. Hence it is of great importance to properly utilize the cross sectional area of the system stem.

As mentioned in Section III.A, FC-4 nickel bellows (Servometer LLC.) are used to form the DS-1 and DS-2. The bellows have a 6.35mm outer diameter. Then two Ø6.35mm arms can only be inserted through the Ø12mm stem one by one. The guiding cannulae are bounded into the irregular shape as shown in the left side of Fig. 5(a). This shape allows the other Ø6.35 arm to pass. The bounded cannulae include 20 channels: 18 channels are for the backbones of the DS-1 and the DS-2; the 19th is for the gripper's actuation line that is routed to the slider as indicated in Fig. 3; the 20th can be used for a pre-curved nitinol suture as proposed in [19, 20].

After both arms are inserted, a 3mm wide bar is inserted between the arms to hold the two arms in place, as shown in the right side of Fig. 5(a).

The upper portion in the cross section is reserved for the 3D vision unit. The continuum camera arm and the flexible PCB for LED and camera chips are passed through here.

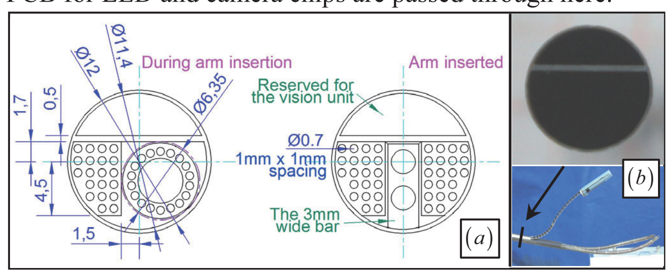

Fig. 5. Layout of the cross section: (a) CAD drawing and (b) prototype

C. Stereo Vision Unit

The 3D vision unit can fold itself into a cylindrical form as shown in Fig. 1(a). This form facilitates the insertion through the skin incision. The 3D vision unit could then be extended and bent upwards to provide visualization of the surgical site.

The vision unit was designed as shown in Fig. 6 and Fig. 7. It consists of the camera head and a 2-segment continuum camera arm.

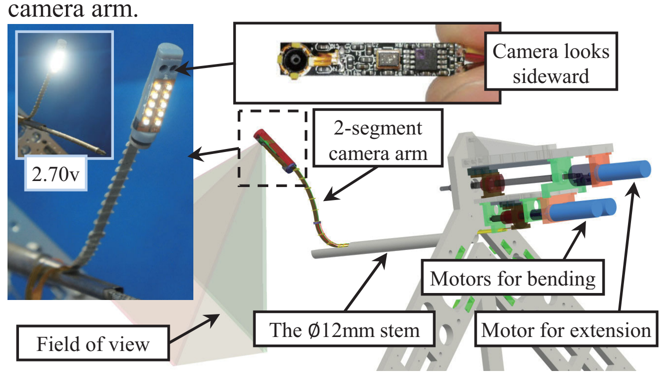

Fig. 6. The stereo vision unit with integrated LEDs for illumination

The camera head uses two MO-BL1204LK chips (Misumi Inc., resolution of 640×480). Each chip is 24mm long and 4.5mm wide. The two chips were placed side by side inside the Ø12mm camera head. The chips' original wires were replaced by customized flexible PCB strips which could be easily passed through the camera arm. Ten LEDs are mounted to the camera head's surface for illumination. These LEDs (nominal voltage 2.95v) are lit at 2.70v as in the inset of Fig. 6. Lighting them at a lower voltage avoids the heating problem. The steady status temperature is around 33℃ when the camera head is in a room environment with no ventilation.

A 2-segment continuum arm is used to orient and position the camera head. As shown in Fig. 7, the continuum arm consists of a nitinol strip, a fixation ring, spacers and a few actuation thin rods. The fixation ring is fixed to the nitinol strip. The division of the nitinol strip from the arm entrance port to the fixation ring is referred to as Camera Segment 1 (CS-1). Two actuation rods are connected to the fixation ring and can slide in the holes of the spacers. The CS-1 is bent upwards by pulling the actuation rods. The division of the nitinol strip between the CS-1 and the camera head is referred to as Camera Segment 2 (CS-2). Another actuation rod is connected to the camera head. Pushing this rod would bend the CS-2 downwards.

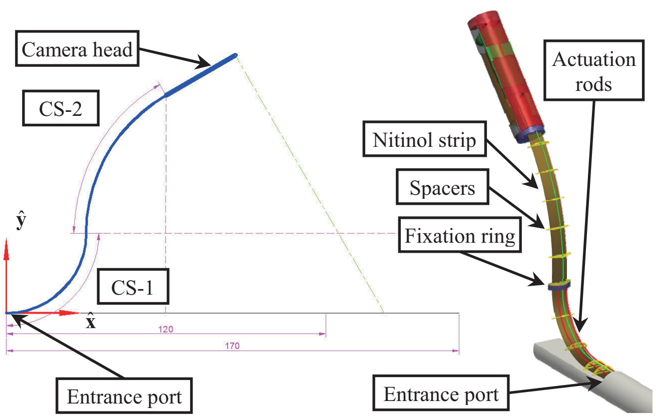

Fig. 7. The 2-segment continuum camera arm

IV. Preliminary Experimentation

Some preliminary experiments were carried out to demonstrate the capabilities of the SURS robot.

A. Deployment

It's critical the SURS robot can be deployed into abdomen through a Ø12mm skin incision. The deployment process of the SURS is shown in Fig. 8.

The SURS robot is in its folded configuration for insertion as shown in Fig. 8(a). After insertion, the 3D vision unit is extended and is bent upwards to generate space for the manipulation arms, as shown in Fig. 8(b) and Fig. 8(c). The LEDs are also lit up to provide illumination in the abdomen. After the camera positioning arm is set to a desired shape, one manipulation arm could be inserted as in Fig. 8(d). After the first arm is fully inserted, enough space would be spared within the Ø12mm stem, the other arm could then be inserted as in Fig. 13(e). The two arms could then perform dual-arm surgical tasks as in Fig. 13(f). Please note that either arm could be pulled out at any time. They just can't be inserted or pulled out simultaneously.

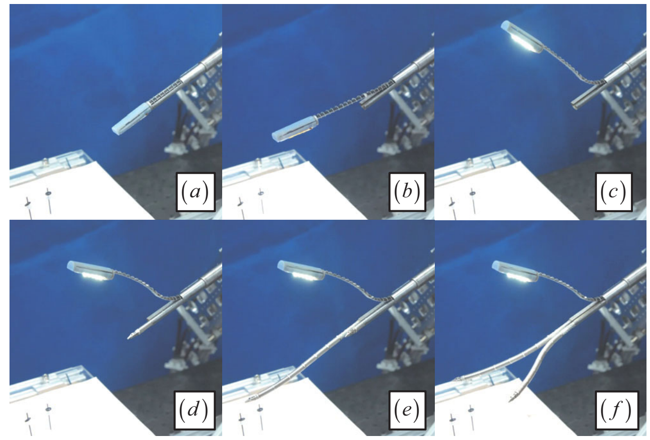

Fig. 8. Deployment process of the SURS robot

B. Objects Manipulations

The SURS robot was tele-operated to perform a pick-and-place task as in Fig. 9 to preliminarily demonstrate the motion capabilities of the SURS robot.

The tele-operation was achieved using a typical setup. Two Phantom Omni devices (Sensable Inc.) were connected to a Host PC for control inputs. The Host PC runs a Windows OS. A customized program sends the tip orientations and positions of the two Omni devices to two Target PCs via LAN (Local Area Network) connections using UDP (User Datagram Protocol) every 10 milliseconds.

Each Target PC controls one manipulation arm and it runs a real-time OS generated by the xPC module of MATLAB. The servo loop on the Target PC is 1 millisecond.

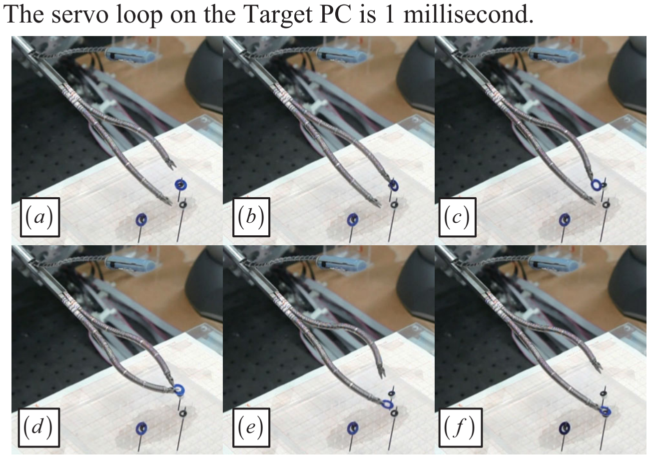

Fig. 9. Pick-and-place motions of the SURS robot

Several motion control cards, including the PCL727 D/A cards (AdvanTech Inc.) and the CNT32-8M counter cards (ConTec Inc.), were used for analog control signal outputs and the encoder readings. The motors (A-max 22 motors, GP22A gearheads, and MR32 encoders) and the amplifiers (LSC 30/2) are from Maxon Inc. In each servo loop, the Target PC (as a controller) generates motor control signals according to the inputs from the Omni devices and the inverse kinematics of the manipulation arm.

At this point, the continuum arm of the vision unit is kept stationary during the teleoperation.

The SURS robot performed the pick-and-place task as shown in Fig. 9.

V. Conclusions and Future Work

The paper presents the design, construction, and preliminary experimentation of the SURS (SJTU Unfoldable Robotic System) for SPL (Single Port Laparoscopy). The SURS robot can be deployed through a Ø12mm access port into abdomen in its folded configuration and can then be unpacked into a dual-arm configuration for surgical operations. This particular design effort aims at achieving improved system specifications of SPL robots for smaller incision ports and enhanced specifications.

The design objectives, the system overview and detailed component descriptions are elaborated. Preliminary experimentation is reported.

Immediate future developments include motion calibration and more systematic experimental characterization. The motion calibration intends to reduce the discrepancy between the desired bending shape and the actual bending shape of the manipulation arm. With the actuation discrepancy corrected, more tele-operated manipulation could be carried out, such as tissue peeling and knot tying. What's more, more exchangeable surgical tools (e.g., cautery and ablation tools) are expected to be integrated so that the SURS robot could be further gauged in animal studies or even clinical tests.

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