A Flexure-based Deployable Stereo Vision Mechanism and Temperature and Force Sensors for Laparoscopic Tools

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Abstract

This paper presents concepts, designs, and working prototypes of enhanced laparoscopic surgical tools. The enhancements are in equipping the tool with force and temperature sensing as well as image acquisition for stereo vision. Just as the pupils of our eyes are adequately spaced out and the distance between them is adjustable, two minute cameras mounted on a mechanism in our design can be moved closer or farther apart inside the inflated abdomen during the surgery. The cameras are fitted to a deployable mechanism consisting of flexural joints so that they can be inserted through a small incision and then deployed and moved as needed.

A temperature sensor and a force sensor are mounted on either of the gripping faces of the surgical grasping tool to measure the temperature and gripping force, which need to be controlled for safe laparoscopic surgery. The sensors are small enough and hence they do not cause interference during surgery and insertion. Prototyping and working of the enhanced laparoscopic tool are presented with details.

Keywords: Laparoscopic tools, flexural joints.

1 Introduction

In this paper, we present three enhancements to laparoscopic tools by developing a deployable mechanism for accurate acquisition of stereo vision data and also by equipping the surgical grasper with force and temperature sensors.

Laparoscopic or other minimally invasive surgeries are the so-called *key-hole surgeries* in which the surgeon operates on the internal organs or tissues by inserting tools through a small incision made in the body. While this reduces the trauma in patients and helps heal them fast, there are many technical challenges in these procedures. The main requirement here is to somehow provide the surgeons ‘a pair of eyes’ and ‘a hand’ through a circular incision of diameter less than 15 mm. Of course, it is figuratively that one can do this. A hand has better manipulative capability and it can feel the force and temperature as compared with a long tool inserted through a small hole. In laparoscopic surgery, the abdomen is inflated with CO_2 gas to create empty space around the organs to be operated for the movement of the tool as well as the laparoscope.

When it comes to providing a pair of eyes inside the inflated body, two things are necessary: (i) a camera system and (ii) a visual display. A typical laparoscope has a small camera or a lens with optical fibers as well another optical fiber for illumination of the operating region. It is a tube of diameter ranging from 5 – 15 mm. Realistic visual information of high quality is crucial because the surgeon is decoupled from the operating site. In particular, stereo vision is important. Hence, stereo endoscopes are available. But they have one drawback in that the two lenses are arranged inside the tube too close to each other. This is in contrast to our eyes which are farther apart. This is called the *optical basis*. In fact, for proper stereo vision, the distance between the two eyes should be adjustable as it happens to our pupils as we focus on near or far objects. In our earlier work [1], we had noted this limitation and had presented a mechanism that can be inserted through a small hole with two cameras which can be moved relative to each other just as the pupils of our eyes. But our prototype was 2.5 times larger than what is required in practice. Reducing the size of that prototype turned out to be difficult as it had jointed rigid-body linkage. In this paper, we improve that mechanism by using flexures or compliant joints and hence make the reduction in size possible. This is explained in Section 3 after briefly reviewing our earlier work in Section 2.

Stereo vision display is provided to the surgeon with a pair of 3D vision goggles or other types of head-mounted displays. In fact, some studies have found that seeing through 3D vision head-mounts is rather cumbersome for surgeons [2]. Hence, there are now auto-stereoscopic systems that enable us to see stereo images without having to wear goggles or head-mounts but on a special screen [1]. Thus, if stereo vision data is captured properly—which is a focus of this work—it is possible to give almost natural stereo vision to the surgeons.

We return the question of inserting *a hand* through a small incision. The force feedback that the surgeons get with a long laparoscopic tool is as good as what one can feel by poking with a long rod. It is far from what one can feel with fingers. Hence, there is a need for a force-sensor at the tip of the surgical tools, mainly the grasping tool. In this work, we add a commercially available force sensor on one jaw of a grasping tool. A feel for temperature is also important to the surgeons. Hence, we add a temperature sensor to the other jaw. This is explained in Section 4. Section 5 concludes the paper by recounting the main points of the paper.

2 Review of Prior Work

We first recollect our prior work (which was presented in [1]) because a part of this paper is an improvement over that.

A primary requirement of the deployable mechanism is to carry two cameras and adjust the distance between them as needed. The first challenge is to make the mechanism collapsible into the laparoscope within a tube of diameter 10- 15 mm, which is the range of diameters of the telescopic instrument used in the surgery today. The cameras should remain attached to the mechanism in the collapsed condition. The cameras we have chosen are one of the smallest available CMOS cameras: PC208 from Super Circuits Inc., USA. Each camera measures 8 mm × 8 mm × 8 mm.

The mechanism, when pushed out of the tube, should deploy into a pre-determined configuration. After this, it should be actuatable to vary the convergence angle and the optical basis. That is, the cameras should be able to rotate as well as move relative to each other. This is to help the mechanism focus in the range of 40–200 mm, which is specification provided by a practicing laparoscopic surgeon, Dr. Ramesh, Director: BEST Institute, Bangalore. This specification translates into a range of 10 – 30 mm for the optical basis. The resultant specification of the desired path of the two cameras in the deployed configuration is shown in Fig. 1. Thick solid lines in this figure show a mechanism schematically. The variable convergence angle and optical basis can be seen in the figure. The dimensions are shown in Fig. 2.

Figures 3(a-d) show solid models of the rigid-link deployable mechanism presented in [1] and Fig. 3(e) shows the prototype. The prototype needed a 30 mm diameter tube rather than 5 – 15 mm diameter. When we attempted to reduce the size, it was learnt that rigid-body joints pose problems in machining at small sizes. Hence, we decided to pursue flexible joints.

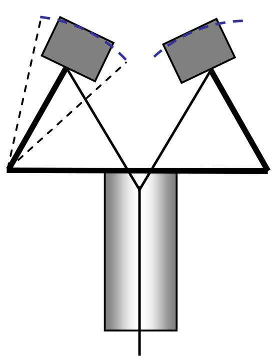


Fig. 1: Desired motion of the two cameras in the deployed configuration of the mechanism.

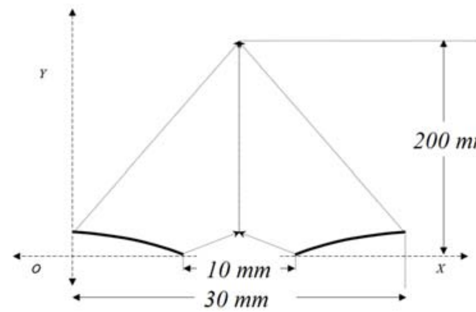


Fig. 2: The required paths to be followed by the two cameras to focus up to 200 mm away inside the inflated abdomen using two movable miniature cameras.

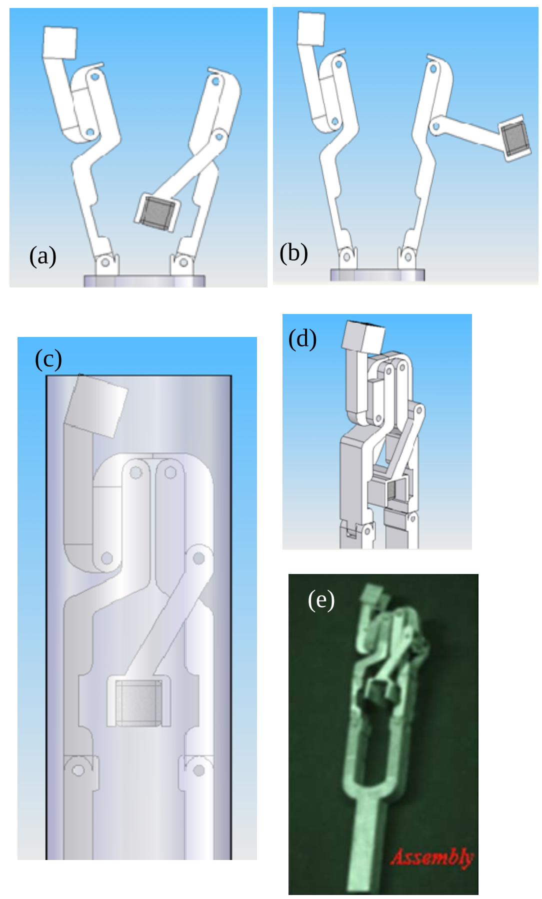


Fig. 3(a-d): Different perspective views of the camera-deploying rigid-body mechanism with the cameras in the deployed and collapsed configurations. (e) shows the aluminium prototype that was fabricated. It fits in a 30 mm diameter tube.

3 Flexure-based Stereo Vision Mechanism

Flexural joints are common in both macro and micro scale devices [3]. They are easily formed by narrowing a cross-section area or a connection between two relatively rigid portions. As shown in Fig. 4, the relative rotation between the two bodies is not perfect because the centre of rotation and the radius may vary during the traversal. But they are useful in applications where precision is not required and manufacturing needs to be simple. The one we are concerned in this paper falls under this category because we want to make it smaller than a factor of two as compared with the prototype shown in Fig. 3(e).

Figure 5 schematically shows the new deployable mechanism for stereo vision capture. It has four flexure joints. As shown in the figure, parts A, B, C and D are rigid arms made up of aluminum strips of 2 mm thickness. The cameras will be attached to the arms A and B. Arms A and C have a flexural joint F1 in between. Arms B and D have a flexural joint F2 in between. There is a flexural joint F3 between the tube and arm D. Furthermore, there is a flexural joint F4 between arm D and the tube. Note that the tube is hollow and the two brass wires W1 and W2 pass through it and connect the arms A and B. The wires can be pulled independently to move the arms A and B apart or closer together and hence changing the distance between the cameras for the purpose of focusing and proper viewing. Wires W3 and W4 are attached to arms C and D respectively and are external to the tube and are guided through a guide G. Wires W3 and W4 can be pulled to move the arms C and D which gives additional degrees of freedom of the mechanism. The flexural joints are made out of a spring steel strip of 100 micron thickness. The initial prototype of a flexure-based deploy mechanism is shown in Fig. 6. This placed inside a 20 mm diameter is shown in Fig. 7.

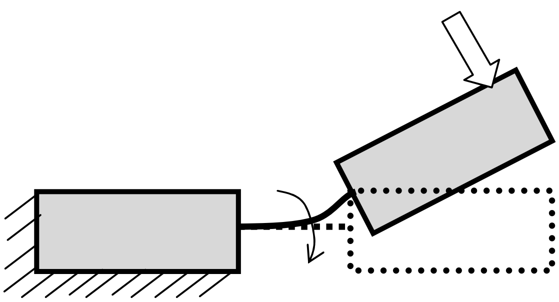


Fig. 4: Schematic of a flexural joint.

A mock-up of the surgery setting was created to test the deployable mechanism. This is shown in Fig. 8. The setup comprises a cardboard box that imitates the inflated abdomen in terms of size but not shape. A light source (a florescent lamp instead of fibre optic illuminator) was attached to the cardboard. Similar to the incisions, holes were pierced in the box from the front and side faces. One face of the box was kept open for video-recording and photographing. Mock-ups for mimicking pick-and-place and suturing tasks were placed inside the box. All these are marked in Fig. 8. Also seen in the figure are the hands of the user who holds the deployable mechanism in the left hand and a real laparoscopic gripping tool in the right hand. The user wears Trivisio head-mounted display that helps see the two images captured by the cameras. Care was taken so that the user

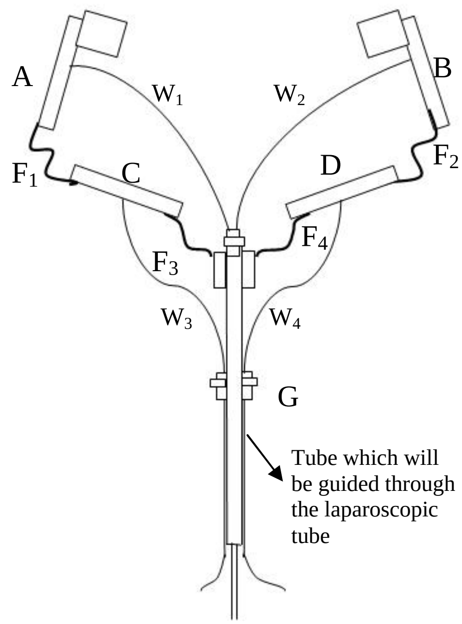


Fig. 5: Schematic of the new flexure-based mechanism. Special shape of the flexures helps in collapsing the mechanism into the tube.

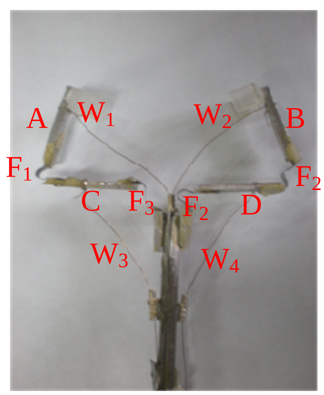


Fig. 6: A prototype of the flexure-based camera deployable compliant mechanism.

Fig. 7: The flexure-based deployable compliant mechanism placed inside a 20 mm diameter tube. Notice that the miniature cameras of 8 mm cube size are in place.

does not directly see the contents of the box; the head-mounted display anyway blocks the eyes.

Two types of tasks were tried with different users. The users did not have any practice with using laparoscopic tools nor are familiar with working while a wearing a head-mounted display. The first task was to pick a ring that is initially placed around one post and place it on another post. This is shown in Fig. 9. The second task was to pass a piece of wire (normal electrical wire) through a loop. This is like needling a thread. This is shown in Fig. 10. The users tried to adjust the camera angle as can be seen in Figs. 9-10. To compare the effectiveness of the stereo vision, a single camera (webcam) was tried with its image shown on a computer screen. But the webcam has a much wider field of view and users found that to be easier to work with. Real comparison has to be made using a laparoscope. This study is yet to be done.

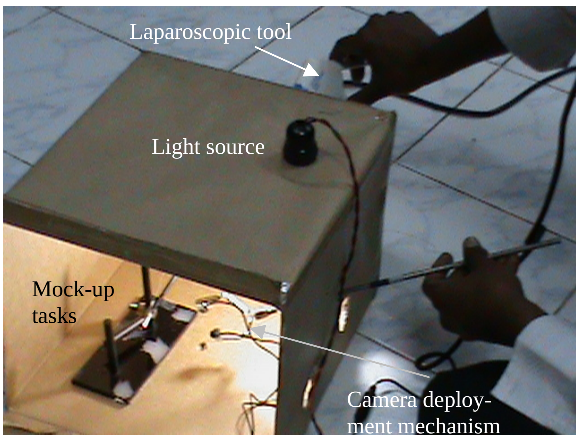


Fig. 8: The mock-up of laparoscopic surgery to experiment with the camera-deployable mechanism.

Fig. 9: The pick-and-place task being done by a user.

4 Mounting the Sensors on a Laparoscopic Tool

During laparoscopic surgery, artificial heating is used in localized regions to control bleeding. Heating can help in blood-clotting. Furthermore, decrease in intra-operative intra-abdominal gas temperature is dangerous and can potentially harm the patient. It can be limited by restricting gas flow and leakage. Some operations are carried out for more than an hour, and during this the core body temperature may drop, and this should be prevented with appropriate heating and by some hydration devices [4]. Therefore, the temperature of the gas as well as the temperature of the body should be maintained by sensing the temperature of the body. In order to aid the laparoscopic surgeon to overcome these problems, we attached a temperature sensor (platinum-based sensor) to the laparoscopic gripper to measure the temperature during surgery.

Fig. 10: 'Needling a wire' task done by a user

Fig. 11: Schematic of mounting the temperature and force sensors on a laparoscopic tool.

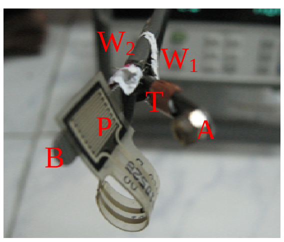
The need for a force sensor was already mentioned in the introduction. It is important to have force-feedback in laparoscopic surgery where the surgeon does not get the real feel for the operating region. By referring to Fig. 11, we note that parts A and B are rigid arms which are actuated by guide G to act as a gripping tool. The temperature sensor T is mounted on the arm A in which I/O of the sensor is transferred through a wire W_1 and the force sensor P is mounted on the arm B and the I/O of the sensor is transferred through a wire W_2 and also output from these sensors are measured by connecting to a digital multi-meter.

The size of the temperature sensor is 6 mm × 2 mm × 0.5 mm and the wire diameter is of 200 microns.

But the size of the force sensor (Freeform from Sensor Products) is 10 mm × 10 mm with a wire diameter of 2 mm. A smaller sensor that is only 3 mm × 3 mm is also tried.

Figure 12 shows the laparoscopic gripper with the temperature and force sensors mounted on its jaws. This force sensor is a bit too large. Both the sensors are commercial sensors that are already calibrated. Yet, we tested them with alternate measurements and found the calibration to be correct. Figure 13(a) shows the close-up view of the sensors and Fig. 13(b) shows the temperature reading shown by a digital multi-meter. The readings can be toggled on a multimeter.

Fig. 12: A laparoscopic gripping tool with force and temperature sensors on its jaws.



(a)

(b)

Fig. 13: (a) Close-up view of the mounted sensors on a gripping surgical tool, (b) temperature reading shown by the digital multi-meter, which can alternately show the temperature and force values.

Displaying the both readings of these sensors, we found out upon consulting a laparoscopic surgeon, should be more qualitative. That is, the surgeons do not necessarily want to know the value of the force. Rather they merely want to distinguish between very hard, hard, soft, and very soft. Similarly, very hot, hot, warm, normal, and cold are the variations they want to be warned about. Using thresholds, this can be done. Hence, our next step is to process the digital readings of the sensors and display this information easily to the surgeon.

Fig. 14: A laparoscopic gripper with temperature and a small force sensor (3 mm × 3 mm) on its either jaw. The button like object on the lower jaw prevents the damage on the force sensor.

5 Conclusions

Providing true stereo vision capture using two cameras, the distance between which can be varied, helps in enhancing the effectiveness of visual perception in laparoscopic surgery. In this paper, we presented a new flexure-based deployable mechanism which is compact as compared to our previous rigid-body linkage design. It is easier to manufacture this flexure-based mechanism in a small size as compared with our previous rigid-body jointed mechanism prototype. An additional advantage of the flexure-based mechanism is the lack of friction and its increased amenability to actuate it by pulling the wires that run through the laparoscope.

We also presented how off-the-shelf force and temperature sensors can be mounted on the jaws of a laparoscopic tool to give the surgeon force and temperature feedback. Upon consultation with a laparoscopic surgeon, we learnt that visual display of semi-quantitative force and temperature information is more useful than displaying numbers on a screen. Hence, our future work will focus on developing an electronic interface that shows four levels of force feedback (very hard, hard, soft, and very soft) and temperature feedback (very hot, hot, moderate, and normal) using the sensor data.

Acknowledgement

We thank Dr. Ramesh Makam, a laparoscopic surgeon, who guided us through this work. We also thank Mr. M. Rajesh, who worked on the rigid-body deployable mechanism, for assisting in the continuation of the work and in using the 3D vision system and the miniature cameras. Funding from the Society for Biomedical Systems (SBMT), DEBEL, Bangalore, is also gratefully acknowledged.

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