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A Foldable Mechanism for Stereo Vision in Laparoscopic surgery

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Abstract

Enhancing the depth perception in laparoscopic surgery is very important. Towards this goal, we have designed a foldable mechanism for mounting two small cameras that enable stereo vision in a laparoscope. The challenge addressed here is to fold the two cameras, the entire mechanism, and the actuating wires within a tube of 15 mm diameter. The mechanism is pre-loaded with springs so that it will automatically deploy into a desired configuration upon pushing it out of the tube. Furthermore, in the deployed configuration, the mechanism can be manipulated by pulling on the actuating wires to change the stereo-base distance between the two cameras for focusing at different depths inside the abdomen. A 2X-scale working prototype has been made and experiments have been conducted on some typical simulated tasks of surgery. The results of the experiments indicate that depth perception improves with the mechanism presented here.

Keywords: Foldable mechanism, Laparoscopic surgery, and Stereo vision.

1 Introduction

Minimally Invasive Surgery (MIS) is a rapidly growing technology in the medical field. In MIS, surgery is performed through two or more small incisions rather than large cuts in the body. Therefore, visual access to the surgical region is significantly reduced in MIS. *Laparoscopic Surgery* (LS) is the most prominent example of MIS. Laparoscopic surgery refers to operative procedures done within the abdomen or pelvic cavity. In LS, an image of the operating site is obtained by inserting an endoscopic camera through a small–usually 10-15 mm in diameter–incision into the body cavity that is inflated with CO_2 gas to create space for surgery. The image is displayed to the surgeon on a monitor. Therefore, the surgeon indirectly views the area under surgery and performs the tasks using laparoscopic instruments. The instruments are also inserted through the small incisions (usually 5 - 15 mm). Thus, unlike in open surgery, laparoscopic surgeons have to manipulate the instruments based on indirect visual input to ascertain the depth, texture and orientation of the operated organ or tissue. The focus of this paper is to design a foldable mechanism for mounting two cameras that will be deployed inside the abdomen and controlled like normal eyes in order to enhance the depth perception.

1.1 Background

Picture acquisition and picture presentation are two important aspects of a laparascope. For stereo vision with depth perception, the picture is to be acquired with two cameras just as we do with two eyes. Picture presentation should be done using one of the many stereo vision displays. Current stereo laparoscopes fall short of optimum performance in both cases. First, we discuss the picture acquisition part.

Figure (1) shows a schematic of a typical stereo laparoscope. Here, the cameras are not inside the abdomen; only the two lens systems are. Thus, the effective distance between the two cameras is fixed and is very small. In order to understand why this is a limitation, we need to consider the 3D vision cues shown in Fig. (2).

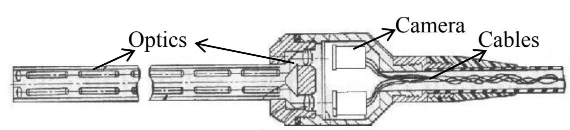


Figure 1: A schematic of a stereo laparoscope. Two lens systems are arranged inside the tube while the cameras are at the far end, outside the abdomen. Source: [1].

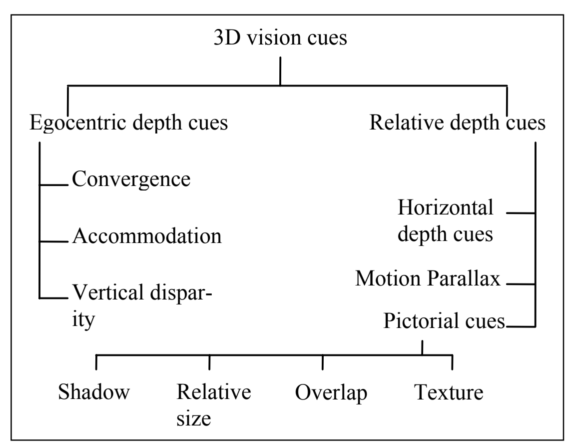


Figure 2: Classification of 3D vision cues.

As shown in Fig. (2), the 3D vision cues can be broadly separated into two types: egocentric and relative depth cues [2]. Egocentric depth cues determine the observer's distance from the viewed objects while relative depth cues help assess the distances among the viewed objects. Convergence (see Fig. (3)) is an important cue. It refers to the angle subtended by the lines of vision of the two eyes at the object. The angle is more for closer objects and less for the farther objects. Our eyes achieve this by moving the eye-balls inwards and outwards. This is currently lacking in the stereo laparoscopes [3]. Accommodation refers to changing of the shape of the lens to bring objects into focus. This is not yet attempted in stereoscopy. Vertical and horizontal disparities refer to the two eyes seeing the sizes of the same object differently, which helps brain create a 3D image. These are restricted in current laparoscopes because of fixed distance between the two lenses (or effectively cameras) and the constant convergence angle [3,4]. Other cues shown in Fig. (2) are not discussed here because the current work focuses on the convergence and the distance between the two cameras.

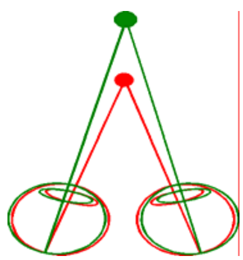


Figure 3: Convergence angle, the angle subtended at the object by the lines of vision of the two eyes, needs to be adjusted to focus at farther and nearer objects than those previously viewed. This is currently lacking in most of the stereo endoscopes.

1.2 Comparative study and motivation for the work

Many investigations have been reported on using stereo vision in laparoscopic surgery. The conclusions of these studies do not confirm that stereo vision improves surgeon's performance. Chan et al. (1997) studied two groups of surgeons (with and without experiences in laparoscopic surgery) who performed a standardized laparoscopic task using a 3D camera system and a 2D camera system and compared their performances [5]. The results could not demonstrate any superiority of 3D system over the 2D system but indicated that only experience in laparoscopic surgery had significant effect on individual's performance. They also concluded that 3D system did improve depth perception and also resulted in a considerable reduction of errors committed during the task. Hanna et al. (1998) made a study in which 60 laparoscopic operations were randomized for execution by either 3D or 2D imaging display [6]. The results projected that there was no improvement in the mean execution time or error rate using 3D system but strain, head ache, and facial discomfort were higher. They also conducted a study involving endoscopic bowel suturing task in 2000, but the conclusive remarks were the same [7]. Radermacher et al. (1998) compared the manipulative performance measured by the time for the execution of a test cycle i.e., grasping and removal of 100 pins on a test board using a laparoscopic forceps [8]. The results suggested that the use of a 3D system improved the performance by 26% compared to the use of a conventional 2D system and also the strain experienced by the test subjects was significantly reduced while performing tasks with a 3D system. The study also pointed out that the experienced surgeon profited more from stereo-3D-visualization than the non-experienced surgeon. Bergen et al. (1998) made a study which was split into three parts, (i) Application in the training center for MIS, (ii) application in standardized tasks in a model and (iii) application in clinical and experimental operations, which included positioning, sewing and knotting [9]. The performance times and number of technical faults were considered for comparison. The results showed that 3D system had an edge over 2D system while performing complex operative maneuvers (sewing, knotting, recognition of anatomic details etc.) but were not superior for simple operative tasks. Herron et al. (1999) evaluated the performance of 3D Monitor and a Head-Mounted Display against a 2D system for standardized laparoscopic dexterity drills [10]. They concluded that number of errors committed was less using 3D imaging, but they were not clinically significant and also there was no decrease in the execution time. Wentink et al. (2002) conducted a study using three advanced laparoscopic viewing technologies (a stereo-endoscope, an image projection display and a TFT display) against a conventional 2D system (a monocular endoscope and a high resolution monitor) [11].The outcome of the study was no different from other studies i.e., there was no significant improvement in the performance time. They attributed this to the inferior image quality provided by all the three viewing technologies compared to standard display. Furthermore, the disparity at infinity was an issue in case of a stereo-endoscope.

Mueller-Ritcher et al. (2003) compared the performance of a 2D system and 3D system (polarization glasses) with the new generation auto-stereoscopic display [12]. The results with 2D were better than those with polarization glasses which in turn were slightly better than the auto-stereoscopic display. They found that the two different pictures provided to the display system are too similar to generate a true spatial impression. The acquisition of 3D vision cues was not proper which lead to the diminished depth perception in spite of advanced 3D display systems.

Apart from few comparative studies, all other indicated that the conventional 2D system has a better ranking when compared to all 3D presentation technologies. This may be due fact that the development in the past is focused on improving the presentation of the image rather than enhancing the acquisition ability. The present study is an effort to improve the acquisition of 3D vision cues and enhance the surgeon's ability to perform as naturally as in open surgery. In particular, we focus on changing the convergence angle and the optical basis (or stereo base distance). Convergence is explained in Fig. (3). Optical basis refers to the distance between the two eyes (or the cameras). We explain that the optical basis differs from person to person. Hence, it is important to make it adjust-able. Furthermore, for the same person too, it must be changed to focus at farther and nearer objects.

The rest of the paper is organized as follows. Section 2 describes the specifications for the foldable mechanism that mounts the two cameras. Section 3 contains the proposed design and details. Section 4 reports on the scaled-up prototype and Section 5 contains the results obtained through the experiments done with test subjects, who are not laparoscopic surgeons. Section 6 has some concluding remarks.

2 Specifications for the Mechanism

The primary requirement of the foldable 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 Supercircuits 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 able to actuatable to vary the convergence angle and 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. (4). The 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. (5).

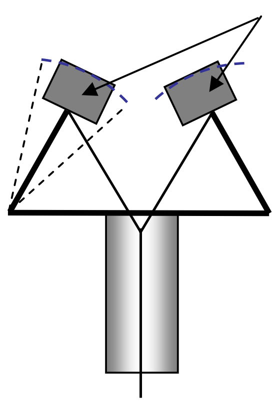


Figure 4: Desired motion of the two cameras in the deployed configuration of the mechanism.

The equations of the circular arcs shown in Fig. (5) are given by:

$$(x+2.86)^2+(y+25.72)^2=(28.75)^2 \qquad (1)$$

$$(x-42.86)^2+(y+25.72)^2=(28.75)^2 \qquad (2)$$

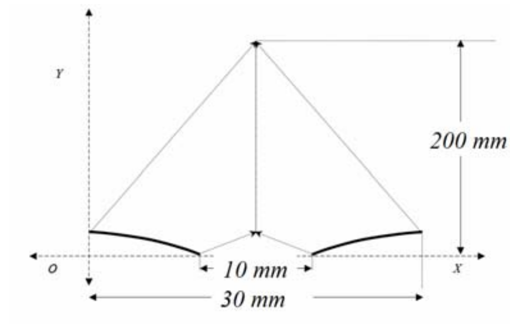


Figure 5: Quantitative details of the desired motion of the two cameras (thick circular arcs) mounted on the mechanisms that should collapse into a tube of diameter 15 mm.

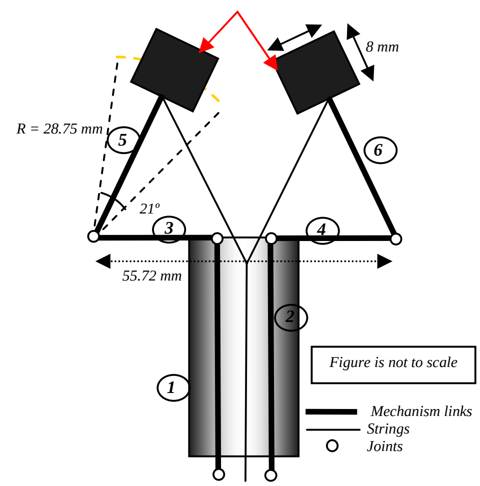
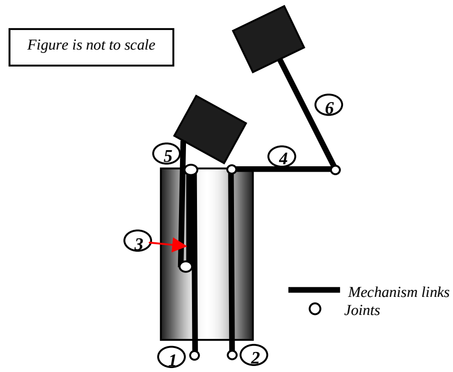


Figure 6: Schematic of the mechanism with the cameras.

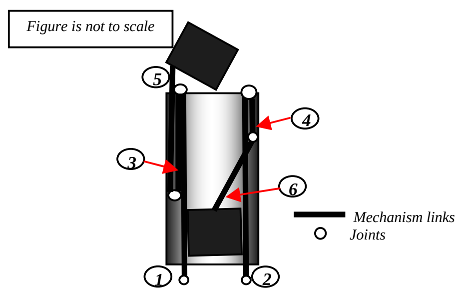
The actuation to vary the optical basis, as shown in Fig. (6), is achieved by pulling the cables. The schematically shown mechanism in Fig. (6) too does not indicate that the mechanism can be collapsed into the tube. In the next section, we present our design that meets the specifications outlined above.

3 Design and Kinematic Simulation

Given that each camera's size is a cube of 8 mm and the diameter of the tube is 15 mm, the only way to collapse the cameras into the tube is by having them one above the other inside the tube. This arrangement leaves some space for the mechanism. Let us call the part of the mechanism that houses a camera as an "arm". We have two arms—one for each camera. In Fig. (7a), we see how the left arm may be folded. If we make the right arm the same the left arm, the two cameras will face each other and interfere with each other. So, we consider an alternate arrangement of folding the right arm as shown in Fig. (7b). The complete mechanism in its collapsed configuration is shown in Fig. (8). The deployment steps are shown in Fig. (9).



(a)



(b)

Figure 7: Kinematic movements of the linkage to suggest a foldable mechanism. (a) a method to fold one camera. (b) a method to fold the second camera.

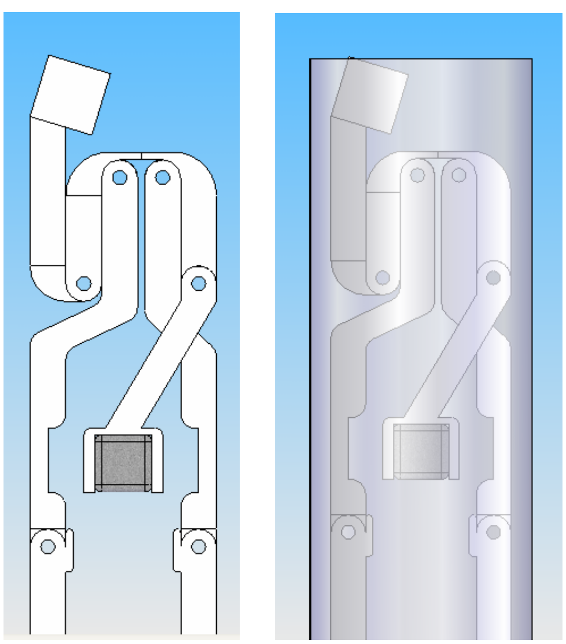


Figure 8: (a) A solid model of the details of the entire mechanism with the cameras. (b) The assembly collapsed into a tube. Passive springs and pulling cables are not shown in this and other figures.

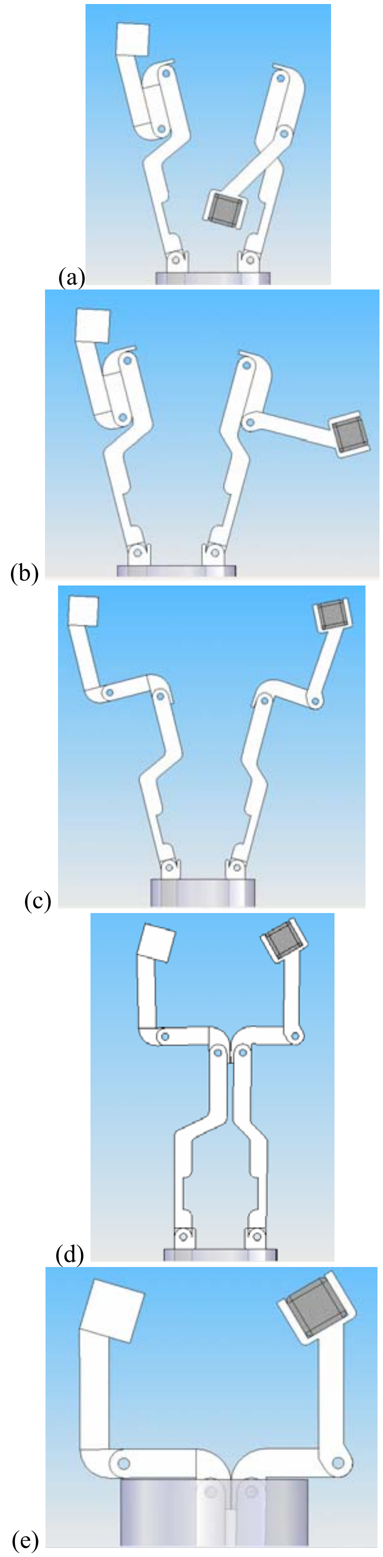


Figure 9: Deployment steps of the mechanism. (a) Pushing it out of the tube takes the two arms apart to enable them to unfold by releasing their torsional springs, (b) Unfolding of the right arm, (c) Unfolding of both the arms, (d) pulling both the arms into their required positions, and (e) pulling the whole assembly to rest against the edge of the tube.

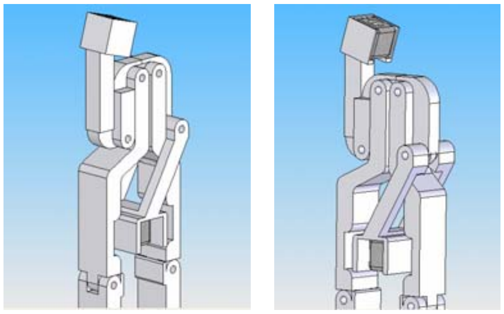


Figure 10: Two different perspective views of the folding mechanism with the cameras in the collapsed configuration.

The deployment of the mechanism when the tube is inserted through the incision in the abdomen is as follows. First the entire mechanism is pushed out. Since the joints are all equipped with torsional joints (not shown in the figures), the two arms will fold out as shown in Figs. (9a-b) one after the other. The sequence is controlled by a cable that restrains the right arm until the left arm folds out. Two other cables that restrain the outer links of the two arms are now released to get the cameras into proper positions, as shown in Figs. (9c-d). The inner links are now pulled by another cable to get the cameras into the desired final positions. At this point, the entire assembly is pulled inwards to make the camera mechanism sit on the edge of the tube. This is shown in Fig. (9e) in a close-up view. In this position, the two cameras can trace the circular arcs shown in Fig. (6).

4 Prototyping and Testing

For the purpose of prototyping and initial testing, we chose to make a 2X scaled-up model. There are seven parts in this mechanism. All these were machined using CNC milling machine and wire-cut Electro Discharge Machining (EDM) using aluminium. The parts and the assembly are shown in Fig. (11). The camera is shown in Fig. (12). The cameras were attached in the slots provided in the mechanism for that purpose. The joints in the mechanisms were attached with tiny torsion springs shown in Fig. (13). Since it is a scale-up 2X prototype, the mechanism was inserted into a pipe of 30 mm diameter. Its effectiveness in providing enhanced depth perception was tested as follows.

4.1 Determining the optical basis

Prior to conducting the tests wherein the subjects were asked to perform simulated tasks of surgery, an experiment was performed to determine the appropriate optical basis. For this, we made an aluminium fixture for mounting the two cameras so that the distance can be varied. Objects were placed at different distance from the cameras. The aluminium fixture is shown in Fig. (14) and the set-up with the cameras and the object in Fig. (15). The subjects were given Trivisio 3D head mounted display (HMD) for 3D viewing (see Fig. (16)).

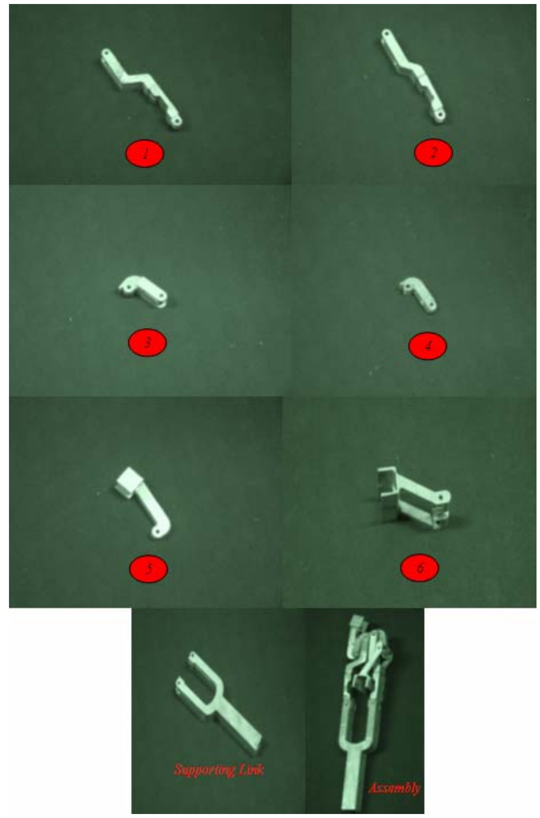


Figure 11: Two different perspective views of the folding mechanism with the cameras in the collapsed configuration.

Figure 12: A CMOS camera that fits within a cube of 8 mm (PC 208 from supercircuits).

Figure 13: Different torsional springs used at the joints in the mechanism. These springs were cut and bent as needed in some cases.

By looking at the 3D image using HMD, the subjects were asked to assess the relative depths of the objects placed in font of the cameras. The slots in the aluminium fixture could accommodate the camera separation distance from 11 to 96 mm in steps of 3 mm. The subjects reported remarkable improvement in the depth perception in the range 29 – 41 mm. Each person's optimum optical basis differed slightly but it was in this range. The mechanism described in the last section can accommodate this range. This is an important finding because current stereo laparoscopes have very small optical basis at which the depth perception is not remarkable as compared with normal 2D displays.

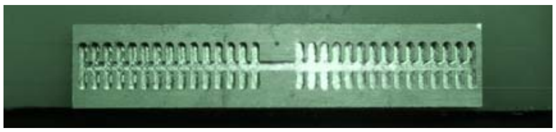


Figure 14: A slotted aluminium fixture for mounting the cameras at different distances.

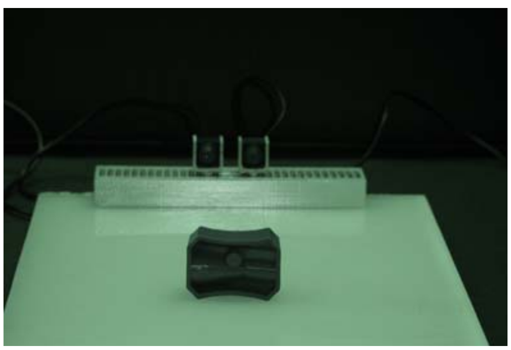


Figure 15: The test set-up for determining the optical basis. The two cameras are mounted in the aluminium fixture with objects in front. The 3D was displayed by HMD.

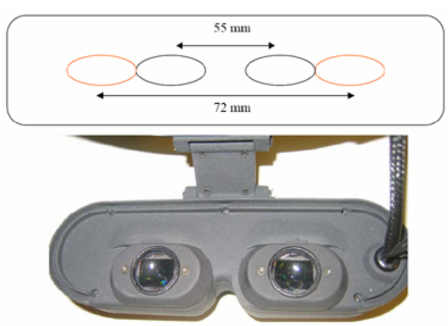


Figure 16: Trivisio 3-scope head mounted display (HMD) for 3D viewing. The inter-papillary distance could be varied from 55 mm to 72 mm.

Another experiment was conducted to assess the effect of convergence angle of the camera-pair. The setup for this is shown in Figs. (17-18) where a different slotted aluminium piece is shown. This, as shown in Fig. (17) accommodates the cameras in different rotated configureations to vary the convergence angle. This experiment was not successful because the angular range of the cameras was very small. Consequently, for a rotation of 2º-3º, the left and right images got separated at the close distances used here.

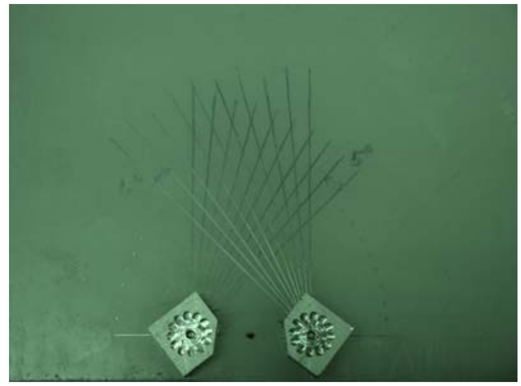


Figure 17: Slotted aluminium fixture for positioning the cameras in configurations of different convergence angle.

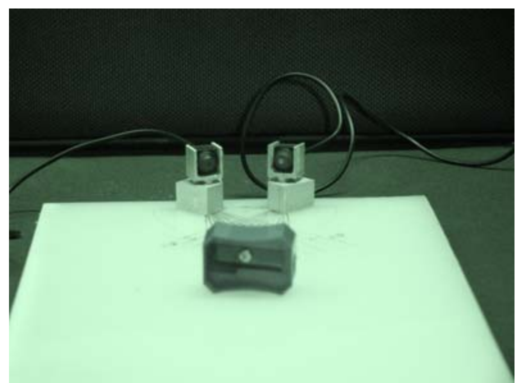


Figure 18: The set-up for viewing 3D images through cameras set at different convergence angle.

4.2 Test set-up for simulated surgical tasks

Four simulated surgical tasks were chosen. The first is the pick-and-place task wherein a ring is to be picked up with a laparoscopic gripper and placed on a cylindrical post. The second is the peg-in-a-hole task. The third is to pass a loop through rings, which were movable around a post themselves. The fourth task is to tie a knot as an imitation of suturing. To perform these tasks, a card-board box was constructed to simulate the abdomen (Fig. (19)). A lamp was placed inside for proper illumination. The images captured by the two cameras were input to the HMD that the subjects wore while performing the task. A laparoscopic tool was inserted through a hole in the cardboard box.

The subjects chosen for performing the aforementioned four tasks have had no experience in surgery. Figure (20) shows the snap shots of the four tasks. After performing the tasks, all of the subjects felt that the depth perception improved after moving the cameras away from each other until some stereo-base distance is reached. Over a range of 29–41 mm the subjects felt that the depth perception is remarkably good. They were also asked to do the tasks by looking at a 2D display on an LCD monitor tasks by looking at a 2D display on an LCD monitor rather than a 3D display on a HMD. Figure (21) shows the average time taken by all the subjects in performing each test task with 3D and 2D displays. As can be observed in the figure, stereo display did help. The time taken in the 2D display case would have been much higher if the subjects did not use tactile perception (by touching the cylindrical rod in task 1) to judge the depth. In the third task of passing a thread through a loop, 3D display helped the most.

Figure 19: The set-up of a cardboard box with interior illumination, cameras for viewing the interior, and a hole for inserting a laparoscopic tool.

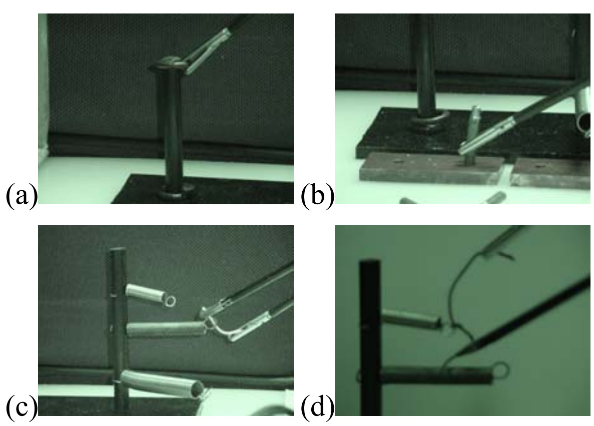


Figure 20: The four tasks performed by the subjects. (a) Picking and placing a ring on a cylindrical post, (b) peg-in-a-hole task, (c) passing a thread through the loop of an object, and (d) tying a knot.

In summary, the above experiments confirm that picture acquisition is an important aspect of stereo vision. However, the literature shows that most of the efforts in stereo laparoscopy are aimed towards picture presentation. In this paper, we have taken an alternative approach by considering the task of acquiring proper 3D images using two cameras. We required that the two cameras be separated by sufficient distance (i.e., adequate optical basis), which can be controlled. Additionally, the convergence angle was also made variable. These two are achieved by the foldable mechanism presented in this paper. Future work will improve the prototype to make it in real size rather than the current 2X size, and conducting experiments with real surgeons.

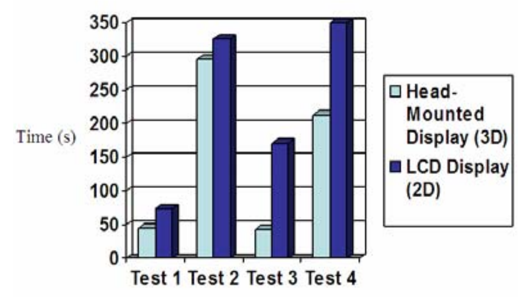


Figure 21: The histogram showing the average time taken by the subjects in performing the four test tasks with and without stereo vision. In all four cases, the stereo vision helped the subjects in performing the tasks in less time.

5 Conclusions

In this paper, we have presented the design, fabrication, and testing of a foldable mechanism for laparoscopic surgery. This work is motivated by the fact that most of the current efforts in providing stereo vision to laparoscopic surgeons are focused more on 3D display rather than image acquisition. In this paper, we show that optical basis (the distance between the two cameras) should be sufficiently large (29 – 41 mm) and should be variable. In current stereo laparoscopes, this distance is small (about 10 mm) and is fixed. The foldable mechanism of this paper can accommodate the two cameras so that their optical basis is large and can be varied as needed even during surgery. Furthermore, the mechanism can be collapsed into a tube of 15 mm diameter. A 2X prototype is made and tested with non-surgical subjects who performed four simulated surgical tasks with and without 3D vision. It was found that performance was better with 3D vision. Future work includes the construction of real scale prototype and further tests.

Acknowledgments

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