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NEW TECHNOLOGY

Initial trial of a stereoscopic, insertable, remotely controlled camera for minimal access surgery

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Abstract
Background Although video-laparoscopy has enabled successful minimal access surgery, the nature of the technology causes many troublesome limitations: (1) the fulcrum effect of the insertion site through the abdominal wall limits the angle of view, (2) the camera operator must use counterintuitive movements, (3) the laparoscope occupies an incision which otherwise could be used for an instrument, and (4) the laparoscope provides a two-dimensional image.
Methods A stereoscopic, insertable, remotely controlled camera was developed to overcome the limitations imposed by traditional video-laparoscopy. Additional functionality included digital zoom, picture-in-picture (PIP), and tracking capability for autonomous function of the camera. Four surgical tasks were performed twice in a porcine model, once using the insertable camera and once using a standard video-laparoscope setup for visualization. Running the bowel, simulated laparoscopic appendectomy, laparoscopic nephrectomy, and laparoscopic suturing and tying were measured for time, blood loss, and complications. Digital zoom, PIP, and the ability of the computer to move the camera to track a marked instrument were subjectively evaluated.
Results The tasks were aborted in one animal because a new three-dimensional (3D) display could not be synchronized with the camera and in another animal because a motor in the camera failed. The tasks were all completed twice in two animals. The mean time was less for all procedures using the insertable camera. There was no significant blood loss and there were no complications. Digital zoom and PIP displaying both a close-up and a panoramic view were subjectively felt to improve visualization by all observers. The computer could reliably move the camera to track a marked instrument to keep it in the center of the field of view.
Conclusions This preliminary proof-of-concept study suggests that a stereoscopic, insertable, remotely controlled camera may provide better visualization during minimal access surgery by overcoming many of the limitations of video-laparoscopy.

Keywords Human/robotic · Imaging · Virtual reality · Surgical · Computing · Minimal access surgery · Stereoscopy

Video-laparoscopy has enabled minimal access surgery, however, there are many constraints associated with the use of a standard laparoscope and video camera. Among these constraints are (1) limited mobility and limited angle of view caused by insertion through a small incision that acts as a fulcrum for movement of the laparoscope and camera, (2) requirement for counterintuitive movements by the camera-holding person and, hence, a significant learning curve, (3) requirement that the laparoscope occupy an incision for the duration of the operation, and (4) a two-dimensional (2D) image representing a three-dimensional

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(3D) space. In multiple previous reports by our group and others, investigators have documented development of an insertable, remotely controlled camera that would at least partially overcome the first three constraints [1–11]. In this report, we present the initial trial of a prototype camera that is stereoscopic, insertable, remotely controllable, and was designed to additionally address the fourth constraint.

Materials and methods

Device design

Our design goals in building this device were:

- Fully insertable into body cavity, leaving the insertion port free for other devices
- Diameter restricted to 15 mm for use with standard trocars
- Pan and tilt functionality to increase internal imaging angle of view
- 3D imaging to enable depth perception
- Intuitive control of the device
- Real-time response for pan and tilt functions to allow visual servoing and tracking
- User-friendly 3D display system
- Low cost and possible disposable use

The most significant improvement in this prototype over the devices described in previous publications is the addition of stereoscopy for the purpose of providing a three-dimensional image. The stereoscopic camera has the same shape, actuation mechanism, and physical properties as the monoscopic camera described in multiple previous publications [3–5]. Stereoscopy to deliver a 3D image was created by adding a second camera within the same housing (Figs. 1, 2, 3). Previous prototypes included integrated light-emitting diode (LED) lighting. This prototype did not include LED lighting because of cost and the fact that LEDs had worked well in previous prototypes and proof of concept had been established. Light for studies described in this manuscript was supplied by a laparoscope inserted through a secondary incision.

The new design, however, required a new personal computer (PC) with a different frame grabber to capture the videos and new software to control the pan/tilt motion, visual servo control, and digital zoom. The external diameter of the stereoscopic camera was 15 mm, designed so that it might be inserted through a 15-mm laparoscopic port, leaving only a small cable exiting through the port. The design was specifically developed to enable the use of the insertion port for other instruments during the course of an operation. The device contained two 6.5-mm charge-coupled device (CCD) chips and two motors as well as

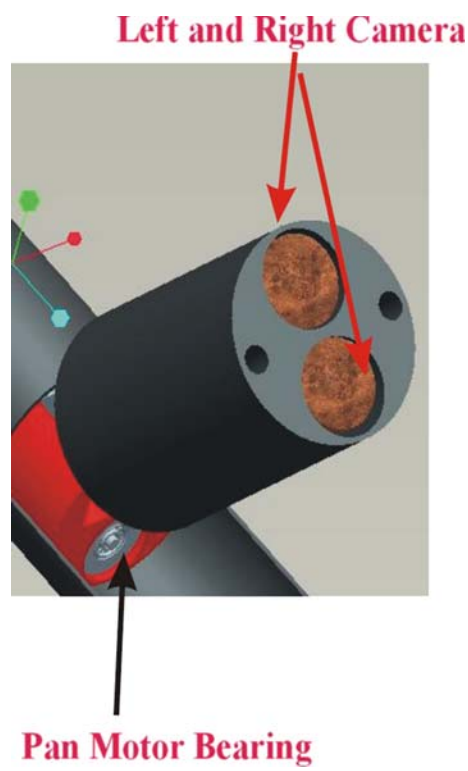

Fig. 1 Computer-aided design (CAD) drawing of the stereoscopic camera

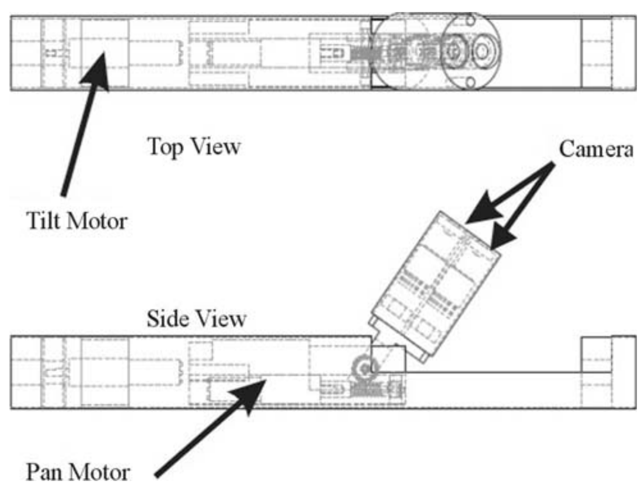

Fig. 2 CAD drawing of the pan/tilt capability of the stereoscopic camera

various screw drives, gears, and mechanical apparatus to actuate pan and tilt functions of the camera system. The cable contained wires to carry power to the motors and the CCD chips and wires to deliver the image data from the CCD chips out to a video-processing computer.

The computer was a standard PC (Intel Pentium III, 863 MHz, 384 MB RAM) with a Hauppauge frame grabber and a motion control board. The configuration consists of an open-loop control system and includes joystick

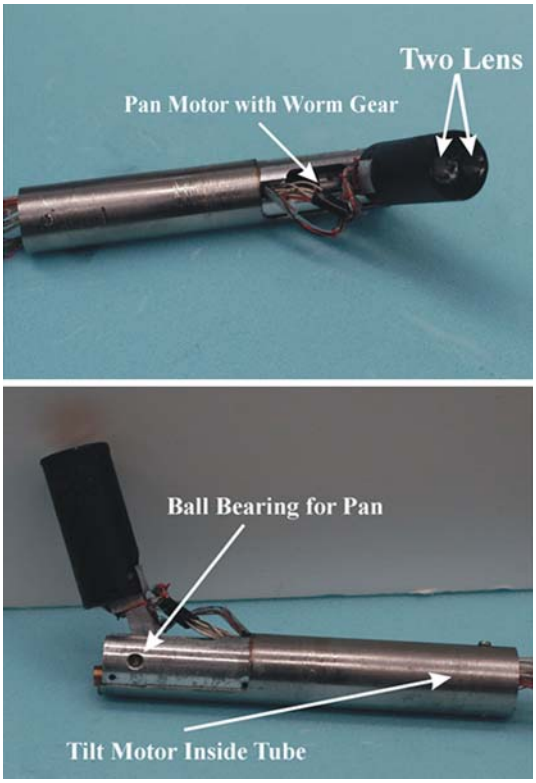

Fig. 3 Prototype stereo imaging device with pan/tilt axes

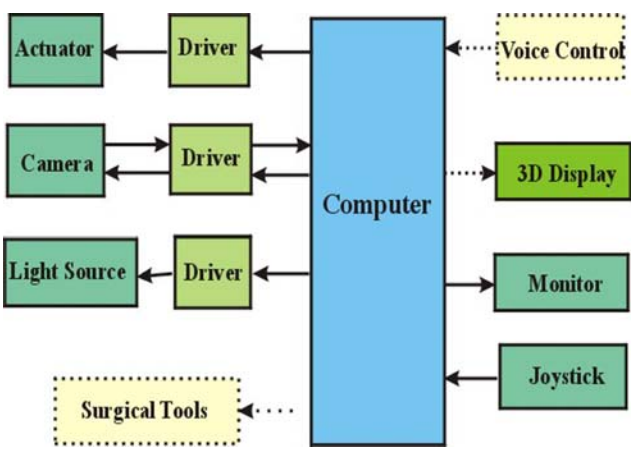

Fig. 4 System configuration of motorized camera for minimally invasive surgery

control, video display, pan/tilt motion control, LED light source control, and stereo display (Fig. 4). Our group developed the software for control of the devices in the system. In addition to joystick control of the movement of the camera, tracking software enabled the computer to keep the tip of a specified instrument within the center of the field of view without need for an assistant to control the movement of the camera.

Display of the 3D image required the use of a double-display system. For this study we used a rear projection display with two projectors, one for displaying the image from each of the CCD chips in the camera (Truevision, Inc., Santa Clara, CA). Surgeons and observers in the operating room wore simple, lightweight polarizing glasses to provide the image from the left camera to the left eye of the viewer and the image from the right projector to the right eye of the viewer. The result was stereoscopic imaging that added depth perception to the displayed image.

This rear projection system did require significant floor space (approximately 10 sq. ft. area) and may be too large for some operating rooms. However, there are available flat-panel displays capable of displaying equally high-resolution 3D images. The flat-panel displays still require lightweight glasses because, for any 3D system, delivering separate images to each eye is essential.

Software design focused on image manipulation capabilities including digital zoom, picture-in-picture, and image rotation. Since the digital zoom is controlled by software, a continuously variable zoom ratio is possible. Image rotation will enable the surgeon to establish a comfortable horizon.

Methods

After obtaining Institutional Animal Care and Use Committee approval to use ten female Yorkshire swine weighing approximately 30–40 kg, we scheduled a laboratory session with one animal each month using a prototype with the newest modifications each session. Because of the limited budget and the desire to maximize use of each animal, we frequently modified the construction and/or function of the camera after each session based on findings from that set of experiments. Improvements in camera design or function were then ready prior to the next laboratory session.

Each laboratory session was designed to include a total of eight operative procedures on the pig. Each of four types of procedures was to be performed twice, once with visualization using a standard laparoscope and video camera and once using the insertable, remotely controlled camera. The four specific procedures were: (1) running the bowel for 150 cm, (2) simulated laparoscopic appendectomy, (3) laparoscopic nephrectomy, and (4) laparoscopic suturing together of two loops of small intestine, including laparoscopically tying that suture with five knots. Objectively measurable parameters included time of procedure, estimated blood loss, and intraoperative complications. Subjective parameters included the perceived need for zoom, surgeon satisfaction, surgeon perception of image quality, limitations created by the image source, and observer perception of the image quality. Each operation was to be performed by the same experienced laparoscopic surgeon (D.L.F.), and the laparoscope and insertable camera were to be operated by the same novice individual (postdoctorate mechanical engineer or second-year medical student) for all the procedures in a given animal.

Additional functionality was tested as it was developed. In the studies with the stereoscopic camera described herein, digital zoom, picture-in-picture, and instrument tracking were also tested. Digital zoom and picture-in-picture were tested repeatedly as needed or desired during procedures using the insertable camera. The instrument tracking function was tested using blue, red, and yellow markers on the laparoscopic instruments to confirm functionality and to identify which colored marker functioned most reliably.

We conducted the first six laboratory sessions using a monoscopic camera, and the results of those studies have been published [5]. We conducted the remaining four laboratory sessions with a new prototype consisting of the two-chip version of the camera described above. Preparation for these sessions included research into and the acquisition of the stereoscopic display for use in the laboratory. We searched the Internet for available 3D displays and consulted with other research laboratories regarding their experience with types of stereoscopic displays before choosing the rear projection device.

Results

In only two of the four laboratory sessions in which the stereoscopic device was available did we complete all the surgical procedures as planned. In the other two animals, there were technical difficulties. In the first case, one of the motors in the device (which had been used in previous prototypes) failed during use, and we were then unable to pan, and, therefore, could not maintain adequate visualization. In another, we had arranged for the use of a new display, and the parameters of the interface between the display and the computer had not been synchronized. As a result, the image was so magnified that only a small portion of the needed field of view could be seen; completing the surgical procedures was impossible. In each case, we could not obtain meaningful data for comparison.

In two animals, the procedures were completed such that we could compare outcomes. In every case the procedure was shorter using the insertable 3D camera. Averages for the two procedures with each image source are presented in Table 1. Despite the shorter times, the surgeon subjectively felt that the times were longer with the insertable camera. Nonetheless, he felt that the stereoscopic image was very helpful, particularly when tying knots. This was most noticeable when suturing first with the stereoscopic camera and then subsequently with the laparoscope. In the latter situation, suturing while using the 2D image of the laparoscope seemed more difficult. There was no blood loss or other complication in any animal.

The use of zoom was highly desirable, probably even essential. The use of picture-in-picture was subjectively felt to be of great value, particularly for displaying both a panoramic and a close-up view simultaneously. When testing the tracking system, the computer could reliably control the movement of the camera to keep the selected instrument in the center of the field of view. A tag with the color blue on it appeared to be the most reliable marker. The surgeon, assistant, and observers all felt that the stereoscopic image was desirable and useful; however, they all subjectively interpreted the image as less clear with the insertable camera, although not prohibitively so. No-one participating in the study felt that the image limited performance of the procedure.

Discussion

This was a preliminary, proof-of-concept study using a prototype camera for minimally invasive abdominal surgery. The camera was insertable, remotely controlled, and it was the source for displaying a stereoscopic image. The entire project was needs based. The camera project is the first phase of a longer-term project for which we have

Table 1 Outcome parameters comparing use of insertable, remotely controlled stereoscopic camera with standard laparoscope and attached video camera

Time (mm:ss)			EBL		Complications	
Procedure	Camera	Laparoscope	Camera	Laparoscope	Camera	Laparoscope
Running the bowel	4:25	6:51	0	0	0	0
Laparoscopic appendectomy	1:36	2:06	0	0	0	0
Laparoscopic nephrectomy	10:17	11:58	0	0	0	0
Laparoscopic suturing	2:31	3:53	0	0	0	0

EBL estimated blood loss

assembled a multidisciplinary team consisting of one or more representatives from each of the following disciplines: surgery, mechanical engineering, and computer science. Our development of the device included design and construction as well as creating the software for control of the device. There are several novel functional aspects of this device. First, the camera is movable within the abdominal cavity. Second, control of the camera is intuitive. Third, the camera is the source for a stereoscopic image. Fourth, using software, the image may be manipulated in real time with digital zoom, picture-in-picture or rotation. Fifth, the camera does not occupy an incision during the procedure.

The surgical procedure begins by inserting the camera into the abdominal cavity and fixing it to the abdominal wall. In the case of this prototype, the camera can pan 120° and tilt 180°. Additional movement such as translation is possible, but was not designed into this prototype. The camera is controlled either with a joystick or with tracking software. Voice control is possible, but that also was not included in the software for this prototype. If the camera is controlled using the joystick, the camera movement mimics the movement of the joystick, i.e., moving the joystick to the right pans the camera to the right. If tracking software is used, the camera becomes an autonomously functioning image source and the surgeon may choose an instrument or an anatomic feature that the camera will keep in the center of the field of view.

Stereoscopy to deliver a 3D image required the use of two CCD chips within the device. Chips that were 6.5 mm in diameter were used because, at the time of design, they were the most affordable chips available with at least 640 × 480 resolution. The "interpupillary" distance of 6.5 mm and the outside diameter of the camera of 15 mm were dictated by the size of chip that we used. The current 15-mm prototype will pass through a commercially available 15-mm port. When affordable, smaller, high-resolution chips become available, the "interpupillary" distance and the overall size of the device may be reduced. We do not know at this time whether the advantages of 3D imaging will justify a larger incision compared with a smaller incision and 2D imaging.

Stereoscopy also required the use of a more complex display than just a simple cathode-ray tube (CRT) or flat-screen display. Although we used a double-projector rear projection system with polarized glasses for observers, other 3D display systems are available, including 3D flat-panel displays (also requiring polarized glasses) and head-mounted displays. Although some observers in the room during our laboratory sessions used head-mounted displays, the surgeons used the rear projection display while wearing the polarized glasses when performing the experimental procedures. The use of digital imaging enabled the creation of software to enable a digital zoom feature. With this software, the use of zoom did not result in reduction of the brightness of the image. Another specific functionality associated with this capability was the ability to display simultaneously as a picture-in-picture image the close-up, zoomed-in view and the panoramic, zoomed-out view. Either image could be displayed as the smaller picture-in-picture image.

The final novel functional aspect of the camera may be potentially the most important to a patient. The camera is inserted completely into the body cavity with only a small cable exiting through a port. This leaves the port available for inserting other instruments during the procedure, resulting in one fewer incision than typical laparoscopic port configurations.

The potential clinical advantages of these functional advances include (1) a 3D image, (2) a reduction of the number of incisions required to complete a procedure, (3) a reduction of the number of personnel required to complete a procedure, (4) a better angle of view because of mobility of the camera, and (5) less frustration with inadequate visualization caused by either a poor angle of view or an inexperienced camera operator.

As has been reported previously [12, 13], this study suggests that 3D imaging can enable faster laparoscopic procedures when precise, fine movements are needed, such as when tying suture laparoscopically. This study is too small to draw conclusions confirming these benefits. However, the work is encouraging in that the device appears to deliver a useful stereoscopic image that can be controlled intuitively by a novice or by the computer. In the past, surgeons and other surgery personnel have been unable to use some types of stereoscopic imaging systems for long periods of time because of subjective symptoms analogous to motion sickness, such as headache or nausea. Our procedures lasted 3 h or less and consisted of intermittent stereoscopy and monoscopy. Although none of the investigators experienced any of these undesirable symptoms, exposure to stereoscopy may not have been long enough to evaluate for these phenomena.

The most widely used endoscopic 3D imaging system is associated with the da Vinci robot (Intuitive Surgical, Inc., Mountain Valley, CA). In this system the 3D imaging is provided in a console located remotely from the surgical patient, and the surgeon views the images on two separate displays within the console. This system requires that the surgeon be at the console and not at the side of the patient. Side-effects from this 3D imaging for the surgeon have been minimal, although it is unclear whether placing the surgeon at a site remote from the patient is an advantage or a disadvantage.

A few small engineering challenges remain before proceeding with broader preclinical and clinical studies.

For reasons of cost and time, this prototype did not include integrated lighting. In previous studies using a monoscopic camera system, integrated lighting with a circle of small light-emitting diodes around the periphery of the end of the lens resulted in satisfactory illumination. We believe that this lighting system would work well with the stereoscopic camera and it will be included in future prototypes. In the current study, the camera was held to the abdominal wall with two sutures. Although this is a workable method of fixation, additional methods are under development and study. The goal would be to have a defined, quick, and reliable method for insertion and fixation. Although we had no instances of fogging of the lens after the camera was fixed to the abdominal wall, the ability to clean the lens easily and quickly will be important. We are designing a lens spray system similar to those used on flexible endoscopes for future prototypes.

We do not believe that a small cable that is 2 or 3 mm in diameter will impair use of the port for other instruments; however, a wireless version of the camera seems desirable. The biggest challenge for making it wireless is power. Power is necessary for lighting, image collection at 30 frames/second, transmission of the image out of the abdomen, and activating the motors for movement. Providing power without wires is possible with either the use of a battery or a wireless method of delivering or generating power within the abdomen. Both methods are under exploration, not only for this project, but for multiple applications, many of which are not related to surgical devices.

Finally, the best display will need to be identified. The display that we used may be too bulky for routine use in an operating room. For monoscopic versions of the insertable camera, any currently used display will be appropriate. For the stereoscopic camera, however, a flat-panel three-dimensional display combined with lightweight polarizing glasses seems like the best solution, both ergonomically for the surgical team and for reasons of optimal space utilization in the operating room.

Reports of the use of in vivo robotic devices in animal studies now include urologic cases [14]. Although initial designs were primarily for intra-abdominal procedures using typical laparoscopic access sites, more recent studies have reported the development of devices for intralumenal use [15], which then potentially enables natural orifice access for intra-abdominal surgery [16–18]. Clearly some surgeons believe there is great potential for robotic devices, including in vivo robotic devices, to improve the technique of surgery [19]. The general acceptance of a simple robot such as this will depend on the value proposition of improved surgical performance relative to the cost of the devices. These devices are likely to be less expensive than current laparoscopic systems that require a laparoscope, a light source, and a light cable in addition to a camera. Ultimately, adoption of technology such as this will depend on the value and benefit to the patient, the surgeon, and the surgical team.

Conclusion

We have completed a preliminary proof-of-concept study using a prototype stereoscopic, insertable, remotely controlled camera for minimal access surgery. These preliminary results suggest that this device can provide imaging for minimal access surgery in the abdomen. This camera platform may provide several benefits over typical laparoscopic imaging; however, larger trials with multiple surgeons will be necessary to define its use in clinical surgery. The development of this camera platform is only the first phase in the development of insertable platforms that contain not only imaging devices, but also other sensors and tools for surgery.

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