In-Vivo Stereoscopic Imaging System with 5 Degrees-of-Freedom for Minimal Access Surgery

Andrew MILLER, Ph.D.[†] Peter ALLEN, Ph.D.[†] Dennis FOWLER, M.D.[‡]
[†]Dept. of Computer Science and [‡]Dept. of Surgery,
Columbia University, New York, NY

Abstract. Endoscopic imaging for minimal access surgery has many limitations that include: 2D and narrow angle imaging, limited workspace of the endoscope caused by the fulcrum effect of the body wall, and the presence of the endoscope in the incision that prevents use of the incision for other instrumentation. We have designed a novel stereoscopic 3D imaging device with 5 DOF and remote control that can be inserted and attached in the body cavity. The device, contained within a 11/16" tube, includes two miniature cameras and five small motors that position the cameras to provide a stereoscopic view of the surgical site. When inserted the cameras are retracted and protected by an outer shell. After the device is fixed within the abdominal cavity, a motor rotates an inner shell to expose the cameras. Once exposed, the cameras can tilt in tandem, translate independently along the axis of the tube, and independently pan. The software controls the cameras to create new views for the surgeon, to move along the adjustable baseline, to verge for stereoscopic viewing, and to potentially track moving organs. We have completed a proof of concept design, which includes CAD models and animations of the device, and we are currently building a physical prototype. Once the prototype is completed, we will begin testing it in a surgical mock-up, followed by animal and clinical trials.

1. Introduction

The goal of this project is to enhance and improve surgical procedures by placing small, mobile, multi-function platforms inside the body that can begin to assume some of the tasks associated with surgery. Our aim is to create a feedback loop between new, insertable sensor technology and effectors we are developing, with both surgeons and computers in the information-processing/control loop. We envision surgery in the future as radically different from today. This is clearly a trend that has been well-established as minimal-access surgical procedures continue to expand. Accompanying this expansion has been new thrusts in computer and robotic technologies that make automated surgery, if not feasible, an approachable goal. It is not difficult to foresee teams of insertable robots performing surgical tasks inside the body under both surgeon and computer control. The benefits of such an approach are well documented: greater precision, less trauma to the patient, and improved outcomes. One factor limiting this expansion is that the laparoscopic paradigm of pushing long sticks into small openings is still the state-of-the-art. While this paradigm has been enormously successful, and has spurred development of new methods and devices, it is ultimately limiting in what it can achieve. Our intent is to go beyond this paradigm, and remotize sensors and effectors into the body cavity where they can perform surgical and imaging tasks unfettered by traditional endoscopic instrument design.

Minimally invasive surgical procedures have dramatically reduced patient recovery times but at the cost of increased complexity for surgeons. Since the surgeon is generally working with both hands holding other instruments, an assistant is necessary to hold the endoscope steady and move it as required. Recent work in robotics has sought to automate that task. One commercially available system called AESOP can orient a traditional endoscope using a robotic arm that is controlled by spoken commands [1]. While this takes the burden off the assistant and provides a much more stable image, it still occupies a large part of the operating room floor. A simpler robotic endoscope manipulator that can be placed directly over the insertion point was developed at INRIA [2]. However, neither of these systems addresses the fundamentally limited range of motion of the endoscope. The fulcrum point created by the abdominal wall restricts the motion of the scope to 4 degrees of freedom, so that the only translation possible is along the camera axis.

Our goal is to develop a robotically actuated, multi-camera system that can be inserted entirely within the abdominal cavity. In this way the insertion point will not limit the camera motions. If a camera and its actuators are small enough to fit through an incision, then using multiple cameras also becomes feasible. With more than one camera, we not only gain multiple selectable view points, but we can also use them as part of a stereo vision system that can be combined with a display system to recreate for a surgeon the sense of depth that is lost with a traditional video monitor. Once inserted, the device would need to be rigidly fixed to the interior abdominal wall to provide a stable base for the actuated cameras. After situating the device near the operation site, the cameras would be extracted, and they would look upon the area of interest.

To our knowledge, this is a unique concept. However, there are a few projects that have some similarities. One system uses a traditional rigid rod endoscope but adds a motor that rotates a 90-degree mirror at the end of the scope to provide an additional degree of freedom [3]. Another system is essentially a multi-link arm that positions a camera using piezoelectric actuators [4]. Theoretically this robot would provide many different viewing angles for an attached camera, but the authors provide no information about the safety of using piezoelectoric electric elements, and do not appear to have attempted any tests within living animals or humans. The pill camera [5] is an example of a camera that operates entirely within the body. It is able to image sections of the small intestine that an enteroscope cannot reach. However, it does not have any means of actuation and simply relies on peristalsis for locomotion.

2. Design

2.1 Design Considerations

The design of our device took into account a number of important factors. Of prime importance were deciding whether to use a mono or stereo camera setup, the number of degrees-of-freedom for the cameras, the imaging technology, remote actuation inside the body, and overall packaging for miniaturization. Figure 1 shows a schematic of the design and figure 2 contains images of the simulated device with cameras retracted for body cavity insertion and opened for imaging. An animated movie of the simulated device can be viewed at the website: http://www.cs.columbia.edu/~amiller/camera.

Mono or Stereo: Traditional endoscopes are monocular in nature and provide the operator with a 2-dimensional of the field of view. Some of the more recentrobotically assisted surgery systems, such as DaVinci [6] and Zeus [7], use a dual camera endoscope and a stereo projection system to provide a surgeon with a 3-dimensional image of the field of view. Research has shown the experienced surgeons have learned to use other cues such as shadows to perceive depth and compensate for the loss of the stereo perception in monocular endoscopes. Some have even found the 3D display systems distracting [8]. However, if the display system is unobtrusive, experienced surgeons as well as less experienced surgeons may find the natural depth perception provided by stereo cameras to be helpful.

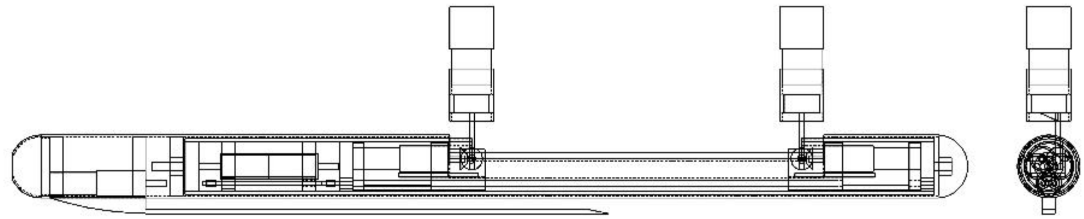

Figure 1: Design for an implantable imaging system with 5 motors and two cameras. An inner shell rotates within an outer shell, which is attached to the abdominal wall. Two shuttles translate independently along lead screws within the shell, and each carries a motor capable of orienting a camera.

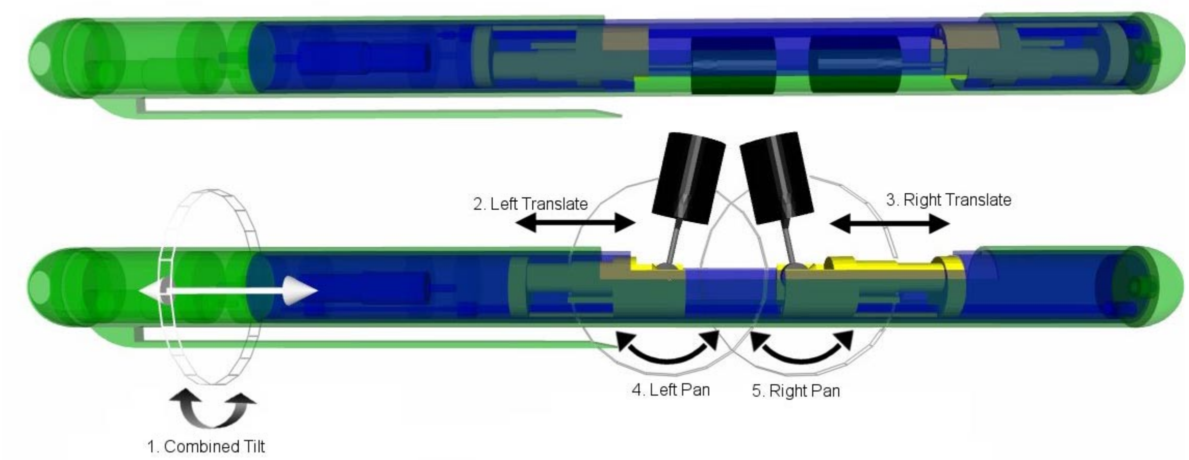

Figure 2: Images from a computer simulation of the device. The first shows the device before insertion, with the cameras retracted and the inner shell rotated 180 degrees to protect them. The second demonstrates the degrees of freedom of the system.

Additionally, with a stereo camera system we can use stereo visual servoing algorithms to control the camera or other instruments. The tradeoff in using multiple cameras is the additional complexity of the device and the additional cabling necessary for the extra camera. We designed a system that could work with either one or two cameras. Our first prototype will have one camera to ensure that we can actuate it properly and provide a good view of the surgical site. Once we have shown that, we will add a second camera to the device and create stereo imagery.

Degrees of freedom: A robot with a full 6 or more degrees of freedom (DOF) is ideal, but the restrictions imposed by the size of the insertion hole make designing such a robot extremely challenging. We have opted to initially restrict ourselves to a total of 5 DOF for two cameras to limit the overall complexity of the system, and as we gain experience with the device we will be exploring options for adding additional motions. Each camera can pan independently, which allows us to control the vergence angle of the stereo pair, but they tilt together about a common axis. This type of action is similar to the human visual system. Additionally, each camera can translate independently along a rail, which gives us a range of viewpoints and an adjustable baseline for stereo imaging. Axial zoom and rotation can be accomplished in software with image processing. The cameras can translate over a 5 cm range, and pan and tilt over a 90-degree angle.

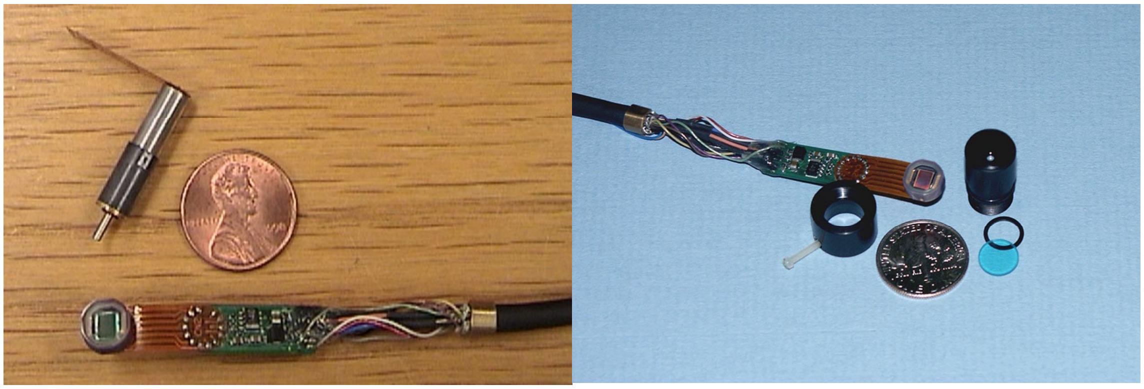

Figure 3: Left: The camera chosen for the device uses an 8mm round CCD package, and is attached to its board with a flexible ribbon cable making it possible to reorient. The motor is a 5mm brushless DC motor. It has a 625:1 gear head on it and will be used with 4 other motors to position and orient the cameras. Right: A 2.4 mm lens, lens mount and color filter.

Cameras: The first choice in selecting a camera was whether to use a CMOS sensor or a CCD. CMOS chips do not require the bulky drive circuitry needed by CCD chips, so they can be used as self-contained camera systems. However, because CMOS sensors have all of their control functions directly on the chip, the actual chip packages are larger than a CCD for a given image area. Additionally, the image quality of these small color CMOS devices has not yet reached the quality of an image produced by a CCD. For these reasons, we chose to look for a small remote head CCD camera that would allow us to move the CCD package separately from the rest of the circuitry. We chose the STC-R640 produced by Sentech. It uses an 8mm round CCD package containing a ¼" full resolution (768 x 494) color image sensor. The chip is connected to a small driver board using a 15mm flexible ribbon cable, and the driver board is connected to the camera control unit (CCU) with a 2-meter cable (see figure 3).

Actuators: We began our search for small actuators by exploring some of the more exotic devices. Piezoelectric actuators produce substantial force for their size, but require high voltages, which could be a potential risk for a patient. Pneumatic actuators are difficult to control precisely and may have difficulty maintaining a given camera position due to the air currents within an insufflated abdominal cavity, and solenoids with their combined sensing are still too large for the length of travel we need. Initially, shape memory alloys seemed promising since they are small, easy to clean and sterilize, and have been used in other medical devices. However, when activated they only contract about 4% of their length, and in order to use them as actuators, a sensor is required for closed loop control. Nanomuscle Inc. produces a linear SMA actuator that combines several strips of alloy with an encoder so that it can be controlled like a motor, but its dimensions are 38 x 6 x 5mm and it only has a stroke of 4mm. This would mean we would need a lever system to increase the total size of the motion.

Although many of these advanced actuation systems are becoming smaller and more efficient, similar developments can be found in the realm of traditional motors. On one extreme, Faulhaber has developed a brushless DC motor that is 1.9mm in diameter, but the torque output is too small for our application. Smoovy has developed a 5mm motor that has a variety of gear heads capable of producing torques within our desired ranges. The motor (shown in figure 3) is 27mm long, runs on 6V, and can be controlled in open loop fashion with a small controller board. To produce linear motion, the motor can be connected to a lead screw, which when rotated, can translate a carriage along its length.

Packaging: Our goal in designing a structure to house the cameras and actuators was to keep it smaller than 20mm in diameter, so that it would fit through a large size surgical port. Since the cameras must translate along one axis, the most natural shape for the device is a long thin cylinder, and because of the length of the motors, they all must be aligned parallel to the central axis of the cylinder. This is not a problem for two of the degrees of freedom because the tilting axis and the axis of translation are parallel to the central axis. However, the panning motion is about an axis orthogonal to this axis, so a method is required to redirect the motion of those motors. There are several possibilities, and we discuss our choice below. Given these restrictions, the device we developed consists of an outer shell, which is attached to the abdominal wall, an inner shell that rotates within the outer one, and two shuttles that translate within the inner shell (see figure 1). Each shuttle has one camera and one motor to control the panning of the camera. When the device is being inserted into the body, the cameras are contained within the inner shell, which is rotated 180 degrees from its normal operational position to protect them (see figure 2, top). After the device has been put into position within the abdominal cavity, the inner shell will rotate to expose the cameras, which will then pan 90 degrees to view the operational site. In the following paragraphs we present the design of the individual components by starting with the outer base shell of the robot and working our way in.

2.2 The Prototype Device

The outer shell of the device is a stainless steel tube that is 9/16" in diameter, 7.8" long, and has a wall thickness of 0.028" (see figure 1). It has spherical end caps to ease insertion, and the cabling emerges from the proximal end. The first motor, which controls the tilting motion of the cameras, is parallel with the central axis of the shell and is near the proximal end. This motor rotates an inner shell that contains both cameras and the other motors. A 2.6" long section of the outer tube is cut away at the distal end to allow the cameras to tilt 180 degrees when they are extracted. Our current method of attaching the device to the abdominal wall is to use a tiny, long rod, positioned in a manner similar to the pocket clip of a pen that will be inserted into the preperitoneal and/or fascial layers of the abdominal wall. By making this rod 1mm thick and 3mm wide, the trauma from this insertion will be insignificant. Another possibility we will be exploring when we are ready to test the device is to add small magnetic plates to the device and use magnets outside the body to hold the device against the abdominal wall.

The inner shell is another stainless steel tube that is 1/2" in diameter, 6" long, 0.028" thick, and it is mounted in bearings in the outer shell that are aligned with the central axis of the device. It can rotate a total of 270 degrees, so that the cameras can tilt 180 degrees when extracted, and they can rotate another 90 degrees when retracted to protect them during insertion. It houses two motors near the proximal end that rotate two lead screws, which control the translation of the cameras. A large portion of the distal end is cut away to allow the cameras to be extracted. This shell also has space for the slack cable of the proximal camera to coil when the camera is translated to proximal end. The camera cable for the distal camera runs at the bottom of the shell between the two lead screws above it.

The two shuttles each hold a small camera circuit board and one motor. They are mounted on the lead screws within the inner shell so that one hole in the shuttle is threaded and meshes with the threads of a lead screw, and the other hole is larger and allows the shuttle to slide along the other lead screw using it as a guide. The CCD package is mounted within a lens housing that has threads to match the threads of the lens so that focus adjustments can be made manually. The CCD and lens housing are mounted on a pedestal, which tilts about an axis that is orthogonal to the shuttle motor. To change the rotational axis by 90-degrees, we rely on a pair of bevel screws. Thus with the rotation of the inline motor, the camera can be retracted into the inner shell or extracted and panned.

Because of the ribbon cable connecting the CCD to the camera circuit board is not compressible along its length, the board, which rests under the motor, is allowed to move as the CCD rotates. The shuttles face each other so that when the cameras are extracted, we can achieve the minimum baseline of 10mm between them if necessary.

In addition to the insertable robotic device, the system also has a small control box that is exterior to the body and connected with a cable 2m long and 10mm in diameter. This cable consists of the two camera cables, which carry power and video, and 3 wires for each motor. The control box contains the power supply for the motors and cameras, the camera control unit, and the 5 motor controllers. It has three serial cable connections, two of which allow a computer equipped with the camera DSP software to control various functions of the camera. The other connection is for a joystick, which will be used initially to control the motions of the robot.

2.3 Software

An effective approach to controlling these cameras would be to use a hybrid controller, which allows the surgeon to control some of the degrees-of-freedom (DOF) of the device and an autonomous system, which controls the remaining DOF. For example, the autonomous system can control pan/tilt on the camera to keep a surgeon-identified organ in view, while the surgeon simultaneously may translate the camera to obtain a better viewing angle – all the while keeping the organ centered in the viewing field. We have developed hybrid controllers and mechanisms similar to this for robotic work-cell inspection [9] and believe we can transfer these methods for use with this device. Further, we have built a constraint-based sensor planning system that can reason about viewpoints of modeled objects [10,11]. The planner incorporates constraints on viewpoint visibility, depth-of-field and image resolution to plan correct viewing parameters and positions. We can incorporate this sensor planning function into surgical constraints on viewpoint to automatically plan where the cameras should be. This becomes particularly relevant when multiple camera systems are in use, and the surgeon has a choice of potential viewpoint. Once the control system is functional, we can implement real time tracking of organs or instruments at the surgical site [9, 12, 13].

Our initial experiments with the device will include testing on a surgical mock-up. This will allow us to perform initial experiments with the control and imaging software and receive feedback from clinicians. In parallel, we can also perform animal experiments that will be used to perform more stringent levels of testing, including packaging, insulation, and real-time vergence control.

3. Summary

We have completed the initial design of our imaging system and are currently building and refining the prototype device. Surgical mock-up and animal trials will be critical in evaluating how successful this device is. Additionally, while we are encouraged by the design's functionality and packaging size, there are still several tasks that need to be addressed:

- test different strategies for fixing the device to the abdominal wall
- evaluate the possibility of including a light source in the design
- evaluate the effects of different sterilization procedures on the equipment
- develop the human-computer interface software for the surgeon.
- evaluate ease of use and effectiveness as a tool for use in the operating room

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