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Abstract Robotic laparoscopic surgery is evolving to include in vivo robotic assistants. The impetus for the development of this technology is to provide surgeons with additional viewpoints and unconstrained manipulators that improve safety and reduce patient trauma. A family of these robots have been developed to provide vision and task assistance. Fixed-base and mobile robots have been designed and tested in animal models with much success. A cholecystectomy, prostatectomy, and nephrectomy have all been performed with the assistance of these robots. These early successful tests show how in vivo laparoscopic robotics may be part of the next advancement in surgical technology.

Introduction

The use of robotics is currently recognized as a major driving force for advancing minimally invasive surgery.[1–3] However, current surgical robots, such as the da Vinci system made by Intuitive Surgical, have several significant limitations. Although one recent report concluded that robotic surgery can enhance dexterity compared to traditional laparoscopy,[4] most studies suggest that current robotic systems offer little or no improvement over standard laparoscopic instruments in the performance of basic skills.[5–7] Current systems are also not available in most hospitals and remain constrained by limited sensory and mobility capabilities, and high cost.

Currently available surgical robotic systems are implemented from outside the body and will therefore always be constrained to some degree by the limitations of working through small incisions. Some work has been done to develop medical robots in which all (or most) of the device enters the body. The simplest such mechanisms have been maneuverable endoscopes for colonoscopy[8,9] and laparoscopy.[10] These devices have actuators that can turn the endoscope tip after it

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enters the body. However, support equipment such as power and control (and sometimes the actuators) remain outside the body.

More advanced in vivo robots have been developed to explore hollow cavities such as the colon or esophagus with locomotion systems based on 'inch-worm' motion that use a series of grippers and extensors,[11,12] rolling tracks,[13] or rolling stents.[14] These devices all use external power in the form of electricity and/or vacuum sources for locomotion.

Another approach is a completely un-tethered pill that is swallowed and passively passed through the entire gastrointestinal (GI) tract. One such commercially available device, called M2A from Given Imaging Ltd,[15,16] returns multiple (thousands) images as it naturally moves through the GI tract. However, because the device is entirely passive, it cannot be directed to image a particular location and the exact locations of the images are not known. Combined with the very large volume of images, the use of this device for diagnosis is difficult.

In order to improve visualization and task assistance in vivo robots are being tested in the abdominal cavity during laparoscopic procedures. The robots have been designed to be either mobile or have a fixed-base. They can now provide vision assistance through onboard cameras and task assistance with simple manipulators. The goal of this robot development is to place the robot completely within the abdominal cavity so that the entry incision does not constrain the motion of the robot. With such technology, the laparoscope port can be eliminated from many procedures as visual feedback will come from the in vivo robots that will be inserted through one of the tool ports. Current efforts are also focusing on task assistance. The eventual outcome will be a family of these robots that can be placed in vivo to assist surgeons, which will improve patient safety and surgical flexibility.

Robot designs

Fixed-base robots

To improve visualization for surgeons an in vivo robotic camera was developed. The first prototype developed was a pan and tilt robot (Fig. 1) that allowed the camera to pan 360 degrees and tilt forward and back 45 degrees. Two independent permanent magnet direct current motors were used to provide the actuation. LEDs were used to provide illumination. The tripod legs are spring loaded so that they can fold down during insertion and retraction. This camera robot was used during porcine surgery to remove a gall-bladder.[17] The additional views provided additional frames of reference and perspectives that were not available with the laparoscope alone. These additional camera angles augmented surgical visualization and improved orientation which proved useful to the surgeon while removing the pig's gall-bladder. This allowed the surgeon to have a better understanding of depth, improving safety and allowing the surgeon to plan and execute the procedure more effectively.

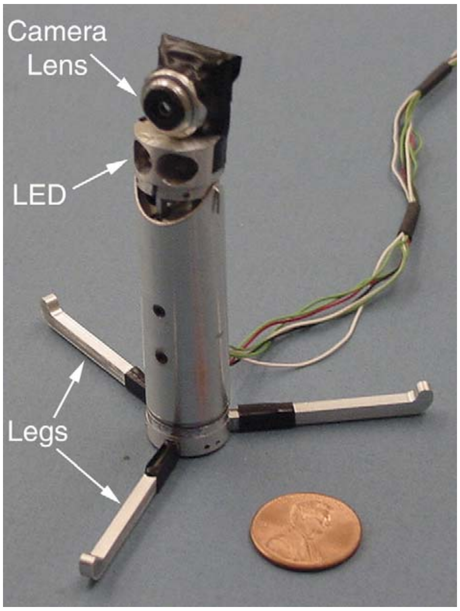

Figure 1 The pan and tilt camera robot can pan 360 degrees and tilt±45 degrees. Torsion springs allow the legs to be abducted after abdominal entry. LEDs provide illumination.

One drawback of the original pan and tilt robot design was a set focal length of the camera lens. The simple lens package allowed for a small footprint, but reduced flexibility in focusing at different distances inside the abdominal cavity. Therefore, the second generation design included an adjustable-focus mechanism that physically moved the lens to and away from the imager to vary the focal length. To maintain the same size constraints the pan motor was used for the focusing mechanism. Therefore, this tilting robot could tilt 45 degrees (Fig. 2). This tilting robot has LEDs for illumination. They are positioned at the end of an arm that folds down in front of the camera. The ring at the end of this arm is used for retraction. The bottom edge of the ring is seen in the camera view so that the surgeon can easily clamp onto it and retract the robot. The tripod legs and this retraction arm are both spring loaded for insertion and retraction.

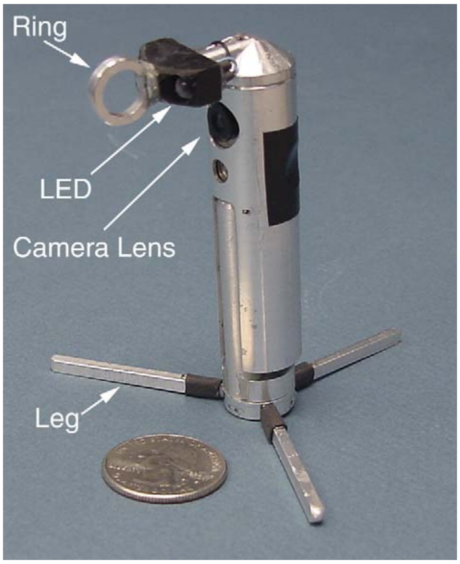

Figure 2 The tilting adjustable-focus camera robot can tilt 45 degrees. Torsion springs allow the legs to be abducted after abdominal entry. LEDs provide illumination.

Mobile robots

While the fixed-base robots work well to provide the surgeon with additional visual feedback, mobility is important for tissue manipulation. Such a mobile platform can also provide visual feedback while navigating the abdominal cavity. This type of camera robot works well for exploring the abdominal cavity. These mobile in vivo robots need to traverse the abdominal organs without causing tissue damage. Mobility is difficult because the environment is slick, hilly, and deformable. Much effort was placed on developing a wheel design that provided sufficient traction without causing tissue damage.[18] The wheel design was improved through viscoelastic modeling, laboratory experimentation, and in vivo testing. The final wheel design incorporates a helical corkscrew treaded wheel as shown in Fig. 3.

To demonstrate the practical applicability of this approach to surgery, the successful wheel design was used to create a wheeled robot with an adjustable-focus camera (Fig. 3). This mobile robot has two wheels each connected to an independent motor. This allows for forward, reverse and turning capability. The tail prevents counter-rotation while the wheels are actuated. The camera lens is located between the wheels as shown in Fig. 3. A third motor is used to adjust the lens position and focus depth.

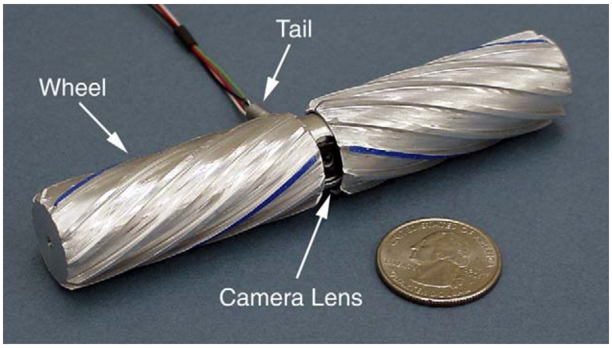

Figure 3 The mobile adjustable-focus camera robot has two independently driven wheels that allow for forward, reverse and turning motion. A small tail prevents the counter-rotation.

This mobile robotic camera system was tested in vivo in a porcine model, and used to explore the abdominal cavity. It also provided the only visual feedback used by a surgeon during a cholecystectomy.[19] By inserting such a mobile camera robot into the abdominal cavity through one of the standard laparoscopic tool ports, the traditional third camera port could be eliminated. This would reduce patient trauma, and has the potential to improve laparoscopy compared to current systems.

A mobile camera and biopsy robot has also been developed (Fig. 4). This robot includes the adjustable-focus camera mechanism, with the ability to biopsy soft tissue. This robot produces sufficient clamping force to sample tissue, and sufficient traction force to retract the tissue sample if it is not completely severed.

Animal surgery results

The tilting adjustable-focus camera robot was used recently to successfully remove a canine prostate and kidney. The robot was placed on the

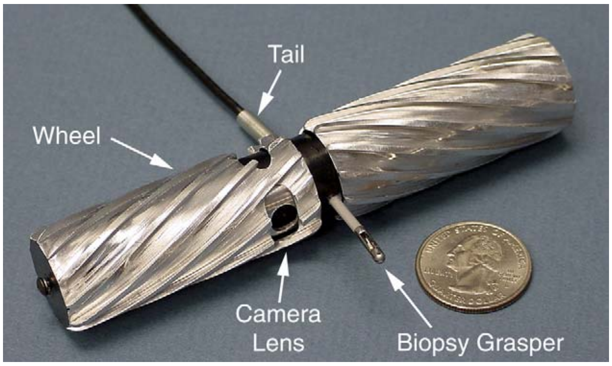

Figure 4 The mobile camera and biopsy robot implement the successful helical wheel design. This mobile platform can both be used for visual feedback and tissue manipulation.

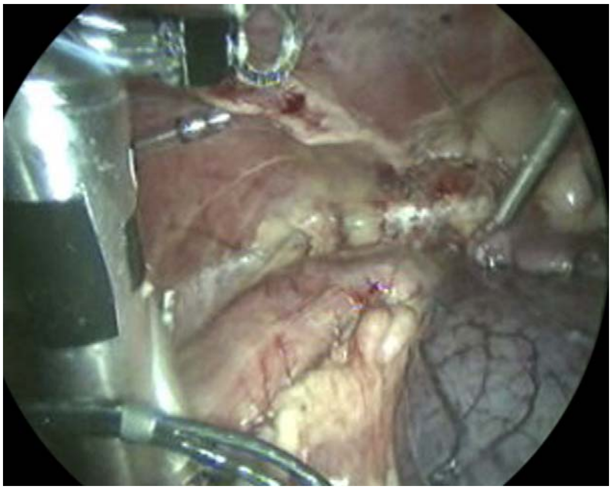

Figure 5 The tilting camera robot observing the prostatectomy. The video feedback from the tilting robot was used exclusively during portions of the surgery.

opposite side of the prostate (Fig. 5), away from the laparoscope. This provided the surgical team with two views of the prostate (Fig. 6), one from both sides. This proved extremely useful while suturing the urethra after the prostate removal. During several portions of the surgery the view from the robotic camera was used exclusively for visual feedback.

The ability to attain a good laparoscope position during urological procedures is often difficult. Using the in vivo camera robots, the view can easily be changed by remotely controlling the robot. Such a robot could be used extensively by urologists operating in the pelvic cavity. These robots could provide additional alternate views for the surgeon, or could in fact provide the sole visual feedback.

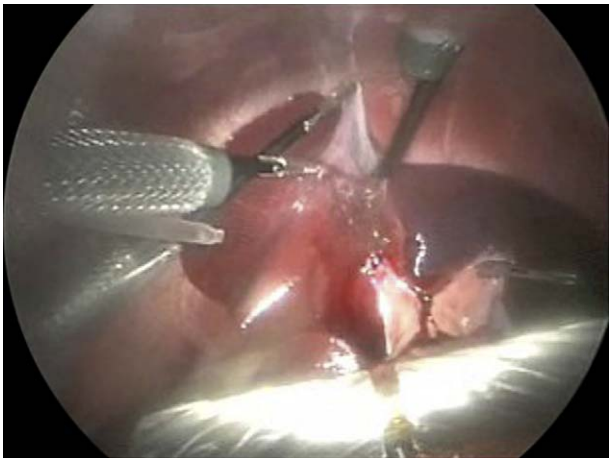

Figure 7 The view from the laparoscope during cholecystectomy with the mobile camera robot.

Three trocar ports were used for the cholecystectomy performed with the mobile camera robot. The robot was inserted through one of the tool ports. After insertion, this port was used for tool insertion. The second port was also used for tool insertion, while the third port was used only for the laparoscope. The laparoscope provided lighting for the robot's camera, but the surgeon did not use visual feedback from the laparoscope during the procedure (Fig. 7).

A cholecystectomy was performed with this mobile camera robot providing the only visual feedback available to the surgeon (Fig. 8) (i.e. the video from the laparoscope was not viewed by the surgeon). The ability of the robot to tilt the adjustable-focus camera 15 degrees without changing the position of the wheels proved extremely useful while retracting the liver. The adjustable-focus capability of the camera system allowed the surgeon to have a better understanding

Figure 6 A view from the tilting robot while suturing after the prostate removal.

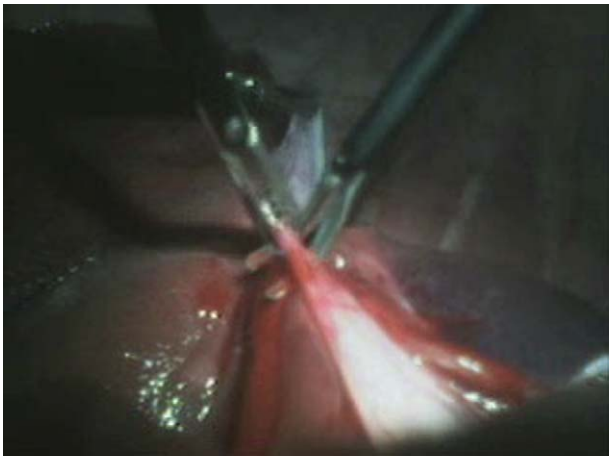

Figure 8 The view from the mobile camera robot during the cholecystectomy.

of depth. The mobile robot also proved very useful for abdominal exploration and observation of trocar and tool insertion.

This cholecystectomy demonstrated the effectiveness of a two port procedure with visual feedback only from the mobile camera robot. This shows that the designated laparoscope port may be eliminated and only two ports may be required for most procedures. The ports could be initially used for robot insertion and then for tools. If the laparoscope view was ever needed for assistance with robot placement it could be inserted through one of the tool ports until the robot was correctly positioned.

Discussion

These tests have demonstrated that it is possible to perform a common laparoscopic procedure using an in vivo camera system as the sole source of visual feedback. This has the potential to reduce patient trauma by eliminating the need for a camera port and instead inserting in vivo camera robots through one of the tool ports. While the initial prototype was slightly larger than a traditional trocar, future robots will be smaller in size, have no tethers, and will incorporate additional sensors.

Miniature in vivo robots will be far more agile inside the abdominal cavity than the current generation of large and expensive external telemanipulators. Current laparoscopic robots are bulky, unwieldy and cannot be easily transported. Because of their cost, they are typically designed for multiple surgical procedures with interchangeable instrument arms. Future miniature robots may be designed for each specific task. Because they are small, multiple robots can be employed simultaneously. Although in the future it might be possible for such robots to perform the entire procedure, current technology is more appropriate for the robots to be used as assistants during surgery, aiding in visualization and micromanipulation. Equipped with additional sensors they will also be able to explore and provide tissue diagnosis.

The long-term goal of this work is to create a team of in vivo robots that could serve as surgical assistants and/or replace traditional laparoscopic tools. The successful animal trials show the great promise for in vivo robotics, and the projected outcomes have the potential to make important advancements in minimally invasive surgery.

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