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In vivo laparoscopic robotics

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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.

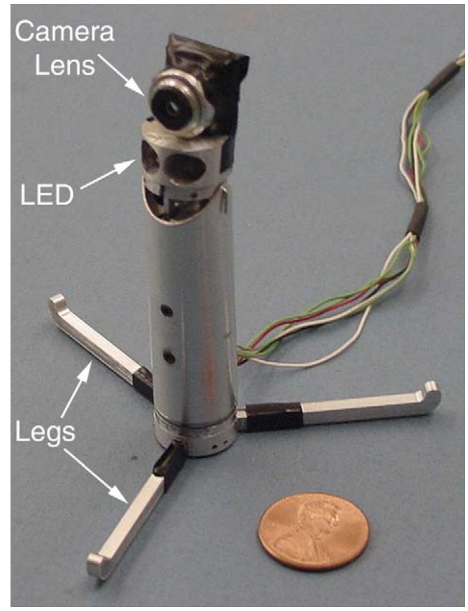

Figure 1 The pan and tilt camera robot can pan 360 degrees and tilt±45 degrees. Torsion springs allow the legs to be abducted after abdominal entry. LEDs provide illumination.

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.