Development of a Low-Cost Inspection Arm to Map the Available Workspace Within the Abdominal Cavity

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1 Background

Laparo-Endoscopic Single-Site surgery allows surgical procedures to be carried out with a single incision, resulting in quicker patient recovery, less risk of infection, and less cosmetic damage to the patient. This method of surgical operation can be carried out via laparoscopic tools, or by small in vivo robots controlled by a surgeon. Either way, it is important to understand the available workspace in order to correctly size tools or in vivo robots to the task at hand. Incorrectly sized tools can harm patients and are difficult to use. Furthermore, it is important to know the position of specific organs with respect to fixed reference points, such as laparoscopic ports. To collect this data in vivo, a 5 degree of freedom (DOF) inspection arm was constructed that is compatible with standard laparoscopic ports. Using this arm, preliminary data was collected from an abdominal model at the University of Nebraska-Lincoln (UNL) mock surgical suite, and the capability of the inspection arm was also assessed.

There are many ways to map an area or 3D space to computer aided modeling software. Methods of mapping can be considered in two categories: with contact and without contact. Without contact, mapping can be accomplished using a line-laser and receptor [1]. To effectively map an object using this technique an object is placed against two intersecting plates, affixed with calibration module. A simple camera is placed viewing the object against the calibration module, and a line laser is shined across the object. Then, a computer calculates the distance to each point of the object based on intensity of laser light as seen by the camera. These points are put into a cloud, and as the camera rotates about the object, or vice versa, multiple point clouds are generated. An algorithm is used to combine partially overlapping point clouds and a model is generated from the combined overlap. This method generates thousands of points in seconds, but has low precision because there is error involved in dynamically generating coordinate system transformations while the relative velocity between the object and the camera is nonzero.

With contact, mapping can be achieved using a kinematically determinate arm to trace an area or object. With this method, the user physically traces an object or area with the end affecter of an arm, while angle sensors at each joint send data back to a computer many times a second. Then, the position of the end affecter is easily determined mathematically as the arm travels through space, generating a point cloud. Such arms have been used to examine gallstones [2], while attached to a cystoscope, but data was limited to several points for rough geometrical calculations. Because such an arm is kinematically determinate, it is highly accurate. Increasing rigidity of the arm's links, obtaining precise measurements of arm lengths, and decreasing play between joints help to keep the arm consistent with a mathematical model, keeping accuracy high.

2 Methods

A low-cost contact-style mapping device was developed based on the available methods for entering an insufflated abdominal cavity, Fig. 1. The inspection arm was constructed using modular revolute joints with high-resolution optical encoders (8192 pulses per revolution). The modular joint design greatly reduced the manufacturing cost, and allowed multiple kinematic configurations of the arm. The modular joints were joined using Commercial-off-the-Shelf (COTS) shoulder bolts and structural tubing. Multiple probes can be secured to the arm such as a laparoscopic tool, various ball diameters, and curved extensions. The inspection arm can then be mounted to any standard bedside rail. The arm's kinematic configuration was based on the kinematics of the FARO Technologies Inc. FARO Gage arm with the first DOF fixed. A National Instruments Compact Rio was used to sample each joint's position sensor at 40 Hz.

3 Results

The inspection arm has gone through rigorous benchtop testing to assess the capabilities of the arm. Testing required the arm to trace a two dimensional (2D) path. A 2D path was selected, instead of a 3D path, to simplify comprehension of results. This

Fig. 1 5 DOF Inspection arm that was developed to map the available workspace of the abdominal cavity for surgical devices such as in vivo surgical robots

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Fig. 2 A path was cut into a piece of basswood using a laser cutter, secured inside a peritoneal training model, and was traced

path, shown in Fig. 3, was cut into a sheet of basswood using a laser cutter and secured to the back wall of a peritoneal training model. A webcam, not pictured, was used to provide visual feedback to the user during the tracing experiment. The tracing experiment was used to simulate the tracing of complex organs such as the colon or small bowel. The planar test setup is shown in Fig. 2.

To assess the drift of the arm, the end effector was held in place on a single point, and the arm's joints were rotated such that its links moved through space. The standard deviation along X, Y, and Z was calculated and found to be less than 6.35 mm (0.25″) along each axis, and as small as 2 mm (0.079″) along X. Also, a single 3D line was traced and the coefficient of determination was calculated for graphs of Z vs. X, Z vs. Y, and Y vs. Z. R^2 was found to be greater than 0.994 in each case and as high as 0.999 for Z vs. X.

These tests were performed in a mock surgical environment at the University of Nebraska-Lincoln. The surgical suite includes a surgical table with bedside rails and a peritoneal training model with a laparoscopic port inserted through the navel of the model. During testing in the surgical suite a laparoscopic tool was secured to the arm to increase ease of handling, and the arm was mounted to a bed side rail.

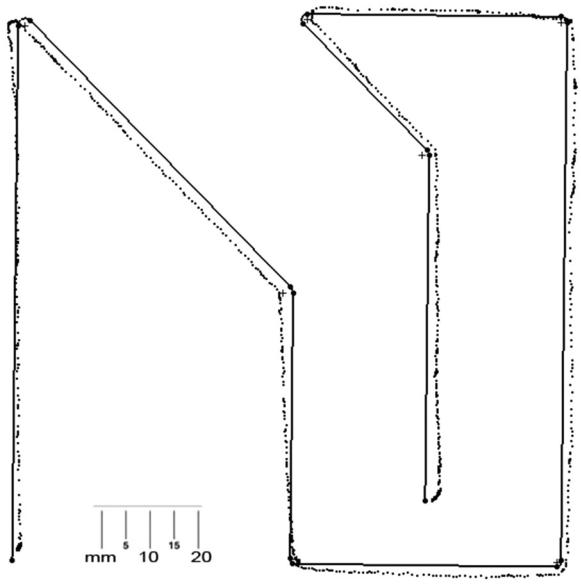

Fig. 3 The dotted path, traced by the arm's operator through a laparoscopic port, is superimposed over the actual path

4 Interpretation

The device was designed to be mounted to any bedside rail and be compatible with most commercially available minimally invasive ports to map and/or accurately locate the position of objects of interest within the abdominal cavity. The presented inspection device was shown to be a feasible method for generating a point cloud of objects within an enclosed environment during bench top testing. Multiple end effectors can be affixation to the inspection arm. Specifically the laparoscopic tool attachment further enables the use of the device for medical applications. The arm's modular design allows for easy reconfiguration of arm kinematics. Future work includes collecting in vivo abdominal traces in a porcine model at the University of Nebraska Medical Center (UNMC) to model the volume of an insufflated abdominal cavity. Such a model will improve understanding of available workspace for in vivo surgical robots.

References

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