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Design and prototyping of a handheld 3-DOF laparoscopic ultrasound manipulator for liver surgery

Hideyuki Sato[a], Kanako Harada[a]*, Jumpei Arata[b], Susumu Oguri[b], Shinya Onogi[b], Tetsuo Ikeda[b], Makoto Hashizume[b], and Mamoru Mitsuishi[a]

[a]*Department of Mechanical Engineering, School of Engineering, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8656, Japan*
[b]*Center for Advanced Medical Innovation, Kyushu University, Fukuoka 812-8582, Japan*

* Corresponding author. Tel.: +81-3-5841-6357; fax: +81-3-5841-6357. *E-mail address:* kanako@nml.t.u-tokyo.ac.jp

Abstract

Laparoscopic ultrasound offers noninvasive, real-time, and low-cost intraoperative monitoring of the intra-abdominal organs. However, because of the lack of degrees of freedom in the positioning of the laparoscopic ultrasound probe, it is difficult to align an ultrasound imaging plane with the longitudinal section of a blood vessel in the liver. This paper proposes a handheld laparoscopic ultrasound manipulator with three degrees of freedom designed to manipulate a miniature laparoscopic ultrasound probe. First, an ideal range of motion, measured using sensors and quantified as the required minimum range of motion of the laparoscopic ultrasound probe, was demonstrated by a surgeon. Thereafter, a double-bevel-gear mechanism enabling a pitch motion of ±40° and a yaw motion of ±30° and a wire-driven mechanism enabling a roll motion of ±60° were designed and implemented to the laparoscopic ultrasound manipulator with three degrees of freedom. A mechanism for assembling the miniature laparoscopic ultrasound probe with the shaft of the manipulator under a laparoscopic view was also designed to minimize the number and size of incisions in the abdomen. A prototype of the manipulator with a drive unit was fabricated and tested on an ultrasound liver phantom. A successful assembly, as well as successful visualization of the longitudinal section of a blood vessel in the liver model was demonstrated in a simulated laparoscopic environment. In future, the design will be revised, and the handheld laparoscopic ultrasound manipulator with three degrees of freedom will be tested for *in vivo* experiments.

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Keywords: Biomechatronics; Medical device; Design.

1. Introduction

Laparoscopic ultrasound (LUS) [1] is an intraoperative imaging modality that enables the observation of the internal structure of the intra-abdominal organs. Figure 1 illustrates the concept of conventional LUS imaging. A surgeon manipulates a LUS device with one or two deflection degrees of freedom (DOFs) to visualize the internal structures such as a vascular network. With such intraoperative visualization of the internal structure of organs, a surgeon can map the preoperative medical imaging information onto the deformable organs. Thus, LUS offers noninvasive, real-time, and low-cost intraoperative monitoring, contributing to accurate and safe operation.

In the detection of liver tumors, the longitudinal sectional view of a blood vessel is important to track the vascular network surrounding the liver and determine a cut line; however, the alignment of a small ultrasound imaging plane with the longitudinal section of a blood vessel is difficult and sometimes even impossible due to the lack of DOFs for positioning the LUS probe. Some researchers proposed the use of a surgical robotic system to manipulate a LUS probe [2-6]. However, the use of a surgical robotic system can be expensive for the target operation. A few other researchers proposed 2D or 3D navigation systems to facilitate the manipulation of conventional handheld LUS devices [7-12]. We propose to develop handheld multi-DOF LUS manipulators and investigate several possible designs

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including the one reported in [13]. This paper describes the design, development, and evaluation of the prototype of a handheld multi-DOF LUS manipulator designed for dexterous manipulation of a miniature LUS probe in the abdominal cavity.

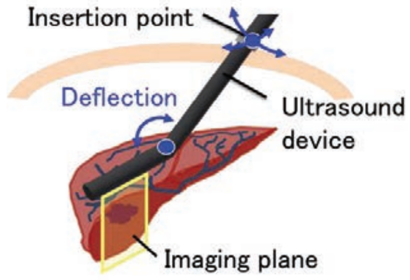

Fig. 1. Concept of LUS

2. Design and prototyping

2.1. Positioning of miniature LUS probe

This study employed a miniature LUS probe (UST-533, Hitachi Aloka Medical, Ltd., Japan). The handheld 3-DOF LUS manipulator was designed to implement three rotational DOFs namely, roll, pitch, and yaw as shown in Fig. 2(a). The implementation of the three rotational motions enlarges the ultrasound imaging range as shown in Fig. 2(b). The yaw motion is important to align the ultrasound imaging plane with the longitudinal plane of a blood vessel in the liver. The roll and pitch motions are more important to land the miniature LUS probe onto the liver surface. In the proposed scenario, the surgeon roughly positions the tip of the handheld 3-DOF LUS manipulator and then precisely controls the motorized 3-DOF motion using the handheld user interface of the manipulator.

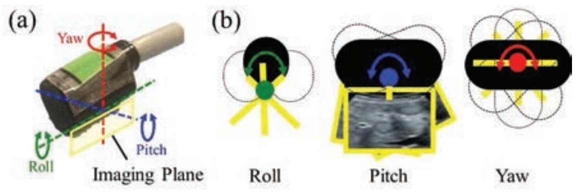

Fig. 2. Miniature LUS probe: (a) Implementation of 3 DOFs; (b) Imaging planes

2.2. Required range of motion

Although surgeons are aware of the lack of DOFs of LUS devices, there is no quantified requirement for the range of its motion. Therefore, an ideal range of motion of the LUS was measured by experiment in a simulated laparoscopic environment.

An ultrasound phantom of the intra-abdominal organs (IOUSFAN, Kyoto kagaku Co., Ltd, Japan) was placed in a box trainer (K-ZWEI ASC-1, B Braun Aesculap Japan Co., Ltd., Japan) as shown in Fig. 3(a). The liver model contained several tumor and blood vessel models that were visible in the ultrasound imaging. A sensor coil of an electromagnetic 3D position tracking system (trakSTAR, Ascension Technology Corp., USA) and an encoder (MES-9-300P, Extcom Inc., Japan) were mounted on the handle of a conventional LUS device with one deflection DOF (UST-5536-7.5, Hitachi Aloka Medical, Ltd., Japan) as shown in Fig. 3(b). The ideal range of motion of the LUS device was measured when the surgeon moved the tip of the LUS device on the liver model as he would in an actual liver surgery. In this experiment, the motion constraint at the insertion point (Fig. 1) was removed by opening the cover of the box trainer, and the surgeon demonstrated the ideal range of motion without any motion constraints by placing his hand in the box trainer to grab and move the tip of the LUS

The tracked motion of the handle was transformed to the tip's position and orientation data. The range of motion of the tip and the ratio of the use of each DOF were used as metrics to evaluate the ideal motion. The ratio of use of a DOF is defined as the ratio of the time in motion to the task completion time. Each DOF was deemed as in motion when a motion of more than 0.5° per 100 ms was detected by the sensors.

Figure 4 shows the experimental result. The range of motion of roll is -54.7°–53.3°, pitch -4.7°–19.6°, and yaw -25.6°–26.2°. The ratio of use of roll is 25.3%, pitch 9.1%, and yaw 20.9%. As observed, the roll and pitch motions were used to place the LUS probe on the surface of the liver model with the roll motion being used frequently. The yaw motion was used to align the ultrasound imaging plane.

Based on the experimental result and observation, the minimum range of motion required for the handheld 3-DOF LUS manipulator is determined as follows: roll: ±60°, pitch: ±20°, and yaw: ±30°. The importance of the three DOFs is in the order of yaw, roll, and pitch.

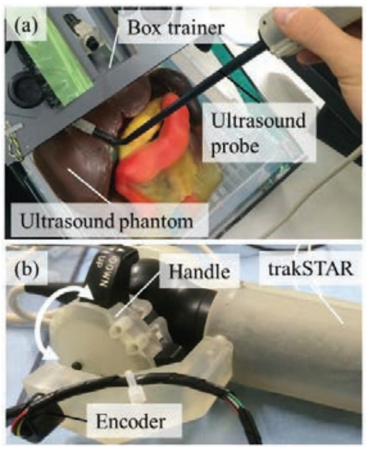

Fig. 3. Experimental setup: (a) US phantom in box trainer, (b) Implementation of sensors

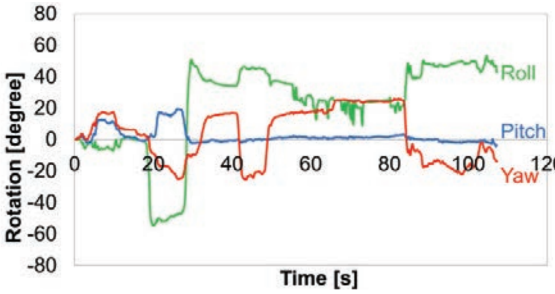

Fig. 4. Measurement of ideal LUS probe motion

2.3. Design and prototyping of 3-DOF LUS manipulator

Figure 5 shows the concept of surgery using the handheld 3-DOF LUS manipulator. To minimize the number and size of incisions in the abdomen wall, the handheld 3-DOF LUS manipulator employed a modular design. A 12-mm trocar accommodating the cable of the miniature LUS probe and a pair of forceps, a 5-mm trocar accommodating the handheld 3-DOF LUS manipulator, and a 10-mm trocar for the laparoscope are inserted through incisions in the abdominal wall, and the miniature LUS probe is assembled to the handheld 3-DOF LUS manipulator in the abdominal cavity under laparoscopic view. To realize this concept, the outer diameter of the handheld 3-DOF LUS manipulator needs to be 5 mm or less.

Based on the above constraint, the assembling mechanism of the handheld 3-DOF LUS manipulator was designed as shown in Fig. 6. First, the claw of the part attached to the miniature LUS probe (Fig. 6(a)) is inserted into the holes in the shaft (Fig. 6(b)). Next, the metal spheres attached to the pair of wires are inserted into the slits, and the wires are pulled to lock the spheres in the slits. These wires are used to actuate the roll motion.

Figure 7 shows the design of the 3-DOF mechanism to move the miniature LUS probe. The double-bevel-gear mechanism, originally designed for a pediatric surgical robotic device [14] and a neurosurgical robotic device [15], is used to enable the yaw and pitch DOFs (Fig. 7). The yaw and pitch axes intersect, which facilities intuitive manipulation by the handheld user interface. The range of motion of the pitch axis is -40°–40°, and that of the yaw axis is -30°–30°. The roll motion is actuated by pulling and releasing the wires in a synchronized manner and a range of motion of ±60° is achieved. The designed ranges of motion cover the minimum ranges of motion derived in Section 2.2.

Figure 8 shows the prototype of the handheld 3-DOF LUS manipulator. The drive unit of the manipulator incorporates four 10-mm-diameter bushed DC motors (DCX10L EB KL 6V, Maxon Motor AG, Switzerland), on each of which a planetary gearbox (GPX10 64:1) and an encoder (ENX10 EASY 128IMP) was mounted. A handle with three encoders, which functions as a handheld user interface, was developed and mounted on the manipulator (not shown in Fig. 8), and a control program was implemented.

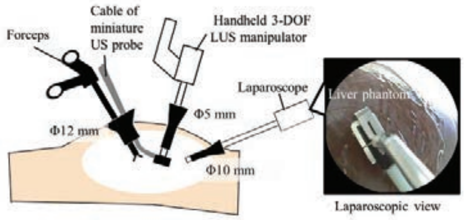

Fig. 5. Concept of laparoscopic surgery using the handheld 3-DOF LUS manipulator

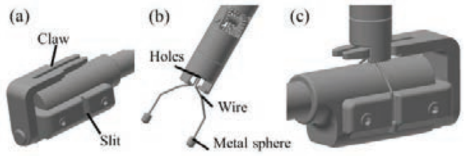

Fig. 6. Design of the assembling mechanism: (a) Miniature LUS probe; (b) Tip of manipulator; (c) Tip after assembly

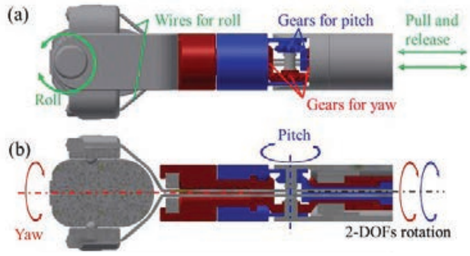

Fig. 7. Design of 3-DOF mechanism: (a) Double-bevel-gear mechanism; (b) Cross sectional view

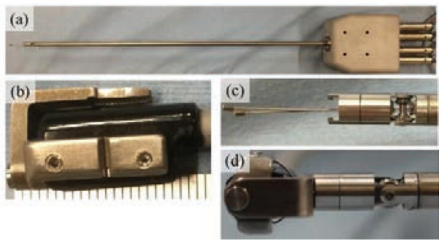

Fig. 8. Handheld 3-DOF LUS manipulator: (a) Overview; (b) Miniature LUS probe; (c) Tip of shaft; (d) Tip after assembly

3. Experiments

3.1. Assembly and disassembly

Figure 9 shows the assembly procedure demonstrated using the prototype. After the insertion of the claw into the holes (Fig. 9(a)), the spheres were placed in the slits and locked by pulling the wires (Fig. 9(b)). The procedure was conducted under a simulated laparoscopic view.

The assembly using a thin and long instrument in a small field of view was not easy but still feasible. The use of additional forceps was useful to precisely control the relative position of the parts to be assembled. Disassembly was also feasible but time consuming. The design of the assembling mechanism can be improved to enable faster and easier assembly and disassembly.

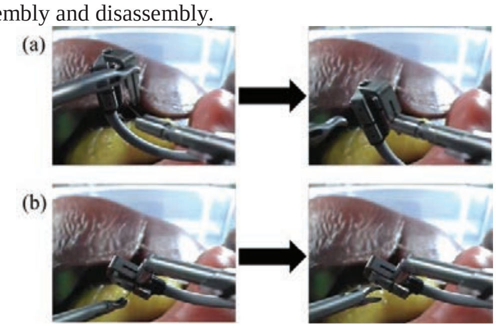

Fig. 9. Assembly: (a) Insertion of claw, (b) Assembly of wires

3.2. Imaging of Liver Phantom

LUS imaging of the ultrasound liver phantom was demonstrated using the prototype. Figure 10(a) shows the endoscopic view during the demonstration. A longitudinal sectional view of a blood vessel model in the liver phantom was successfully obtained by using the handheld 3-DOF LUS manipulator as shown in Fig. 10(b).

During the demonstration, the motions of roll and pitch were smoothly actuated; however, the weight of the miniature LUS probe cable influenced the friction in the double-bevel-gear mechanism and sometimes blocked the motion. The handling of the cable needs to be considered when revising the design of the manipulator.

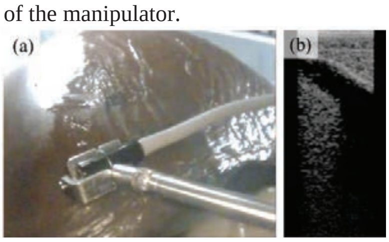

Fig. 10. Imaging of liver phantom: (a) manipulation on liver phantom; (b) Ultrasound image of vein

4. Conclusion

This paper presented the design, prototyping, and evaluation of a handheld 3-DOF LUS manipulator. First, the minimum range of motion required for ideal LUS imaging was demonstrated by a surgeon and was quantified to define the requirement. Based on the minimum range of motion, the prototype of the handheld 3-DOF LUS manipulator was designed and fabricated. A prototype of the handheld 3-DOF LUS manipulator with a drive unit was fabricated and tested on an ultrasound liver phantom. Successful assembly and visualization of the longitudinal section of a blood vessel model were demonstrated in a simulated laparoscopic environment. The quantification of requirement using sensors prior to the mechanical design was helpful for a better understanding of the demands of doctors. In future, the design will be revised, and the handheld 3-DOF LUS manipulator will be tested for *in vivo* experiments.

Acknowledgements

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