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Estimation of Boundary Surface Based on Bulk Modulus for Cutting Work

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Abstract: Endoscopic surgery has become popular as a less invasive treatment in medical fields because of the increasing focus on the patient's quality of life. It is difficult to determine the positions of organs and blood vessels during endoscopic surgery because visual information is lacking due to the narrow operating area. This surgery requires advanced techniques and is difficult to perform, so it can only be done by doctors with proper training. Methods of preventing invasions into organs or blood vessels and the damage that comes with such invasions, but that do not depend on the practitioner's knowledge of advanced operating techniques, are required. We propose a method for estimating the boundary surfaces between objects using the bulk modulus, which is one of the physical properties of an object, as one way to obtain information that is useful in endoscopic surgery.

Keywords: Robotics, Bilateral control, Machine tool, Model-Based Design

1. INTRODUCTION

Recently, the patient's quality of life has received a lot attention in medical fields. Treatments that are not highly invasive and that contribute to the maintenance and improvement of patients' physical and mental health have become popular. Endoscopic surgery is an example of a popular low-invasive treatment. In Japan, the use of endoscopic surgery is increasing and replacing abdominal surgery. Its use has increased 60 fold from 1990 to 2011 (JSES (2011)). The changes in the number of endoscopic operations performed are shown in Fig. 1. Endoscopic surgery has the advantage of faster social rehabilitation because the amount of pain associated with the surgery is low due to the use of small incisions, and the patient's hospitalization is shortened (JAOG (2004)). But endoscopic surgery is performed using forceps instead of the hands while viewing a two-dimensional and unclear endoscope image. Therefore, it is difficult to secure ample working space and to obtain the positions of organs and blood vessels in a narrow operating area because it is not only the lack of visual information but also the lack of tactile information. Endoscopic surgery requires advanced technique and is difficult to perform, so it can only be done by doctors with proper training. Therefore, Methods to get the forces right are important and be required. Research and development on surgical support robots that can operate safely and with high precision have been undertaken since the 1990s. Since the main control system is a master-slave control, it is possible that organs can be damaged in the use of such a robot given that a good and reliable estimate of the position of the organs is difficult to obtain. It is necessary to develop ways to prevent invasion into the organs and blood vessels and to prevent damage without depending on the technical skill of the operator.

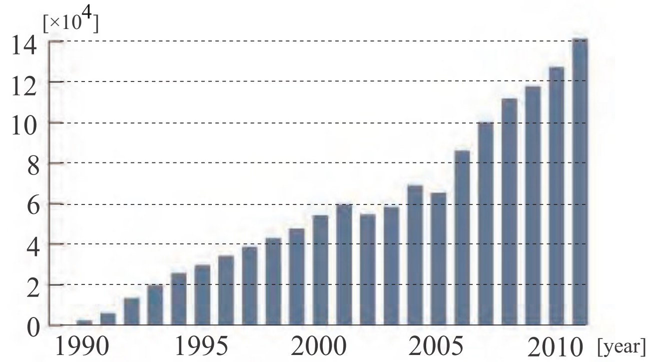

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Fig. 1. Changes in the number of endoscopic operations

The bilateral control system has features which handle not only the finger positions and joint angles of the master robot and slave robot but also manage force information with regard to the operating force, external force, and so on at the same time. Force information related to the slave robot is communicated to the operator. To improve operational accuracy, unnecessary forces can be eliminated. Moreover, this system can amplify necessary forces and communicate the level of these forces to the operator. This system has many useful features in that the amount of movement of a robot can be corrected and the amount of unnecessary movement such as tremors can be cut because the robot that the operator holds is separate from the robot that actually performs the surgery. In a previous study, Bicchi et al. proposed a system which extracts the viscoelastic characteristics of an object and identifies an object being held by endoscopic forceps using the reaction force applied to the forceps and the angular displacement (Bicchi (1996)). This system is able to identify a held object without looking at it directly. Additionally, Lorenzo et al. proposed a system for sensing the breaking of a tissue membrane by a needle (Lorenzo (2011)). This method identifies the breakage of a

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soft tissue by feeding back to the operator the cutting forces applied to the tips of needles and the friction forces between the sides of the needles and tissues. In a previous study on ensuring the safety of a master-slave-type surgical support robot, Inoue et al. constructed an autonomous avoidance algorithm for avoiding movement into dangerous areas (Inoue (2009)). To perform stable and precise movement near a dangerous area, the dangerous area is determined using an image obtained by a three-dimensional position-measuring instrument and by introducing a virtual vector field. Invasion into the dangerous area is prevented using the three-dimensional image, but it is difficult to perform smooth work because the visual repulsive force presented to an operator because of virtual vector field is proportional to the distance from the dangerous area.

When visual information is lacking in operating the master-slave robot, unexpected contact can occur due to involuntary movement of the operator. In this study, we developed a system which can estimate boundary surfaces. Our system employs a master-slave robot with bilateral controls, which are the controls of the master robot and those of the slave robot. It is thought that safety is improved when boundary surfaces are estimated. When pressure or tension is exerted on an object, its volume is generally reduced or expanded. Pressure and bulk strain are in proportion when the range of pressure is small. We focused on the bulk modulus, which shows the volume deformation ratio due to pressure applied to an object, and we clarified the thickness of an object.

2. EXPERIMENTAL DEVICE AND WORK PIECE

2.1 Experimental Device

Most conventional automated machining robots have a serial link mechanism, which is problematic because the device can bend under the machining force and the worker's operation force during cutting, thus leading to decreased machining accuracy. In this study, to solve these problems, we developed a 4-degrees-of-freedom (4-DOF) parallel fixture-type robot with a force sensor and a drill at the far tip of the end effector by installing a rotating structure in the end effector of a 3-DOF manipulator. A photograph of this device is shown in Fig. 2. The new parallel link mechanism used in this study should improve the stiffness of the body considerably. The servo motors FHA-11C-100-E200 made by Harmonic Drive Systems Inc. are used in the parallel link manipulator. The maximum torque was 11 [Nm], the maximum revolving speed was 60.0 [rpm] and the resolution was 800000 [p/rev]. The end effector used rotary actuator FHA-8C-100-E200 made by Harmonic Drive Systems, Inc., with a maximum torque of 4.8 [Nm], a maximum revolving speed of 60.0 [rpm], and a resolution of 800000 [p/rev]. A 6-DOF force sensor was also installed in the end effector. The master robot was a haptic device, the Falcon, made by Novint Technologies, Inc. This device is shown in Fig. 3. The working space was $101.6\times10^{-3}\times101.6\times10^{-3}\times101.6\times10^{-3}$ [m^3], the positional resolution was 400 [dpi] and the sampling time was 1.0 [ms]. A drill with a diameter of 3×10^{-3} [m] was set as the end tool. The drill dose not rorate, but is just pushed into the surface to obtain an estimate of the surface boundary.

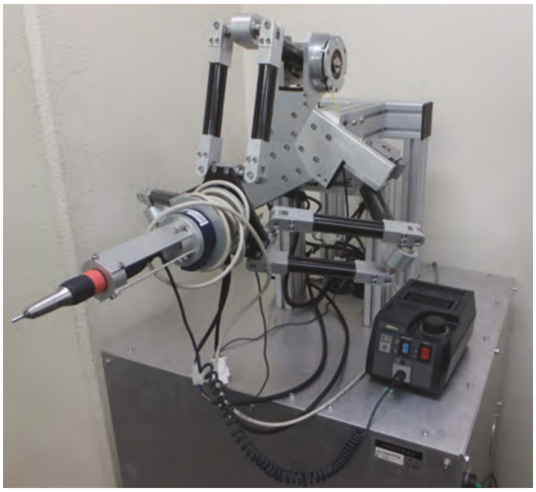

Fig. 2. Slave Robot

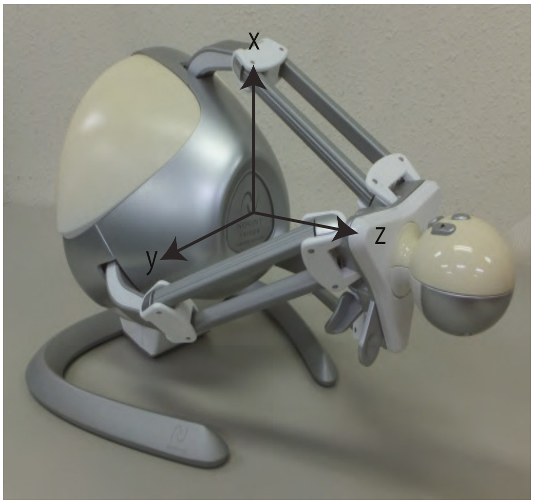

Fig. 3. Master robot: Falcon

The base of the robot used in this study was a parallel-link-type manipulator called DELTA with three legs; the robot's end effector could be moved horizontally without changing the robot's posture. In this section, the kinematics of the 3-DOF robot, shown in Fig. 4, were calculated. We referred to Laribi's method for solving kinematics with a delta parallel link manipulator (Laribi (2007)). Here, L_1 was the length of link 1, L_2 was the length of link 2, r_A was the distance from the center of the base to the joint, r_B was the distance from the center of the end effector to the joint, and $\theta_j (j = 1,2,3)$ was the angle formed between the X-axis in the coordinate system and the vector directed toward the first joint of each link from the center of the base. The kinematic parameters of the arm ($j = 1$) of the

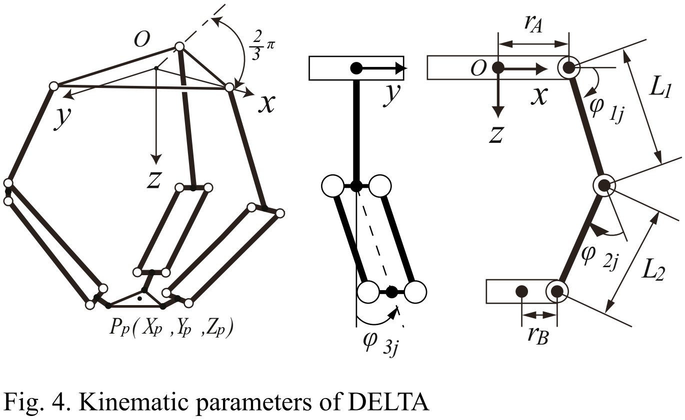

Fig. 4. Kinematic parameters of DELTA