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Development of Support System to handle Ultrasound Probe by Coordinated Motion with Medical Robot

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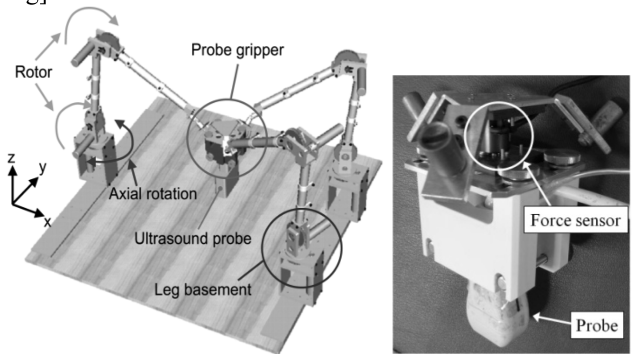
***Abstract*—We have developed a support system using our ultrasound diagnosis robot, which is able to support manual handling of ultrasound probe in echography to alleviate fatigue of examiner. This system realizes a coordinated motion according to the motion of the probe, which is hold by the robot and is moved by an examiner. We have established four kinds of situations, which are initial fixation, coordinate motions with/without contact on the body surface, and automatic chase motion of an internal organ. The system recognizes when the examiner grasps the ultrasound probe by 6-axis force sensor and touches it on body surface by processing echograms. Not only unskilled examiners but also a professional sonographer have evaluated the performance of the system after elucidating multiple parameters for compliance control and self-weight and moment compensation of the probe. As the results, this system has the potential to be able to support advanced diagnosis for conventional echography.**

I. Introduction

ECHOGRAPHY (ultrasonography) is now indispensable in every field of medical diagnosis because of its safety and cost-effectiveness. Because of recent progress in minimization for the portable equipment, echography is recognized as the only medical image modality, which is able to apply to a ubiquitous medicine or telemedicine. Therefore various kinds of systems for remote diagnosis of echography [1-3], which is called as tele-echography, have developed to enable a remote diagnosis under a condition where the operator is apart from a patient. Another application was also considered by moving the ultrasound probe automatically to acquire three-dimensional information of internal organs [4-6]. However, a system to support examiner's manual handling of the probe directly has not been considered. Thus we applied our robot [1,6], which is a light robot with the contact force sensation and multiple legs, to realize a passive coordinated motion according to the motion of the probe. In this paper we describe a support system to handle the probe considering the relation among the probe, the hand of the examiner and the body surface of the subject.

II. Specification of the Robot

We have designed the robot with 6 degrees of freedom to move the probe in three dimensions and to detect the contact force on the body surface. The main construction of the robot consists of an unsymmetrical parallel mechanism with three legs as shown in Fig.1 (a). By using unsymmetrical location of legs, it can correspond to various attitudes of a patient. The probe is grasped by the probe gripper, which is sustained by the tip of the three legs of the parallel mechanism, as shown in Fig.1 (b). The parallel mechanism enables redundant three-dimensional translation and rotation of the probe. In the probe gripper, three-axial force sensor (XFS-18M20A25-M10, Nitta Co., Ltd) is installed to sense three-dimensional contact force on body surface [4]. Movable area of the tip of the probe is 300x300 [mm^2] in x-y plane with 50<z<250 [mm] in Fig.1 (a), where z=0 indicates the surface of the bed. Rotational angle is maximum 60 [deg] from vertical position around x- and y-axis, and 50 [deg] around z-axis.



(a) Whole view of the robot (b) Probe gripper part
Fig.1 Schematics of the ultrasound diagnostic robot

III. Methods

A. Overview of the support system

Figure 2 shows the concept of the support system with the robot. It realizes a coordinated motion according to the motion of the probe, which is hold by the robot and is moved by an examiner. We have established four kinds of situations as follows;

i) Initial fixation to keep the position of the probe,
ii) Coordinate motions without contact on the body,
iii) Coordinate motions with contact on the body,
iv) Automatic chase motion of the targeted internal organ.

The system recognizes when the examiner grasps the ultrasound probe by 6-axis force sensor and touches it on body surface by processing echograms. i) The system starts after

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a subject lies on a bed without touching the probe. When the examiner moves a probe, ii) the system performs to compensate the force and moment to be put on the probe by the examiner by introducing compliance control method. If a certain object of internal organ was visualized on echogram (ultrasound image), iii) the system recognizes that the tip of the probe touches on body surface to take into account that the detected force includes restitution from the body. During the situation ii, when the examiner releases the probe, the system returns to the situation i. And when no internal organ was visualized on the echogram in the situation iii, the system recognizes the probe detached away from the body to shift to the situation ii. Also the examiner can change the situation from iii to iv by manual, before he releases the probe, to make the robot follow breathing automatically. Figure 3 shows the block diagram of the system.

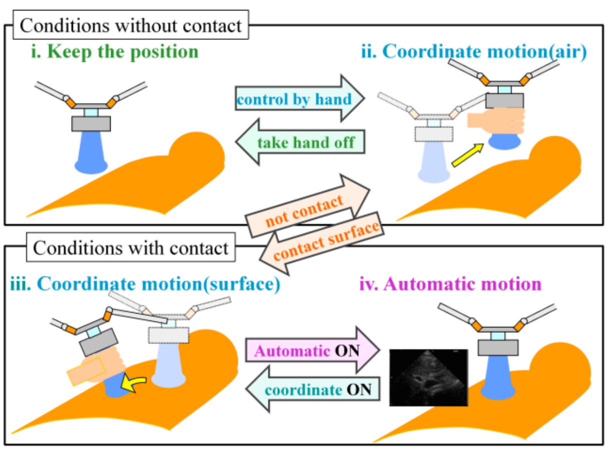


Fig.2 Transition among 4 conditions of the system

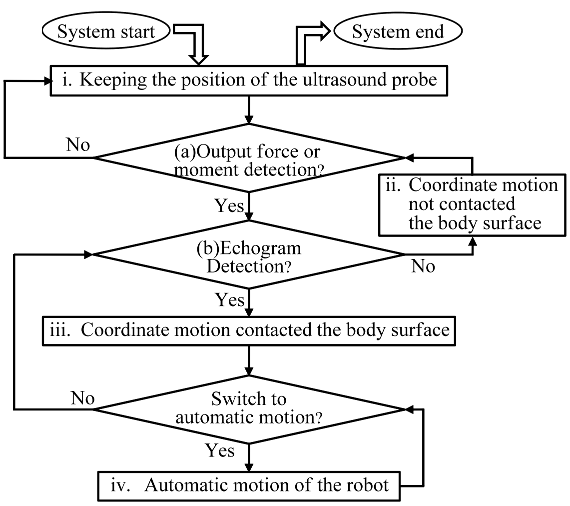


Fig.3 Block diagram of the support system

To realize above-mentioned coordinated motion ii and iii, the robot moves the probe to compensate the position and angle of the probe, which is produced by the examiner. In this system following equations for compliance control are applied to the robot to determine the position and the angle of the probe x from detected force and moment F.

$$F - F_i = M\ddot{x} + c\dot{x} + kx \tag{1}$$

$$x = [p \quad \phi]^T \tag{2}$$

$$F = [f \quad m]^T \tag{3}$$

$$m = m_{se} - m_0 - m_p \tag{4}$$

Here p, ϕ, f and m indicate the position of the probe, the angle of the probe, applied force by the examiner and applied moment by the examiner, respectively. In eq. (1), M, c and k indicate the coefficients of inertia, viscosity and stiffness, respectively. In this study, we established the parameter k=0 because there is no necessity to produce extra loads in a coordinated motion. F_i indicates additional force only for the situation iii, which is produced by the robot and explained in the next section of this chapter. In eq. (4), m_{se}, m_o and m_p indicate the moment from the output of the force sensor, the moment compensation in the situation i and ii, and the moment compensation in the situation iii, respectively. For the situation iv, we have already published as the reference [4].

B. Coordinated motion with the robot by compensating self-weight and moment of the probe

In the coordinated motion of situations ii and iii, if the angle of the probe moves off the gravity direction, self-weight and moment of the probe affect the output of the force sensor because of the installation of the sensor as shown in Fig.1 (b). Therefore the weight and the moment of the probe with the probe gripper should be calculated to reflect to eq. (1) according to three-dimensional angle of the probe in Fig.4. Average weight of the probe ranges between 60 and 140 [g] with length of 150 [mm]. Though mechanical compensation method is generally applied by using a counterweight, we realized with software because of the operability of the probe and safety for the subject.

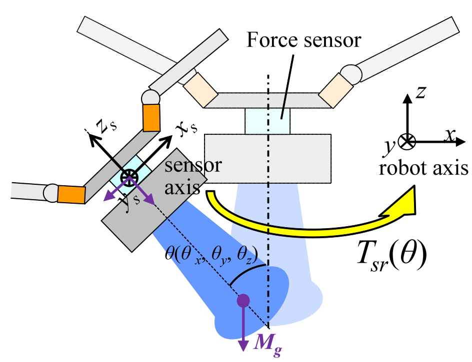


Fig.4 Compensation of weight and moment of the probe

Figure 5 shows a schematic of the coordinated motion in the situation ii. When the examiner holds and operates the probe as a conventional operation method of echography, displacement in position and angle is calculated by using eq. (1) of compliance control with applied force and moment. To realize free motion of the probe, F_i in eq. (1) should be zero where the robot does not have to produce additional force for the examiner.

On the other hand, in the situation iii, we have established to produce additional force by the robot. In general method of echography an examiner pushes the probe by manual, which is one of the reason of physical fatigue to continue diagnosis. Thus we took into account the term of F_i in eq. (1) to assists force to body surface in the situation iii. As shown in Fig.6, to produce the additional force F_i, moment compensation m_p is calculated from compensation moment.

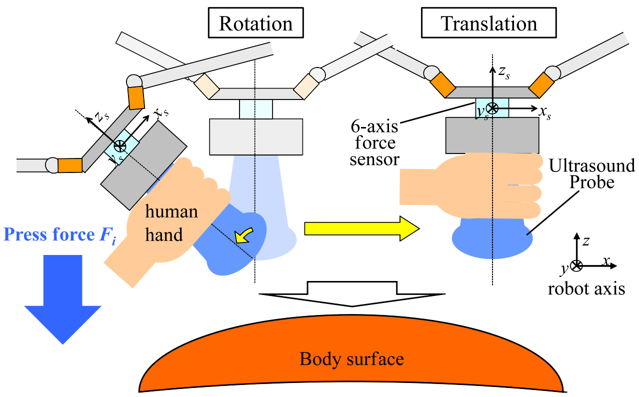


Fig.5 Translation and rotation of the probe in the coordinate motion

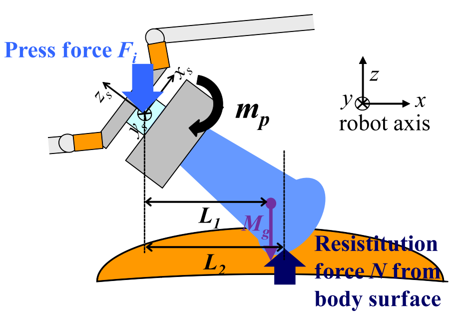


Fig.6 Production of press force to assist push on body surface

C. Judgment of the contact on body surface

The function of situation iii, where the tip of the probe contacts to body surface, is the same as situation ii except that the additional force is produced. However, restitution force from body surface cannot be distinguished from the output of the sensor. Therefore we have established judgment method to recognize the contact on body surface by introducing brightness information of echogram. As shown in Fig.7 (a), while average brightness in the region of interest (ROI) is low, the system regards that the probe is away from body surface. If the probe contacts on body surface, spatial variation of brightness is confirmed as Fig.7 (b). The threshold of the judgment is established according to the initial brightness of echogram.

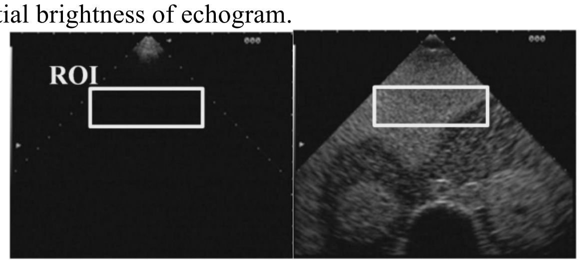


Fig.7 Recognition of contact between body surface and the probe (left: non contact, right: contact)

IV. Experiments and Results

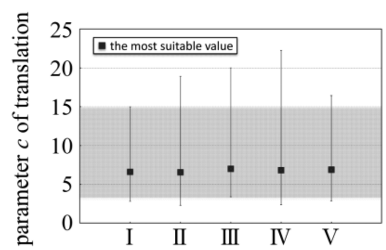
A. Introduction of parameters for compliance control

First we have determined the coefficient of inertia M of the probe. We used the probe of sector scan (2.5 [MHz], Hitachi Medical Co. Ltd.), which size is 97.7x36.3x36.3 [mm^3]. Table 1 shows the result of the measurement.

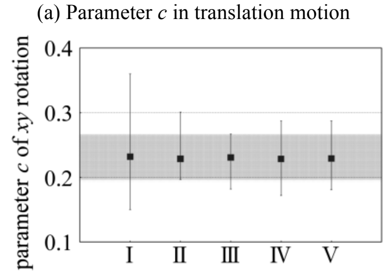
Table 1 Establishment of M for compliance control

	Translation [kg]	x_s, y_s-axis rotation [kg m^2]	z_s-axis rotation [kg m^2]
M	0.100	3.27x10^{-4}	1.72x10^{-5}

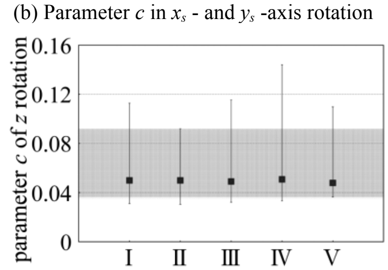
Next we determined the coefficient of viscosity c of the probe. For this parameter the operability of examiners has to be respected because the viscosity of the robot is the most important factor in coordinated motion. Therefore we have prepared five examiners, who have experiences to handle ultrasound probe. And each examiner (I-V) moved the probe as his desired directions and rotations with various number of c. Figures 8 show the results of the measurement, where the marks and bars indicate the most suitable value for examiners and allowable range, respectively. Because gray-colored areas, which indicate common value through examiners, were confirmed, there is not significant difference of the parameter c between examiners. Thus we have established the parameter c [kg/s] in the translation and [kgm^2/s^2] in the rotation as the average of the suitable values.



(a) Parameter c in translation motion



(b) Parameter c in x_s - and y_s -axis rotation



(c) Parameter c in z_s -axis rotation

Fig.8 Estimation of suitable compliance parameter c

B. Performance of the system

Not only unskilled examiners but also a professional sonographer have evaluated the performance of the system after elucidating multiple parameters for compliance control and self-weight compensation of the probe. Figure 9 shows a scene of the evaluation when the robot performed with coordinate motions of the situation iii, where the tip of the probe contacted on the body surface of a volunteer. In the coordinated motion, the probe followed three-dimensionally according to the way of scanning of the examiner by compensating detected force in real-time. As the results, this system has the potential to be able to support actual diagnosis for echography.

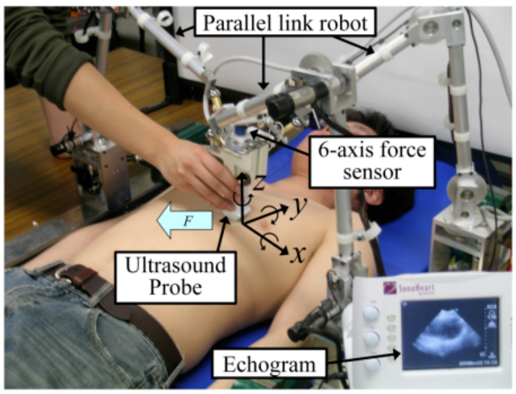


Fig.9 A scene of experiment of the coordinated motion

During the experiment, we measured time variation of multiple parameters. Here the threshold of brightness in the ROI was set as 30. Also the value of the additional force F_i was set as 1 [N]. Figure 10 shows the results, which are probe position, detected force, probe angle, detected moment and average brightness in the ROI, respectively. When the system was started, the force and moment were all 0 because of the weight and moment compensation. When the force and moment were detected, the system moved to the situation ii, by translating and rotating the probe to compensate applied force and moment. After 12 [sec] the system moved to the situation iii, where the examiner contacted the probe on body surface and value of brightness became higher. After 23 [sec] the system moved to the situation iv of automatic chase motion of internal organ, where the position and angle were stable. Finally after 39 [sec] the system returned to the situation iii.

V. CONCLUSIONS

We have developed a robotic system to be applied coordinated motion for echography. We have established four kinds of situations according to the relation among the probe, the hand of the examiner and the body surface of the subject. We have confirmed the operability of the systems through our experiences. We are going to enhance the accuracy of the system in cooperation with medical doctors under actual situation of diagnosis.

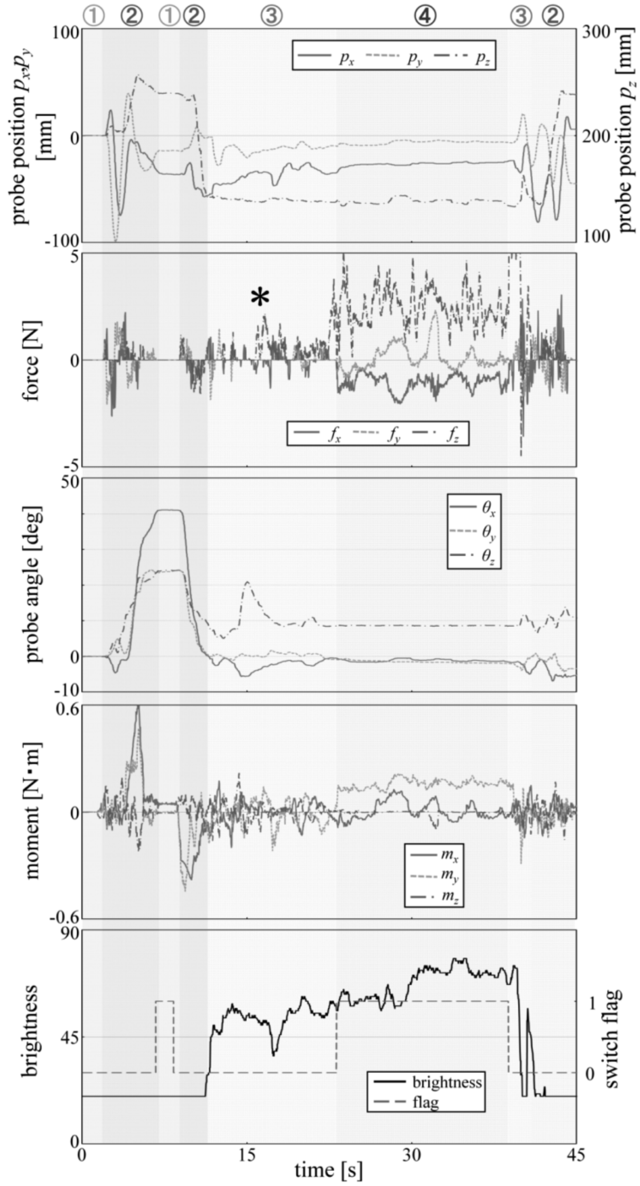


Fig.10 Time variation of parameters during the experiment

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