links, one linear guide and links are added for rotation axis. In order to increase the total drive range, these actuators are set in the vertical direction. A parallel link is added in this translation axis and the initial position of the tip link is changeable by adjusting the node of the parallel link.

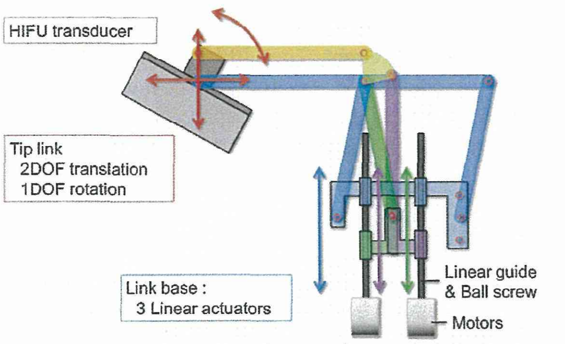

Fig.4 Link mechanism of 2nd prototype robot

The overview of the developed robot is shown in Fig. 5. The HIFU transducer (without the ultrasound probe) is mounted on the tip link. This robot will be attached to the bedside rail.

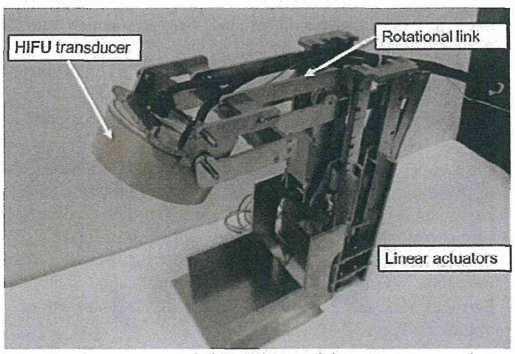

Fig. 5 Overview of the robot with HIFU transducer (without US probe)

3. System configuration

Fig. 6 shows the system configuration of HIFU robot. It comprises a 3D-US probe, US imaging system, the HIFU transducer with its control system, the robot and its device control system using PIC. The position information are transferred via USB communication and integrated in the graphic workstation which has a customized image visualization software, robot control software and HIFU irradiation control program.

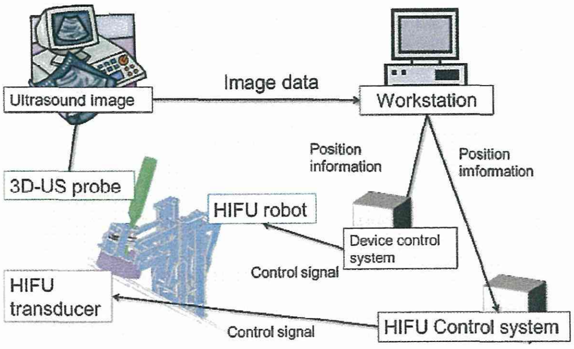

Fig. 6 System configuration of the HIFU robot system

By using this system, we can perform observing the ultrasound imaging real timely and put/track the target and transmit the power to the focal point consecutively. Image feedback control system for HIFU is already researched in e.g. [6][7], and they realized the semi or automatic detecting and tracking of the target region unless the target is appeared in the US image. Besides, our HIFU transducer is based on the basic research development in [8] and a multi phased array are distributed in the hemisphere, so the focal point are movable within the region of about 20mm cube. Thus we're considering that the combination with the multi-phased array HIFU and this robot will increase efficiency of the procedure.

4. Experiments of the positioning of the robot

4.1. Experimental setup

Positioning accuracy of this robot was evaluated. Fig. 7 shows the experimental setup of each axis. A reference marker by 3D measurement system (Polaris™, NDI, Canada) are used to measure the tip transducer's position (Mockup metal material of 1.5Kg mounted on the tip). From the initial point of the robot (at the original point), designated values are sent to the robot. Then the robot is moved to each lattice node points. We measure the 3D position of the tip by 3D measurement system. The coordinate system between the evaluation lattice (Fig.7 left) and 3D position measurement sensor space was calibrated in advance. The affine coordinate transformation are used for calibration and calculation of each points. The displacement errors between the theoretical lattice nodes and the measured points are calculated. The number of the trial is 5 times.

4.2. Result of the positioning accuracy

Total average of the positioning accuracy error for each axis is shown in Table 1. Each error results in quite good performance despite the use of 3D measurement device which has inherent RMS of 0.35mm. And more, the 1.5Kg mock is mounted at the tip, there seem to be no influence for the positioning accuracy.

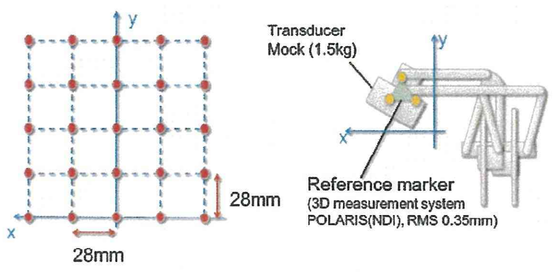

Fig.7 Evaluation setup for positioning accuracy

Table 1. Positioning accuracy error

Axis	Average error [mm] (N=5)
x	-0.2±0.3
y	-0.1±0.1
z	-0.0±0.1

5. Discussion and Conclusion

In this paper, our 1st and the 2nd prototype of HIFU positioning robot are presented. A newly designed 4DOF mechanism is developed to hold a phased array HIFU transducer with a 3D ultrasound probe for target observation. Using this system, the surgeon is able to put the target on the image, and the robot can track the target position and transmit the power to coagulate the target region. The HIFU transducer will perform precise targeting by using phased array system. So, once the target region is moved outside of the focusing area, the robot can perform a large movement. It is a kind of hybrid control and we plan to optimize the controller in future research.

The movable region of the tip position is restricted by rigid link system in this robot, so the risk of interfering with the patient is reduced and the robot would not harm the patient by unintended movement. One of the clinical concern is the use of water bag, which should be set between the HIFU transducer and the patient. For more strict feasibility experiment and clinical application, a suitable design of the water bag is needed.

At present, evaluations on this hybrid positioning are not tested, because the HIFU transducer itself requires more precise evaluation including quality and effectiveness of the treatment in-vivo. Especially, because of ultrasound's refraction in the tissue on the way to target, the image is distorted resulting in displacement of the coordinate system and the robot. So we consider to move robot not in absolute coordinate but in relative coordinate system. We will perform the total evaluation of the whole system in the next step.

In this paper, we present a newly developed HIFU positioning robot which holds a HIFU transducer and the US probe. We conclude that the initial evaluation test of the 2nd prototype robot was performed and high precise positioning was achieved in the experimental settings.

Acknowledgements

This research is partly supported by Health Labour Sciences Research Grant. The HIFU transducer will be provided by one of the research project member, Prof. Umemura, Tohoku University, Japan, and we like to express gratitude in this place for his laboratory.

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