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Development of Assisted-Robotic System Designed to Measure the Wave Intensity with an Ultrasonic Diagnostic Device

Ryu Nakadate, Hisato Uda, Hiroaki Hirano, Jorge Solis, IEEE Member, Atsuo Takanishi, IEEE Member, Eiichi Minagawa, Motoaki Sugawara, Kiyomi Niki

Abstract— **In recent years, due to the increasing rate of elderly people in Japan, the needs to detect adults' diseases at the early stage becomes a high priority. In particular, an increased interest in detecting heart and cerebrovascular diseases at an early stage may allow clinicians to begin treatment sooner, when interventions are generally more effective and less expensive. Recently, the Wave Intensity (WI) has been proposed as a new hemodynamic index that provides information about the dynamic behavior of the heart and the vascular system and their interaction. However; the repetitiveness and accuracy of the WI measurement depend on the precision of the positioning of the ultrasound probe. Therefore a positioning device for ultrasound probe is required. Such a device should not only be used to keep the position but also for the fine positioning of the probe. For this purpose, at Waseda University, we have proposed the development of a robot system to assist a carotid blood flow measurement using ultrasound diagnostic equipments. In this paper, the development of Waseda-Tokyo Women's Medical-Aloka Blood Flow Measurement System No. 1 Refined II (WTA-1RII) is detailed. The system consists of an ultrasound diagnostic device, a 6-DOFs parallel link manipulator, a serial link passive arm, ball joint, and a joystick type controller. The WTA-1RII has improved the design of the gravity compensation mechanism. In addition, a genetic algorithm has by implemented to determine the optimal link's position of the 6-DOFs parallel manipulator to increase the workspace. Finally, a set of experiments were carried out to determine the usability of the proposed system.**

I. Introduction

THE heart and vascular diseases are among the main causes of death in the world, especially developed countries. In particular, 29% of the cause of death in the world is cardiovascular diseases which include myocardial ischemia, acute stroke, etc. [1]. Henceforth, due to the effects of the elderly society, it is important to detect and treat arteriosclerosis and myocardial dysfunction, which cause the abovementioned adult diseases, at an early stage when more treatment options are available.

For this purpose, recently a methodology to measure the force of cardiac contraction has been proposed. Such methodology is based on the measurement of the index Wave Intensity (WI). Basically, the WI is a hemodynamic index that can be defined any location in the circulatory system proposed by Parker et al. [2]. It can be defined at any site in the circulatory system, and provides information about the interaction of forward and backward traveling waves, and hence, information about the dynamic behavior of the heart and vascular system and their interaction. Wave intensity was originally defined as the product of $\triangle P$ and $\triangle U$, where $\triangle P$ and $\triangle U$ are the changes in blood pressure P and velocity U, respectively, during constant short time intervals. Wave intensity has the dimension of rate of energy flux per unit area and corresponds to acoustic intensity. This original wave intensity depends on the sampling interval, $\triangle t$, which makes it difficult to compare data measured at different sampling rates. Therefore, Sugawara et al. normalized wave intensity by dividing $\triangle P$ and $\triangle U$ by $\triangle t$ [3]. Thus, the time-normalized wave intensity (WI) is given by as Eq. 1.

$$WI = \left(\frac{dP}{dt}\right)\left(\frac{dU}{dt}\right) \tag{1}$$

WI is usually measured at common carotid artery. Blood pressure P is determined by tracking the maximum/minimum diameter of the vessel observed in ultrasound image and calibrated by the blood pressure measured by blood pressure cuff. Blood flow velocity U is measured by Dopplar ultrasonography [4-6]. Conventional WI measurement is done manually by a doctor or technician. Basically, the operator manipulates the ultrasound diagnostic system while fixing a probe to the measurement point (in which the patient must adopt a supine posture). The change of the vessel diameter is very small; therefore the probe has to be kept at exactly the center of the vessel. The allowable error from exact center to ultrasound beam is considered as maximum of 0.5mm. In the case that probe or patient moves, the measurement may be incorrect so that it has to be done again. Therefore the overall measurement time takes long time

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Ryu Nakadate, Hisato Uda, Hiroaki Hirano is with the Graduate School of Advanced Science and Engineering, Waseda University (r-nakadate@takanishi.mech.waseda.ac.jp)

Jorge Solis is with the Faculty of Science and Engineering, Waseda University; and a researcher at the Humanoid Robotics Institute (HRI), Waseda University (solis@kurenai.waseda.jp).

Atsuo Takanishi is with the Faculty of Science and Engineering, Waseda University; and one of the core members of the Humanoid Robotics Institute (HRI), Waseda University (contact@takanishi.mech.waseda.ac.jp)

Eiichi Minagawa is with ALOKA Co. Ltd., Japan (http://www2.aloka.co.jp/)

Motoaki Sugawara is with Department of Medical Engineering, Himeji Dokkyo University, Japan

Kiyomi Niki is with the Biomedical Engineering Department, Musashi Institute of Technology, Japan

(around 18 minutes). Up to now, there are different passive probe holding devices, however; such devices cannot enable adjusting the position once fixed.

Up to now, there are different kinds of robot-assisted ultrasound diagnostic systems have been proposed [7-10]. Most of them are mainly designed to implement a tele-echography system and their researches are focused on path planning and force control of the ultrasound probe, methods of image data transmission, etc. However; few of them have tried to scan vessels. Pierrot *et al*. [11] developed a 6-DOFs serial link arm and implemented a 3D image construction of carotid artery. Zhu *et al*. [12] developed a 6-DOFs serial link manipulator and a counter balanced with orthogonal three rotational axes by employing parallelogram mechanism for one link. In addition, visual servoing and 3D-image construction of carotid artery for tele-echography has been implemented [13]. Ikeda *et al*. [14] are developing 5-DOFs serial link manipulator, which also has orthogonal rotational axes by using arch-shaped slide link. This research aims in measuring brachial artery diameter. From all the above systems, all of them are designed for implementing vessel echography based on serial link mechanisms. However, diagnosis of vessel does not require wide workspace, whereas accuracy of positioning is important. Furthermore, optimal workspace is rather preferable for safety reasons. Therefore we have chosen the parallel link mechanism for manipulator. The main advantages are as follows: workspace can be optimized and higher precision of positioning can be achieved.

Therefore, at Waseda University, we have proposed the development of an active 6-DOFs manipulator based on a parallel mechanism designed to provide assist to doctors for assuring the accurate positioning of ultrasound while performing the measurement of the WI, increasing the accuracy of the measurement and enhancing the user-friendliness of the assisted-robotics system.

As a result of our research, in 2006, we have developed the Waseda-Tokyo Women's Medical-Aloka Blood Flow Measurement Robot System No. 1 (WTA-1) [15]. The WTA-1 is composed of an ultrasound diagnostic system, a probe-supporting device and a controlling device. The probe supporting device consists of a compact actuated parallel manipulator for fine positioning of ultrasound probe, and 6-DOFs passive arm for the approximate positioning of the manipulator close to the patient's neck. Even that the WTA-1 has demonstrated to reduce the required time for doing the measurement of the WI and enhance the user-friendliness, further mechanical improvements were required, i.e., the workspace of the manipulator was not enough, passive arm for holding manipulator added a small force including gravity and friction to operator's hand during positioning.

For this purpose, in this paper, we present the Waseda-Tokyo Women's Medical-Aloka Blood Flow Measurement Robot System No. 1 Refined II (WTA-1RII) which has been developed at Waseda University. In particular, the parallel manipulator of the WTA-1RII has been designed to optimize the workspace by means the Genetic Algorithm. Furthermore, a gravity compensation mechanism has been proposed to eliminate any force while the operator is grasping the manipulator. A set of experiments are proposed to verify the effectiveness of the redesigned manipulator of the WTA-1RII.

II. WTA-1RII System

A. System Overview

The overall system is composed of the ultrasound diagnostic system (Pro Sound II SSD-6500SV that is commercialized by ALOKA Ltd.), a probe supporting robot

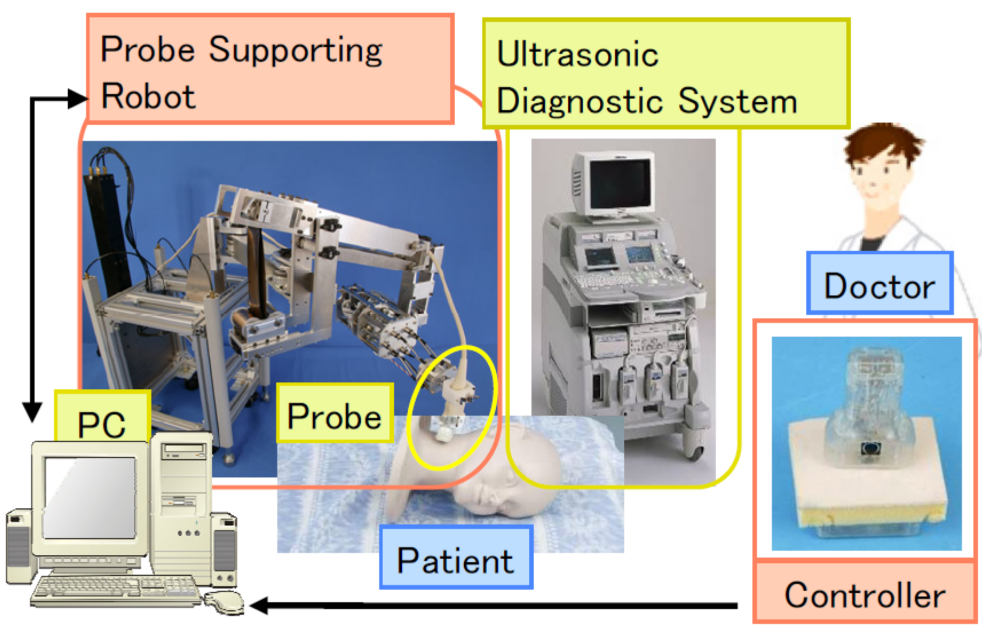

Fig. 1. Waseda-Tokyo Women's Medical-Aloka Blood Flow Measurement Robot System No. 1 Refined II (WTA-1RII)

and its controller as shown in Fig.1. The probe supporting robot is composed by 6-DOFs passive serial link arm, 3-DOFs passive ball joint and a 6-DOFs active parallel link manipulator (Figure 2). The detailed configuration of the mechanism is shown in Fig 3.

All passive joints of the serial link arm include magnetic brakes which are used to lock/unlock the joints controlled by foot switch controller. On the other hand, a push switch controller is attached to the probe holder. The magnetic brakes unlock the joints when power supply is on, so that risk of injury caused by power shut down is minimized.

The active manipulator employs the linear parallel link mechanism, which each contains an actuation system composed by a DC servo motors, a ball screw and universal joint (Figure 4). The actuation mechanism is used accurately control the positioning and posture of the end-effector (where the ultrasound probe is attached). The control system calculates the inverse kinematics of linear parallel link mechanism according to the target position commanded a joystick-styled controller designed at our laboratory.

In particular, the joystick-styled controller is attached with a set of sensors to measure the position and posture of the tip of the device. In particular, the following sensors were embedded: accelerometers, gyro, photo reflectors and laser mice. Thanks to the design of the controller device, the adjustment of the probe position can be easily done with high level of precision.

By using the proposed WTA-1RII, the operator can unlock the passive joints and accurately control the positioning the manipulator close to measurement point by hand (rough positioning), then lock the joints, and finally, adjust the positing with precision by means of the joystick-styled controller. In the first step of the procedure, it is important that the operator do not perceive any affect due to external forces (gravity, friction, etc.), so that the probe can be positioned just on the measurement point. On the other hand, for the next step, if the workspace of the parallel link manipulator is too small, the positioning in the first step should be highly accurate. Therefore, we have improved the workspace of manipulator and gravity compensation mechanism of WTA-1.

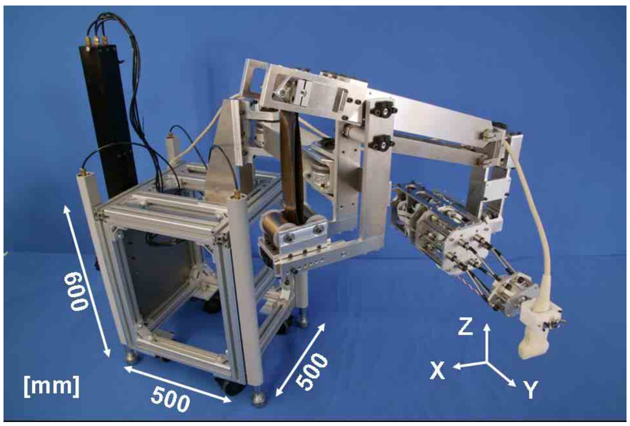

Fig. 2. Details of the probe supporting robot; where the passive arm is used to roughly positioned the probe on the patient body and the parallel manipulator is used to refine the location of the probe.

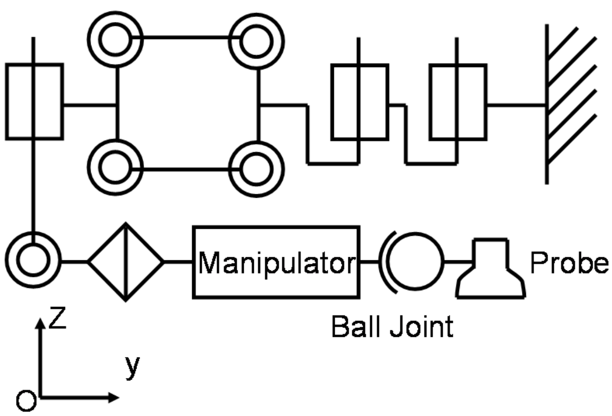

Fig. 3. Details of the mechanism configuration of the probe supporting robot which is composed by a passive arm mechanism and a 6-DOFs parallel mechanism manipulator

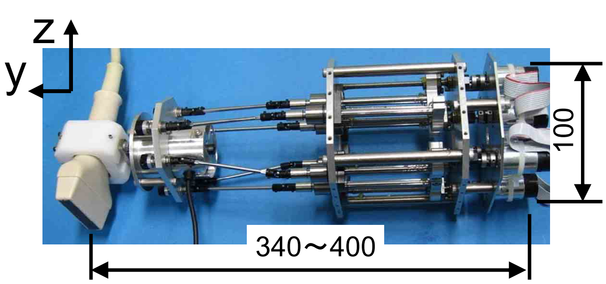

Fig. 4. Detail of the 6-DOFs Parallel Link Manipulator of the WTA-1RII

B. Gravity Compensated Passive Arm

We have designed a gravity compensation mechanism for the passive arm based on a constant force spring (Figure 5). The constant force spring is attached on a slide guide so that the direction of spring force is always vertical. As a result, the proportion of the moment arm length of right and left side of the joint is always the same regardless of any change in the angle of link. Thus, this mechanism works as counter balance weight (but substantially more light). However, the constant force spring adds non-linearity components. In order to counteract such effect, the angle of the slide guide respect to the base of the arm can be mechanically adjusted. As a result, the non-linearity of the output of constant force spring is effectively cancelled. From these improvements stated above,

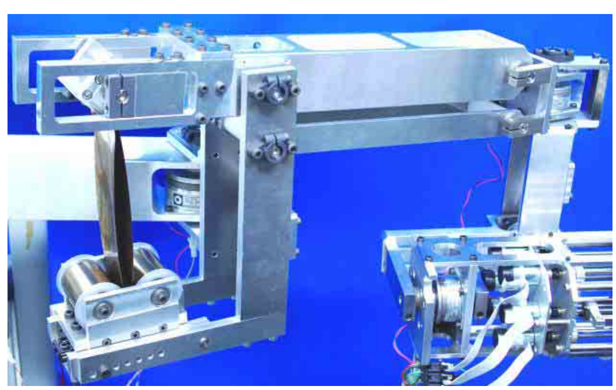

Fig.5 Screenshot of the passive arm designed for the WTA-1RII which includes a gravity compensation mechanism

a higher level of controllability of the passive arm can be assured.

C. Design of Link's Position based on GA

The maneuverability of the probe supporting robot is highly related to the designed workspace of the active manipulator. If the workspace of the 6-DOFs parallel manipulator is small, the operator is required to accurately positioning the passive arm to assure the effectiveness of the measurement. In contrast, if the active manipulator is designed to have a wider workspace, the time for adjustment of the positioning of the passive arm can be considerably reduced. In order to increase the workspace of the active manipulator, there are two possible strategies: to increase the dimensions of the manipulator or to optimize the link position of the parallel links. The first strategy may cause a considerable increase of the weight of the active manipulator. Therefore, in this paper, we have proposed to apply the Genetic Algorithm in order to optimize the workspace of the active manipulator by setting the position of the links. In particular, as it is shown in Table I, we have defined the target workspace of the active manipulator based on our discussion with doctors.

The chromosome (C) is defined as in Eq. (2) where *i* represent the link number, *b* denotes the base of the link and *e* denotes the end-side of the link [16]. The positions of three of the links of the manipulator are defined on the *zx* plane as it is shown in Fig. 8 (considering the symmetry properties regarding the other three links).

$$C = \{z_{bi}, x_{bi}, \cdots, z_{ei}, x_{ei}, \cdots\};\ i = 1,2,3 \tag{2}$$

In particular, in this paper, we focused on finding the optimal position of each of the links so that the resultant workspace of the parallel manipulator satisfies the specifications shown in Table I. For the present model, GA has been developed in real code representation using Roulette wheel selection, arithmetic crossover and uniform mutation [16]. In particular, the mutation rate has been experimentally determined (0.05). The cost function is the volume of the workspace in which the target posture (Table I) is achieved. Moreover, in order to avoid the singularity problem of the proposed parallel mechanism, the following considerations were taken into account.

The computed length of each link (h_i) corresponding to the movement of the end-effector along the x-axis can be expressed as $\mathbf{h_x} = (h_1\ h_2\ h_3\ h_4\ h_5\ h_6)$. Based on the same principle, the other five vectors $\mathbf{h_y}$, $\mathbf{h_z}$, $\mathbf{h_{\phi x}}$, $\mathbf{h_{\phi y}}$ and $\mathbf{h_{\phi z}}$ can be defined. As a result, the motion of the end-effector can be easily expressed as a linear combination from those vectors, as is shown in (3).

$$\mathbf{h} = \lambda_x \mathbf{h}_x + \lambda_y \mathbf{h}_y + \lambda_z \mathbf{h}_z + \lambda_{\Phi x}\mathbf{h}_{\Phi x} + \lambda_{\Phi y}\mathbf{h}_{\Phi y} + \lambda_{\Phi z}\mathbf{h}_{\Phi z} \tag{3}$$

If we consider that the six vectors are linear independent, the link position will not have singularity. For this purpose, we have rejected those solutions obtained by the GA algorithm when the following condition is fulfilled, as is shown in (4). The parameter k is a threshold that is determined as twice the minimum value of the determinant measured on our first prototype which had no singularity.

$$\left|\det\left(\mathbf{h}_x \quad \mathbf{h}_y \quad \mathbf{h}_z \quad \mathbf{h}_{\Phi x} \quad \mathbf{h}_{\Phi y} \quad \mathbf{h}_{\Phi z}\right)\right| < k \tag{4}$$

However, in some cases the above determinant may not be satisfied; particularly if any two vectors are nearly parallel depending on the other vectors. As a result, we have implemented an additional condition as is shown in (5).

$$d = 1 - \left|\frac{(\mathbf{h}_x, \mathbf{h}_y)}{\|\mathbf{h}_x\| \cdot \|\mathbf{h}_y\|}\right| = 1 - \left|\cos^{-1}\theta\right| \tag{5}$$

By using (5), those solutions which fulfills the condition $d < d_o$ are rejected. In this case, d_o is a threshold which is determined as twice of the measured d of our first prototype. Therefore, for each computation step of the GA algorithm, the resultant workspace is calculated. If the resultant workspace does not satisfy the target requirements, a further computation step is performed by slightly increasing the link length until the target workspace is satisfied.

Based on the above computations, the position of each of the links has been determined as it is shown in Fig. 6. The target specifications were satisfied when the link length was set to 70mm.

Table I. Required specifications of the workspace of the active manipulator designed for the WTA-1RII

Parameter	Axis	Specifications (mm)
Position	x	±10
	y	±10
	z	0 ～-10
Rotation	x (pitch)	±5.0
	y (roll)	±7.5
	z (yaw)	±10.0

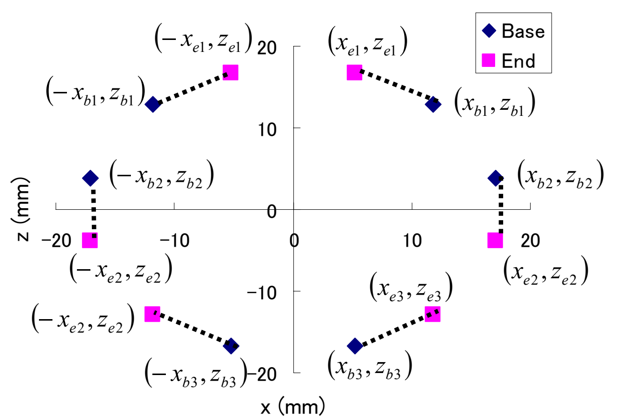

Fig. 5 Definition of the chromosomes applied for the Genetic Algorithm in order to optimize the workspace; where each of the chromosomes represents the position of each of the links of the 6-DOFs parallel manipulator.

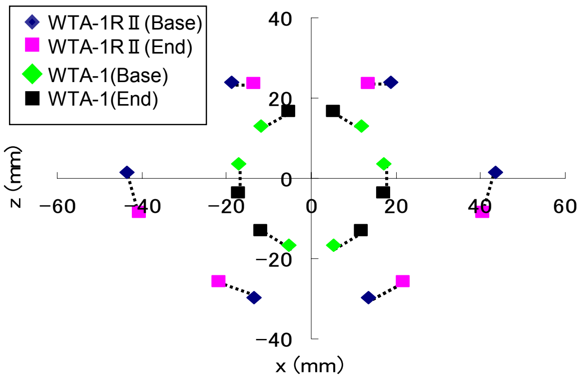

Fig. 6. Experimental results while applying the GA to optimize the workspace of the parallel manipulator designed for the WTA-1RII. The length of the links was designed to 70mm and the position of each link is shown in the graph.

D.6-DOFs joystick type controller

A joystick-styled controller has been designed with a set of embedded sensors to measure the position and posture of the tip of the device (Figure 7). In particular, the transitional *x* and *y* axes are detected by laser mouse sensor. Yaw rotation is also detected by multiple laser mouse sensors. Regarding the roll and pitch rotation as well as the transitional *z* axis, we can measure them by means of potentiometers. However, mechanical design at the joint will be slightly complicated. Therefore, we used rate gyro and acceleration sensors to detect roll and pitch angle, and photo reflector to detect the transitional *z* axis.

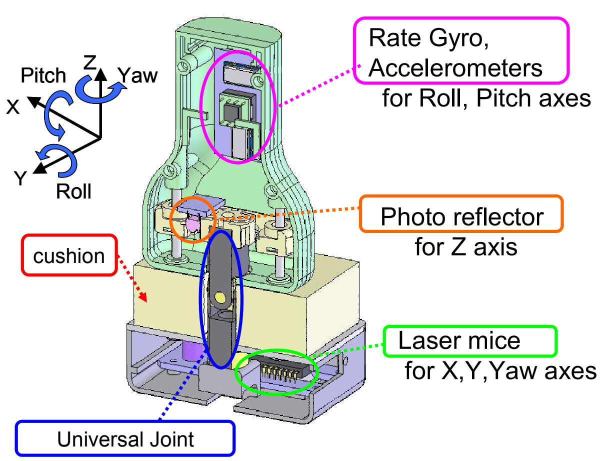

Fig. 7 The joystick type controller detects 6 axes of movement.

E. 3-DOFs Magnetic Ball Joint

As it was previously detailed, the passive arm for the rough positioning of the probe is designed to simplify the task of the operator. However, in some cases, an operator may require to adjust the positioning of the manipulator in order to synchronize the direction of the probe respect to the carotid artery. For this purpose, three passive degrees of freedom have been implemented between the manipulator and ultrasound probe. Figure 8 shows the mechanism of the ball joint. When power is off, the permanent magnet pushes the

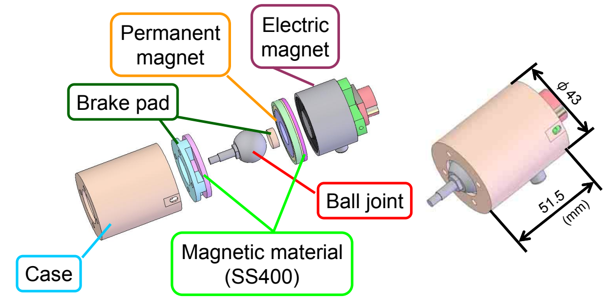

Fig. 8 Detail of the 3-DOF ball joint mechanism. A permanent magnet is used to lock the ball when power is off. On the contrary, the electric magnet unlocks the ball when the power is on.

ball and locks it. When the power is on, the electric magnet withdraws the permanent magnet from the ball, and ball is free.

III. EXPERIMENTS & RESULTS

A. GA's Optimization Results

In this experiment, we have focused in confirming the real workspace by using the determined position of each of the links of the parallel manipulator based on the GA. In Fig. 9, it is shown the actual workspace of the parallel manipulator of the WTA-1RII. As observed, the target workspace is within the obtained workspace. Moreover, as it shown in Table II, the maximum reachable range which the target rotation specification is not considered for transitional axes and maximum rotational axes are at the center position. Furthermore, we have plotted the actual workspace based on the optimal position of the links. The experimental results are shown in Fig. 9. As we may observe, the target workspace is satisfied in any position along the *z* axis (from 0mm to -10mm). In addition, in Table II, we have compared the range of motion of the WTA-1's parallel manipulator with the WTA-1RII's one (Table II).

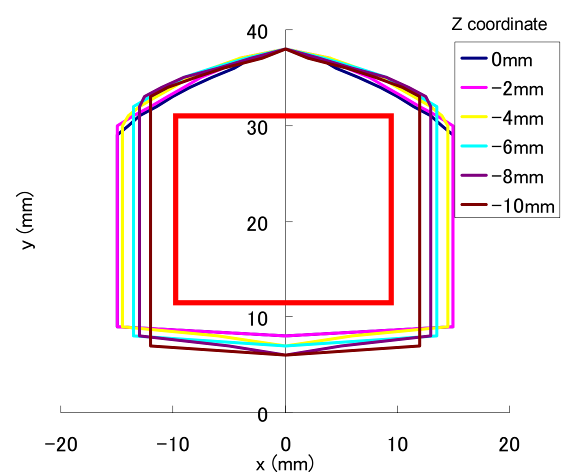

Fig. 9 Experimental results while analyzing the actual workspace of the WTA-1RII's parallel manipulator. In those areas surrounded by lines, the rotation specification is satisfied. Each color shows specified "*z*" coordinate.

Table II
Maximum movable range
Transitional axes (with no rotation)

	movable range (mm)		Increased (%)
	WTA-1	WTA-1RII	
x	±27	±45	67
y	±20	±30	50
z	-32～29	-48～43	49

Rotational axes (at the center position)

	movable range (deg.)		Increased (%)
	WTA-1	WTA-1RII	
x (pitch)	-14～8	-25～16	86
y (roll)	±21	±27	28
z (yaw)	±13	±25	92

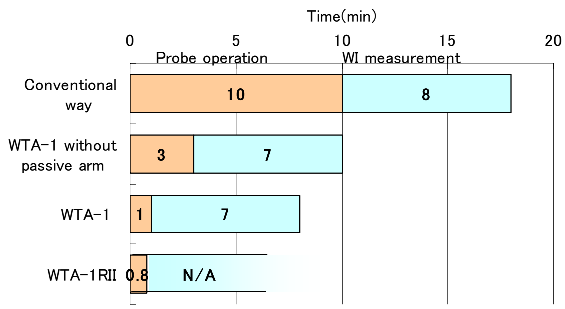

Fig. 10. Experimental results while doing preliminary clinical tests to measure the carotid blood flow with the WTA-1R (before expansion) and the WTA-1RII (after expansion).

B. Clinical Test

A doctor and a sonographer were asked to perform the measurements of carotid blood flow with a human volunteer by using the WTA-1RII and the time required to perform the task was recorded. Figure 10 shows the measurement time spent for the positioning of the probe based on the following cases: WI measurement in conventional way, with WTA-1 without passive arm (with existing upholder using clincher to fix), with WTA-1, and with WTA-1RII. As we may observe, the mechanical improvements on the WTA-1RII contributed to reduce the required positioning time. Although the reduction of time was not significantly different, operators commented the WTA-1RII is easier to manipulate during the WI measurement.

IV. Conclusion and Future Work

In this paper, we have presented the WTA-1RII, a robotic assisted ultrasound diagnostic system to measure carotid blood flow. In particular mechanical design of each part of the robot which contributes the user-friendliness was described. A set of experiments were carried out to verify the effectiveness of the proposed mechanism. From the experimental results, we have confirmed the proposed system contributed to reduction of the time spent for positioning.

As a future work, we will extend the usability of the proposed robotic system to measure other parts of the body. Moreover, an automated measurement system will be proposed to improve the repetitiveness of the ultrasound diagnostics by implementing a feedback control based on the ultrasound image processing.

References

[1] The World Health Organization, "The World Health Report 2004 statistical annex: Annex Table 3 Burden of disease in DALYs by cause, sex and mortality stratum in WHO regions, a estimates for 2002", Available: http://www.who.int/whr/2004/annex/topic/en/index.html

[2] K.H. Parker and C.J.H. Jones, "Forward and Backward Running Waves in the Arteries: Analysis Using the Method of Characteristics," *ASME Journal of Biomechanical. Engineering.*, Vol. 112, 1990, pp. 322-326.

[3] C.J.H Jones, M. Sugawara, R.H. Davis, Y. Kondoh, K. Uchida, and K.H. Parker, "Arterial wave intensity: physical meaning and physiological significance," In: S. Hosoda, T. Yaginuma, M. Sugawara, M.G. Taylor, and C.G. Caro (eds), "Recent progress in cardiovascular mechanics," *Hanvood Academic Publishers,* Chur, Switzerland, 1994, pp.129-148.

[4] K. Niki, M. Sugawara, et al., "A noninvasive method of measuring wave intensity, a new hemodynamic index: application to the carotid artery in patients with mitral regurgitation before and after surgery.", *Heart Vessels*, vol. 14, 1999, pp.263-271.

[5] A. Harada, T. Okada, M. Sugawara, and K. Niki, "Development of a Non-invasive Real-time Measurement System of Wave Intensity," *in 2000 IEEE Ultrasonics Symposium,* 2000, pp. 1517-1520.

[6] M. Sugawara, K. Niki, N. Ohte, T. Okada, and A. Harada, "Clinical usefulness of wave intensity analysis," *Medical and Biological Engineering and Computing*, doi: 10.1007/s11517-008-0388-x, 2008.

[7] A. Vilchis, J. Troccaz, P. Cinquin, K. Masuda, and F. Pellissier, "A New Robot Architecture for Tele-Echography," *IEEE Trans. on Robotics and Automation*, vol.19, no.5, 2003, pp.922-926.

[8] C. Delgorge, et al., "A Tele-Operated Mobile Ultrasound Scanner Using a Light-Weight Robot," *IEEE Trans. on Information Technology in Biomedicine*, vol.9, no.1, 2005, pp. 50-58.

[9] K. Masuda, E. Kimura, N. Tateishi, and K. Ishihara, "Three dimensional motion mechanism of ultrasound probe and its application for tele-echography system," *in proc of the 2001 IEEE .International Conference on Intelligent Robots and Systems*, 2001, pp. 1112-1116

[10] N. Koizumi, S. Warisawa, M. Nagoshi, H. Hashizume, and M. Mitsuishi, "Construction Methodology for Remote Ultrasound Diagnostic System", *IEEE Trans. on Robotics*, vol.25, no.3, 2009, pp.522-538.

[11] F. Pierrot, E. Dombre, E. Degoulange, L. Urbain, P. Caron, S. Boudet, J. Gariepy, and J.-L. Megnien, "Hippocrate: a Safe Robot Arm for Medical Applications with Force Feedback," *Medical Image Analysis, Special Issue on Medical Robotics and Computer Assisted Surgery*, vol3(3), 1999, pp. 285-300.

[12] W.-H. Zhu, S.E. Salcudean, S. Bachmann, and P. Abolmaesumi, "Motion/Force/Image Control of A Diagnostic Ultrasound Robot," *in proc.2000 IEEE International Conference on Robotics and Automation*, vol. 2, 2000, pp. 1580-1585.

[13] P. Abolmaesumi, S. E. Salcudean, W.-H. Zhu, M. R. Sirouspour, and S. P. DiMaio, "Image-Guided Control of a Robot for Medical Ultrasound", *IEEE Trans. on Robotics and Automation*, vol.18, no.1, 2002, pp.11-23.

[14] Y. Ikeda, et al., "Study on automatized evaluation of arterial endothelium function," *in proc of 2009 Japan Society for Precision Engineering*, 2009, pp. 39-40 (in Japanese).

[15] Y. Sadamitsu, A. Fujita, C. Arino, A. Takanishi, A. Harada, M. Sugawara, and K. Niki, "Development of a Robotic Carotid Blood Flow Measurement System - A Compact Ultrasonic Probe Manipulator Consisting of a Parallel Mechanism," in *Proc. of 2006 IEEE International Conference on Robotics, Automation, and Mechatronics*, 2006, pp.1-6.

[16] Holland, H.J. "Adaptation in Natural and Artificial Systems: An Introductory Analysis with Applications to Biology", *Control and Artificial Intelligence (2nd ed.)*, MIT Press, Cambridge, 1992.