31st Annual International Conference of the IEEE EMBS
Minneapolis, Minnesota, USA, September 2-6, 2009

Development of 3D space-sharing interface using augmented reality technology for domestic tele-echography

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***Abstract*— We propose a domestic tele-echography system linking between the patient's home and a hospital because of the demand due to increase in the number of patients by aging society and recent progress in portable echography enabled us to develop this system. In previous researches three-dimensional position of the ultrasound probe was difficult to specify because a remote doctor observe the patient through a video camera. Therefore we have developed a reproduction system of the probe position and angle using the ARToolKit and GUI interface using OpenGL. Only an USB camera and two markers for the body surface and the probe are necessary to memorize and transfer three-dimensional position of the probe. We have also designed a doctor side interface including echogram, patient scene and CG to instruct probe operation. As a result of evaluation experiments, guided position was satisfied to reproduce the echogram for diagnosis.**

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 telemedicine. In almost all advanced nations, requirement of telemedicine is increased because of the insufficiency of doctors in rural areas due to the advance of the aging society. Therefore a remote diagnosis of echography, which is called as tele-echography, has been proposed and developed by many researchers. Blaivas [1] reported medical image transfer in emergency to save time for diagnosis before arrival of patient at the hospital. Suenaga [2] proposed a direction system of the position and the angle of the ultrasound probe to the remote operator using computer graphics and AR(Augmented Reality) technology. However, if the operator is not experienced to handle the probe, it takes much time to obtain echogram for diagnosis because three-dimensional position has to be directed using only voice and two-dimensional guide image. On the other hand, several attempts were reported to quantitatively measure three-dimensional probe position and angle by using magnetic [3] and optical [4] sensors to perform three-dimensional visualization of a cross section of echogram on AR interface. These researches were developed for assisting system of interventional treatment so that the tracking accuracy of the probe was mandatory and total system became costly.

Therefore we have developed a reproduction system of the probe position and angle which were recorded by a doctor in past diagnosis. Reproduced information for an unskilled operator is visualized by using ARToolKit [5], which is developed not only to measure the distance between an object and the camera, but also to superimpose virtual graphics on an actual image captured by the camera. We considered that it is suitable for various environment of remote patient because the system requires inexpensive equipments of square markers, which was printed to paper, and an ordinary USB camera. We applied it to measure the probe position and angle and to instruct the way to handle the probe even between the hospital and the patient's home.

We have also designed an interface including echogram, patient scene and CG to share the three-dimensional probe operation. We have already experienced the communication technology in our tele-echo system [6] using a robot and a controller. Instruction and present position of the probe are shared as quantitative information in both sides. It this paper, we report about our system and the results of evaluation.

II. Configuration Of The System

We have developed a communication system between the doctor and the operator using TCP/IP protocol. Fig.1 shows the configuration of our domestic tele-echography system. To realize remote diagnosis, we have designed a communication program as is shown in the following procedures.

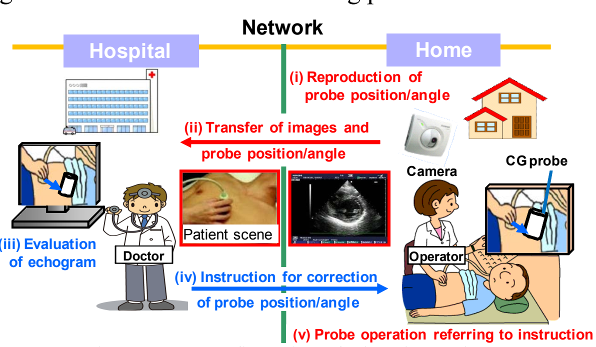

Fig.1 System configuration of tele-echography

(i) The probe position and angle recorded in past diagnosis are reproduced on the patient side before the tele-echography system is started.
(ii) The echogram and the patient scene (outlook) are sent to the doctor side with the present probe position and angle estimated by ARToolKit.
(iii) The doctor evaluates echogram for diagnosis by referring the patient scene.

Manuscript received June 20, 2009

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(iv) The doctor sends an instruction for correction of the position and angle by using CG and augmented reality technology.

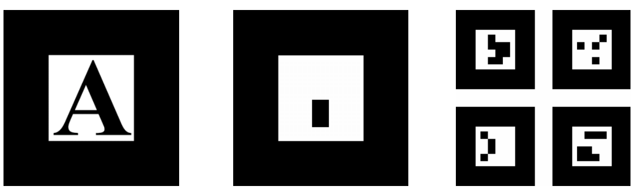
(v) The operator in the patient side corrects the position and angle by referring the relationship between the instructed position and the actual position.

After finishing (v), the procedures from (ii) to (v) should be continued. In this system, we used Motion-Jpeg compression to reduce transfer rate of images. Therefore, the size of the 24bit Bitmap image grabbed by DirectShow is reduced to less than 10[%] of the size of original image.

III. Tracking System Of Probe Position And Angle

A. *Tracking system using ARToolKit*

We used ARToolKit, which is the open-source library to track the probe position and angle by calculating its transformation matrices in real time. ARToolKit is the primary inexpensive optical tracking solution used for many Augmented Reality developers [7, 8], since it works with a single camera and square marker in the visible light range. This library uses computer vision techniques to estimate the marker position and angle relative to the camera. Fig.2 shows examples of the square markers. An internal pattern of a single marker can be freely designed as shown in (a) and (b). Furthermore, it is also possible to define multi markers as one marker as shown in (c).



(a)Single(Alphabet) (b)Single(Dot) (c) Multi Marker

Fig.2 Example of square marker

Fig.3 shows the configuration of probe tracking system. Two types of markers are separately attached on the probe and the body surface of patient, respectively. Then the camera captures the markers together in the same frame. The position and angle of two markers are calculated at the same time using the following equations in eq.(1), $\boldsymbol{T}$ is a rigid transformation matrix from the marker coordinate system to the camera coordinate system composed of rotation matrix $\boldsymbol{R}$ and transfer matrix $\boldsymbol{t}$. $\boldsymbol{T}_{cp}$ and $\boldsymbol{T}_{co}$ are the rigid transformation matrix of the probe-marker and the patient-marker, respectively.

$$\boldsymbol{T}_{4\times4} = \begin{pmatrix} \boldsymbol{R}_{3\times3} & \boldsymbol{t}_{3\times1} \\ 0 & 1 \end{pmatrix} \qquad (1)$$

Therefore, eq.(2) is used to transform any position of the probe-marker coordinate system $\boldsymbol{v}_p$ to the patient-marker coordinate system $\boldsymbol{v}_o$.

$$\begin{pmatrix} \boldsymbol{v}_o \\ 1 \end{pmatrix} = \boldsymbol{T}_{co}^{-1}\boldsymbol{T}_{cp}\begin{pmatrix} \boldsymbol{v}_p \\ 1 \end{pmatrix} \qquad (2)$$

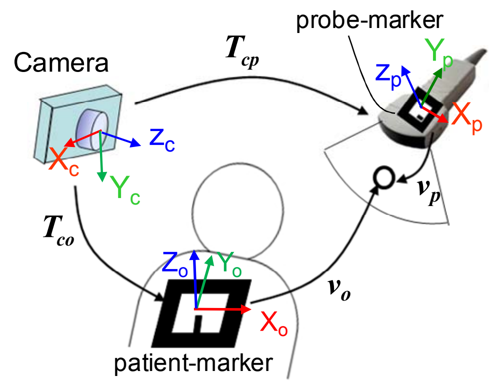


Fig.3 Tracking system of the probe to body surface using ARToolKit

B. *Evaluation of tracking accuracy of ARToolKit*

The measurement accuracy of the distance by ARToolKit depends on the size of the marker in the frame and its resolution. The measurement error of distance between the camera and the marker has been investigated by some researchers [5,9]. However, these results are not enough to define usable size of marker in arbitrary situation. Thus, we examined relationship between the size of marker and the measurement error of distance to decide the condition to track the probe with high accuracy. We prepared two types of the markers where one is the single marker as shown in Fig.2(b), and the other is the multi marker as shown in Fig.2(c). For the pattern of the multi marker, we adjusted the degree of similarity between each marker less than 0.7 in order to prevent misidentification.

Fig.4 shows the relationship between the camera and the marker. We defined the FOV(Field of View) θ to normalize the size of multi marker as eq.(3), where L is diagonal length of the marker and r is a distance between the camera and the marker.

$$\theta = 2\tan^{-1}\frac{L}{2r} \qquad (3)$$

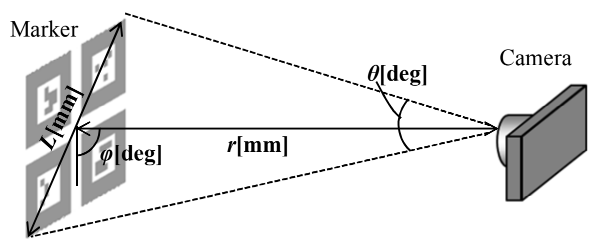


Fig.4 Relationship between the marker and the camera

Fig.5 shows measurement error of distance versus θ when elevation angle of the camera φ in Fig.4 is 30, 60, 90[deg]. The true distance was measured with microBIRD (Ascension Tech. Corp.), which is a three dimension positional sensor. As the result, the distance measurement error is less than 1[%] with a multi marker regardless of the angle φ, if the FOV is more than 6[deg]. Therefore, we decided to use the multi marker with the condition that the FOV is more than 6[deg].

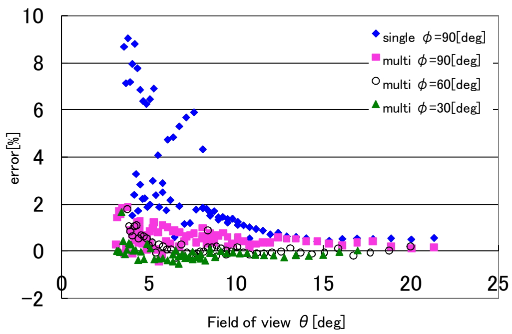
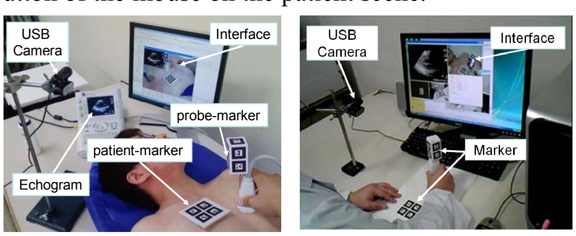


Fig.5 Distance measurement error versus field of view

IV. Development Of The User Interface

We assumed the situation that the operator sat on patient's right arm side and had the probe by a right hand to observe heart. Then, so as not to hinder the probe operation, the above-mentioned multi marker was employed as a patient-marker to determine the origin of the patient body coordinate as shown in Fig.6(a). Also the combination of markers, which forms a hexahedron and has 9 single markers on 5 faces, was employed as the probe-marker to be set on the extension of the probe axis. The camera was set 500[mm] above the patient's right shoulder to prevent the patient-marker from hiding by the probe. Thus the length of the width of the patient-marker is 60[mm] to maintain its FOV more than 6[deg].

Fig.6(b) shows the environment of the interface for the doctor. The relation of the camera and the markers is similar to the interface of the patient side. The probe angle for instruction is obtained by tracking of the handle using ARToolKit. To instruct the probe position, the doctor clicks the button of the mouse on the patient scene.

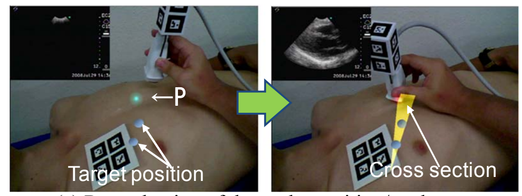


(a) Patient side (b) Doctor side

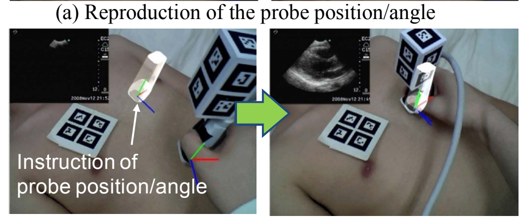
Fig.6 System configuration of both sides

Fig.7 shows the demonstration according three situations as in GUI (Graphical User Interface) of both sides. When reproducing the probe position and angle in Fig.1(i), the operator adjusts the tip of the actual probe to be superimposed to translucent point P on the body surface in the interface, which is reloaded from past diagnosis, as shown in Fig.7(a). According to the distance between the tip of the probe and the point P, the color of the point varies to notify the error to the operator. When the echogram detects internal organ on it which indicates contact of the tip of the probe, the interface displays graphics of multiple targets, which are also reloaded from past diagnosis, with cross section of echogram so that the operator adjusts the probe angle.

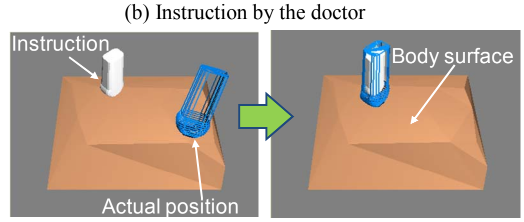
When instructing the probe operation for correction in Fig.1(iv), the doctor adjusts the probe position and angle as his desire by referring the graphics on patient scene, as shown in Fig.7(b). Then the operator controls the probe to be superimposed it to the graphics of the instruction. Furthermore, we implemented virtual surface of patient body to recognize the three-dimensional environment of the patient, as shown in Fig.7 (c). To reconstruct the shape of patient's body, the technique of the Delaunay triangulation [6,10] was introduced. The virtual surface of patient body is possible to change the viewpoint to enhance three-dimensional space-sharing for both of the doctor and the operator.



(a) Reproduction of the probe position/angle



(b) Instruction by the doctor



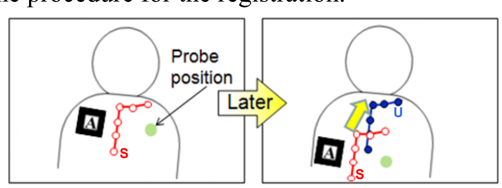
(c) Display image of virtual environment

Fig.7 Three situations displayed in the interface

V. Experiments

A. Reproduction method of the probe position and angle

The most important point in the system is the accuracy of reproduced point on body surface because the original position of the patient body coordinate is not guaranteed. Thus we propose a registration technique by determining a rule to trace the body shape with the tip of the probe. Fig.8 shows the procedure for the registration.



(a) Saving information of body shape and diagnosis (b) Calibration of position of information of diagnosis

Fig.8 Method of correction in the probe position

(i) When memorizing the probe positions on the body surface, the doctor traces the centerline and the left collarbone continuously as shown in Fig.8(a). Three-dimensional "L"-shape and the probe position are preserved as the relative position from the patient-marker.

(ii) When reproducing the probe position by other operator, the marker is put on the left chest approximately to load the memorized probe position. Afterwards, the operator traces patient's body to match the new track, with the memorized "L"-shape as shown in Fig.8(b). As a result, the probe position in past diagnosis is reproduced and determined.

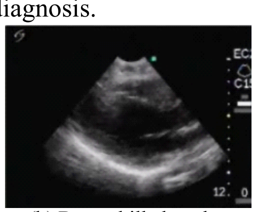
To match the points between the new track $\boldsymbol{U}=\{\boldsymbol{u_i}|i \in \boldsymbol{N}\}$ and the memorized one $\boldsymbol{S}=\{\boldsymbol{s_i}|i \in \boldsymbol{N}\}$, we defined error index as a distance between the corresponding points (See eq.4). Transformation matrix $\boldsymbol{M}$ is led when two tracks are overlapped each other by the iterative calculation to minimize the value of error function.

$$E = \sum_{i=1}^{N} \left\| u_i - \boldsymbol{M} s_i \right\|^2 \qquad (4)$$

Then we experimented to measure the error index after reproducing the probe position. The original patient-marker was put on the right chest of a normal male volunteer to acquire the probe position where the long axis-view of the heart was obtained. The probe with the probe-marker was handled by an expert medical doctor of echocardiography. The probe position and its relative position to the original "L"-shape are memorized by using both of ARToolKit and microBIRD, to calibrate the probe position. In the next step, the patient-marker was moved from the original position (about 50, 100[mm]) to reproduce the probe position and the echogram previously obtained by five unskilled students of the echography as operators. As stated above, the difference of the position of patient-marker was corrected. As a result, the average of error index was about 9[mm] regardless of the moved distance of the marker, which is able to be recovered by remote instruction of a medical doctor when the system is applied for actual domestic tele-echography.

In addition, we compared the echogram obtained by the doctor with the reproduced one obtained by the unskilled student. Fig.9(a) shows standard echogram acquired by the doctor, Fig.9(b) is reproduced echogram by one of the student. As a result, the doctor evaluated that the orientation of the echogram satisfied with actual diagnosis.

(a) By the doctor



(b) By unskilled student

Fig.9Comparison of an instructed echogram with the original

B. Evaluation of tracking accuracy of ARToolKit

This experiment was carried out by four unskilled students of echography as a operator. In another room, an experienced technician observes the behavior of the operator and instructs the way to handle the probe. To verify the effectiveness of the instruction used our interface, the following two methods of instruction were carried out.

(i) Operator hears only voice from the remote technician.

(ii) Operator refers to CG that represents the probe operation instructed by the remote technician with voice.

Fig.10 shows comparison of average time required to obtain echocardiogram. As a result, instructing the probe operation contributed to shorten time to obtain echogram. Therefore, it was confirmed to be able to support tele-echography by using this interface.

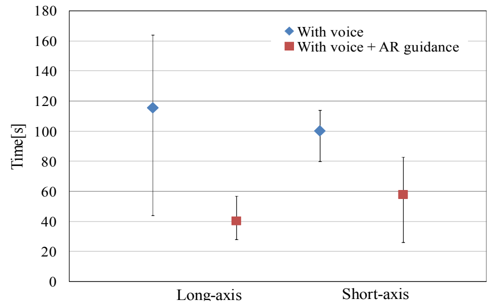


Fig.10 Time required for operators to obtain echocardiogram

VI. Conclusion

The tracking system that used ARToolKit was developed to record the position and the angle of the probe. Graphical interface was developed to instruct the operator the method of probe operation by superimposing CG on the patient's body based on AR technology. The probe position and angle that the doctor acquired echogram in the past was reproduced and displayed by correcting the position of the patient-marker from the original. As a results, reproduced echogram was evaluated to satisfy an actual diagnosis and time to obtain echogram was shortened. We are going to enhance the accuracy of the system in cooperation with medical doctors under actual situation of diagnosis.

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