TOF-based 3-Dimensional Head-Tracking System for Repetitive Transcranial Magnetic Stimulation

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Abstract— Many survivors from brain infraction and hemorrhage get peripheral nerve damage that sometimes causes neuropathic pain even without external injury. While no medication is useful for neuropathic pain, repetitive transcranial magnetic stimulation (rTMS) has gathered attention for mitigating this pain. Existing rTMS treatments requires precise localization of the stimulation target in the brain and it is necessary to bind a patient to a bed. This paper proposes a new localizing system scheme for keeping the patient unconstrained, using a TOF camera to measure the three-dimensional shape of an object in realtime.

Fig. 1. Existing rTMS method[4]

I. Introduction

A. Repetitive trans-cranial magnetic stimulation

Lesions or diseases of the central or peripheral nervous system can cause neuropathic pains. There are no specific treatments for curing neuropathic pains completely, since decisive medication has not been found yet. While the current treatment is performed for the purpose of easing pain, repetitive transcranial magnetic stimulation (rTMS) is expected to be a more effective way to ease such pain. rTMS uses electromagnetic induction to induce weak electric currents in the brain by rapidly changing the magnetic field from the outside of the cranium. rTMS is a noninvasive treatment which provides stimulation on a specific brain nerve by focusing the magnetic field by using a hand-held coil. It is reported that rTMS is effective against depression and Parkinsonism, and safety standards of rTMS have been clarified by clinical research as well [1].

B. Existing treatment methods

To acquire the beneficial effects of rTMS, precisely localizing the stimulation spot on the brain during every treatment is necessary. The existing rTMS treatment method performs a positional alignment between the pre-scanned magnetic resonance imaging (MRI) data of the patient's head, the real head, and the stimulation coil. Often, optical tracking systems are used for this alignment[2]. The alignment is technically performed by a marker-based sensing that tracks 3-dimensional (3D) positions of multiple retro-reflective markers attached on the bed and to the stimulation coil[3]. The MRI data aligned to the real head is used to show and target the spot on the brain from outside of the head. A doctor manually does this by pointing to several medical feature points in both the MRI and the real head since the physical markers cannot be attached to the real head constantly. After this MRI alignment, maintaining the positional relation between the markers on the bed and the patient's head is key, and thus, the patient is bound to the bed during the treatment as shown in Fig.1. Since this situation is painful for the patient and is not easy to set up for non-specialized physicians, the popularity of the rTMS has not spread.

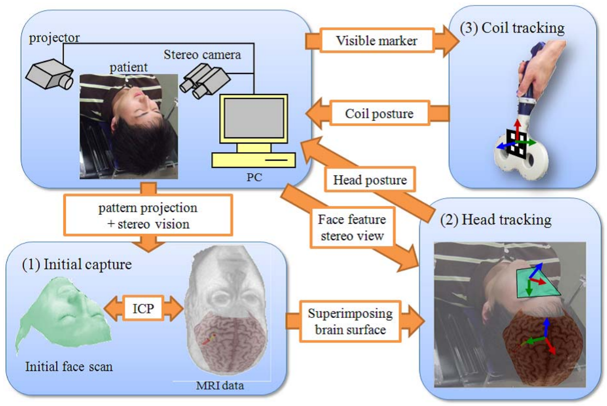

Fig. 2. Prior system process[4]

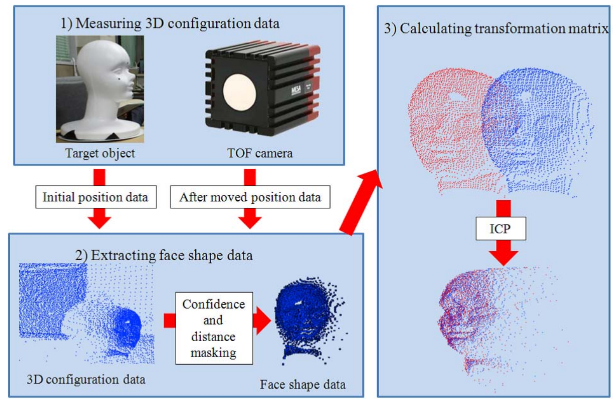

Fig. 3. Proposed system process

C. Related research

To solve the problem of existing rTMS treatment methods, Yasumuro proposed a marker-less, non-contact 3D tracking system, employing a stereo video camera[4]. The main functions of this system are automated MRI alignment, head tracking, and coil tracking. Fig.2 shows an overview of the system. Using a stereo camera and a projector, dense face shape can be captured and shape matching allows the initial MRI alignment. The same stereo camera tracks both the motions of the head and the coil as well. To speed up the tracking process, only imagery feature points are tracked and triangulated and eventually realtime 3D positioning is achieved. However, the accuracy is not always adequate, due to the limitation of the image size and the baseline length of the stereo camera. In fact, these limitations are intrinsic for the stereo camera approach. Image capturing with a pair of cameras requires a constant overhead, and higher image resolution brings further process overheads synergistically. The longer baseline theoretically enhances precision, but makes stereo matching difficult, since the target appearance varies from each camera. Furthermore, in the future, a long baseline stereo camera and a dual frame grabber with projection equipment might be too big configuration for packaging as a commercial product.

II. Proposed method

A. Overview

Since the problems of previous research come from the measurement scheme, we propose a localization method using a time-of-flight (TOF) type of camera. A TOF camera is capable of acquiring not only 3D range information but also luminance images and range measurement confidence for each pixel. In addition, the camera's functions can recently be packed into a small device[5, 6]. This paper reports the fundamental applicability of TOF cameras for rTMS use. The proposed method consists of three steps. First, the 3D configuration data is measured by a TOF camera. The TOF camera obtains all the surface data of the objects in its field of view as a set of points in realtime. Secondly, face shape is extracted by applying confidence and distance masking for the obtained configuration data. The confidence mask eliminates the low sensitivity confidence areas, which are possibly noisy configurations. The distance mask excludes the improper range parts. This step operation is performed again after the target has been moved. As a result, shape data about before and after change posture is obtained. Finally, the transformation matrix is calculated by the iterative closest points (ICP) algorithm, which uses postural change parameters[7]. The ICP algorithm calculates a transformation matrix about how to match the position of two-shape data. The transformation matrix indicates how the object moved. Calculating the transformation matrix in realtime, it is possible to get a patient's posture movement from the initial position. In this way, the fast and non-contact tracking of the patient's face posture is realized. Due to this, position alignment can be performed without binding a patient to a bed. Therefore, lightening the burden imposed on the patient is possible.

B. Time-of-flight camera

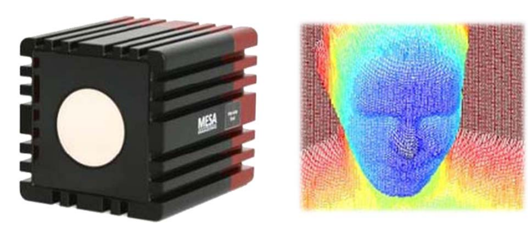

Fig. 4. TOF camera and obtained data[6]

TOF camera sensing is based on the time of flight principle; The time taken for light to travel from an active illumination source to the target objects is measured to

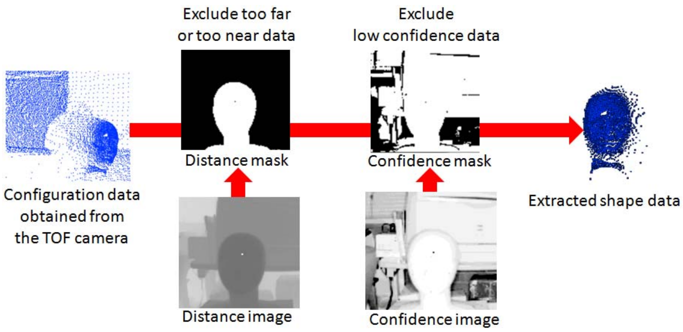

Fig. 5. Distance and Confidence masking

calculate the distance to the target object. The light-receiving sensor has a number of pixels, each of which measure the phase of a modulated light signal independently. Giving the speed of light c, we can calculate the distance corresponding to one full cycle by:

$$D = \frac{c}{2f}\frac{\phi}{2\pi} \tag{1}$$

Where f is the modulation frequency of the illumination and ϕ is the detected phase shift by matching the modulation pattern and the reflection signal. This principle allows the TOF camera to obtain (near-infrared) luminance images and confidence images as well as range images. The confidence image is composed of matching scores that come from the phase shift calculation simultaneously. All these imaging functionalities can be achieved in a single sensing device, but are equivalent to the stereo camera's properties, which are stereo-vision disparities, intensity images and stereo- matching confidences.

C. Distance and Confidence masking

Considering the use of rTMS, the proper distance of the target patient from the camera can be assumed. This assumption allows us to make a filter to exclude too far or too near data. The proper distance is naturally defined by the field of view of the camera, which specifies the framing size of the patient relative to his/her distance. The configuration data obtained from the TOF camera sometimes contain low confidence data. Most of the low confidence parts might be objects so far away that the distance mask excludes them. However, there are a few remaining low confidence data such as shiny objects or too dark parts, whose distances seem appropriate, but are low sensing confidences. These areas can be bothersome noises for further processing and need to be removed.

D. ICP algorithm

As used for the initial alignment[4], the iterative closest point (ICP) algorithm is a method for aligning three-dimensional models[7]. The ICP algorithm calculates rigid body transformation parameters, minimizing the distance between the 3D point cloud sets by an iterative calculation. The basic ICP algorithm is composed of six stages of the algorithm:

1. *Selection* : Selection of some set of points in one or both meshes.
2. *Matching* : Matching these points to samples in the other mesh.
3. *Weighting* : Weighting the corresponding pairs appropriately.
4. *Rejecting* : Rejecting certain pairs based on looking at each pair individually, or considering the entire set of pairs.
5. *Errormetric* : Assigning an error metric based on the point pairs.
6. *Minimizing* : Minimizing the error metric.

In every iteration, corresponding points' pairs seek to find the best match of the overall point cloud. Finding the rigid body transformation is equal to finding postural change parameters for how the point cloud moved. By calculating these parameters in realtime, it is possible to track changes of the head pose. In the same manner, initial MRI alignment is also possible easily and the entire process becomes straightforward.

III. Experimental result

We implemented a tracking software module based on TOF camera sensor output and conducted an experiment of accuracy evaluation for tracking rotational and translational movement of the head. We used a polystyrene human head model to give quantitative movements. The devices and software used in the experimental system are listed in Table 1. The equipment was placed as shown in Fig.6. First, we measured and recorded the face model configurations of 1,500 3D points by the TOF camera, giving 2.5 deg and 5.0 cm movement intervals for the rotation and translation, respectively. Secondly, we matched consecutive 3D data sets by the ICP algorithm using a Visualization Tool Kit (VTK)[8]. The ICP algorithm provides the transformation matrices, which track the face

TABLE I
Devices and Softwares for experiments

TOF camera	SR4000, MESA Imaging AG[6]
	176 x 144 pix
PC	CPU:Core2 Duo, 3.00GHz
	2.00GB RAM
Library	MS Visual studio on windows 7 32bit
	OpenCV, OpenGL, VTK[8]

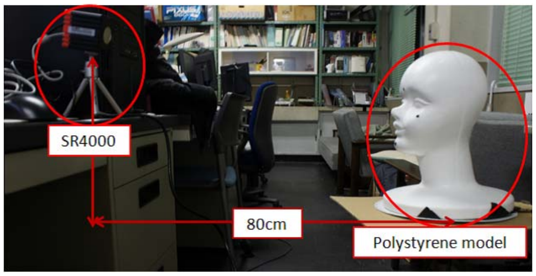

Fig. 6. Experimental setup

positions. Finally, we compared the tracked face position data and the actual position data to verify the positioning error. Experimental results are shown in Figs. 7 and 8 for translational and rotational movements, respectively. The coordinate system is fixed to the camera and the x and the y axis are parallel to the camera-image plane.

IV. Discussion

The rTMS is supposed to target a spot of 1cm size in diameter[1]. Our result shows that the tracking error level satisfies rTMS specification within ±10 deg and ±20 cm variation from the initial position. The average of the computation time for the ICP was 0.3 sec of interactive performance rate. In both results, the error of z-axis direction tends to be larger than in the other direction. The most likely cause comes from the nature of the TOF-based measurement based on phase shift detection by modulation pattern matching. And thus, the range value for each pixel contains flickering. Since the capturing rate is about 50 fps, the post process can be improved to stabilize the range images.

V. Conclusion

This paper proposed a TOF-based head tracking method for rTMS. The experimental system which uses a combination of a TOF camera and position matching by an ICP algorithm satisfied the required accuracy for rTMS, and showed a potential for non-binding rTMS treatment and its feasibility. In addition, the system composition is quite compact due to the TOF camera sensing module whose chip is capable of outputting several types of imaging signals that are advantageous for effective filtering for human interface. Our next focus is to apply this method to the actual human face and to accomplish the same error level together with the coil tracking to achieve compact packaging as a stand-alone system configuration.

Acknowledgements

This paper was financially supported in part by Kansai University Research Grants: Grand-in-Aid for Joint Research, 2010-2011, and was also supported by a grant from Teijin Pharma Limited.

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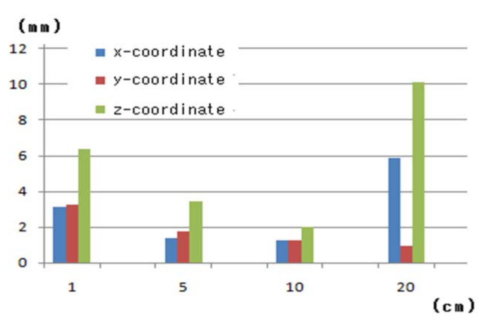

Fig. 7. Tracking errors in translational movement

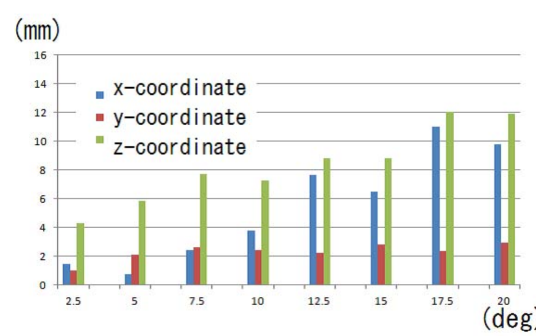

Fig. 8. Tracking errors in rotational movement