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Coil Positioning System for Repetitive Transcranial Magnetic Stimulation Treatment by ToF Camera Ego-Motion

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Abstract— **Repetitive transcranial magnetic stimulation (rTMS) is a non-invasive method for treating various neurological and psychiatric disorders. With the growing demands of neuropathic pain patients and their increasing numbers, rTMS treatment tools are becoming more necessary. rTMS uses electromagnetic induction to induce weak electric currents by rapidly changing the magnetic field. Targeting the electric current to a specific part of the brain is one treatment for pain relief. This paper focuses on treatment for neuropathic pain caused by a lesion or disease of the central or peripheral nervous system, including stroke, trauma, or surgery. However, the current style of rTMS treatment is still developing and is so technically specialized that only a limited number of hospitals and only a handful of specialists can provide this therapy. The existing rTMS systems use an optical marker-based 3D sensing technique that positions the stimulation coil to target the small region of interest in the brain through co-registration with pre-scanned MRI data. This system requires the patient to be immobilized on a bed. The optical markers for 3D sensing are placed on the patient's head to maintain accurate positioning. We propose a constraints-free, markerless rTMS system, which employs ego-motion, a computation technique to estimate relative 3D motion of a camera to what the camera sees. We use a ToF sensor as a camera, which is capble of capturing shape information from a single viewpoint instantly. The markerless target spot is based on the shape features of the patient's face. This paper shows the process of a prototype system and its potential for achieving an easy-to-handle system framework.**

I. INTRODUCTION

Repetitive transcranial magnetic stimulation (rTMS) has been gathering attention as a non-invasive method for treating various neurological and psychiatric disorders including strokes, Parkinson's disease, and depression. rTMS uses electromagnetic induction to induce weak electric currents by the rapid changes of a pulsed magnetic field; thus, rTMS treatment is capable of stimulating specific parts of the brain, including the primary motor area for neuropathic pain, with minimal discomfort [1], [2].

The existing treatment method of rTMS is achieved by an optical three-dimensional (3D) sensing technique that positions a stimulation coil to target the small region of interest (ROI) in the brain that needs to be stimulated [3], [4], [5]. As shown in Figure I, before the treatment, doctors measure the 3D position of feature points on the patient's head, for example: the nasal point, nose top and anterior auricular points. These positions allow the system to co-register the pre-scanned MRI data with the sensor coordinates of the corresponding measured feature points. Then the positioning sensor tracks the coil by using the set of optical markers on the patient's head. Showing the relative position of the coil and the registered MRI data helps the doctor to target the spot in the brain. To ensure positioning accuracy, the patient must be immobilized on the bed throughout the treatment, because the patient's feature points are based on the fixed optical markers.

Fig. 1. Example of current rTMS procedure

Especially, since the desired effects of rTMS last several hours only, rTMS treatments need to be available whenever recommended for the patient. In reality, current rTMS treatments are only available at specialized clinics such as university hospitals, because only experienced physicians in a limited number of hospitals can use the expensive and complicated rTMS system.

This paper focuses on a new treatment to alleviate neuropathic pain caused by a lesion or disease of the central or peripheral nervous system, including stroke, trauma or surgical operation. This new treatment is a constraints-free, markerless rTMS system, which employs a single time-of-flight (ToF) camera and a compact-sensor module. By using the relative position of the ToF camera, The target spot based on the patient's face shape is determined.

II. RELATED WORK

Fukushima et al. proposed a magnetic navigation system using inexpensive and small magnetic sensors. Their system was designed for home use of rTMS [6]. By collecting the spatial data samples of the magnetic field to record the proper position and orientation of the stimulation coil during the initial treatment by an expert doctor, the system helps the user navigate and reproduce the coil position to

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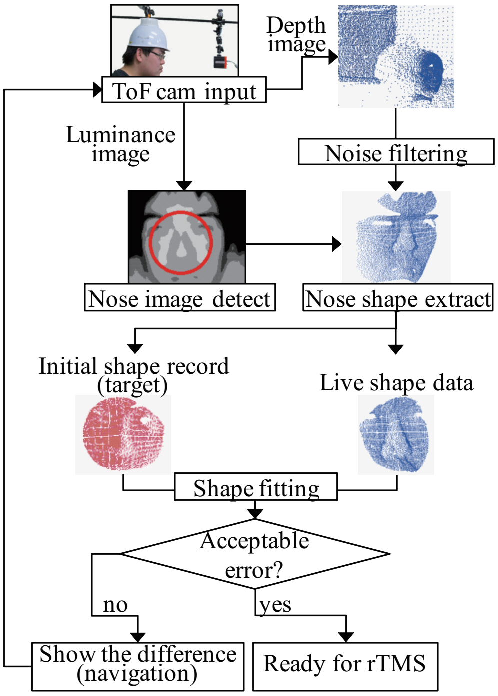

Fig. 2. Process of the proposed system

target the treatment spot for subsequent home treatments. This system theoretically allows any user, even one without medical knowledge and techniques, to easily position the coil for subsequent treatment. The magnetic sensors are fixed on a glasses-style mounting device that the user can wear when applying the treatment. The user does not need to be immobilized on the bed. Since the positioning accuracy depends on the reproducibility of the glasses-style mounting device, this device must be precisely adjusted to the individual patient. Yasumuro et al. also proposed a 3D navigation system for rTMS that uses stereo-camera sensors capable of capturing the 3D depth images of the patient's face shape [7]. The 3D shape features in the face can be used as landmarks to track the patient's head in a constraints-free manner. The limitations of the tracking range of the head posture in [7] come from the sensing scheme of the stereo-camera configurations.

The approach proposed in this paper improves upon the previous tracking systems based on depth-image sensing. This system takes advantage of the constraint-free setup for patient comfort and the stable positioning accuracy that is independent of the sensor mounting conditions.

III. APPROACH

A. *Overview*

The previous stereo-camera approach tracks both motions of the head and those of the coil [7]. However, occasionally the accuracy is inadequate due to the image size and the baseline length of the stereo camera. In fact, these limitations are intrinsic to the stereo-camera approach. Image capturing with a pair of cameras is required and the higher image resolution brings additional process overheads. The longer baseline theoretically enhances the precision, but it makes stereo matching difficult, since the target appearance varies from each camera, and occlusion occurs in the worst cases.

We propose a localization method using a time-of-flight (ToF) type of camera. A ToF camera is capable of acquiring 3D depth images from a single viewpoint, unlike a stereo-camera sensor. Single viewpoint measurement has the advantages of capturing characteristic uneven shapes and avoiding occlusions caused by different viewpoints in the stereo camera. A ToF camera also outputs luminance images and confidence images. The confidence image contains reliability information of the range measurement for each pixel. In addition, the ToF functions can be packed into a small device [8], [9]. In the proposed system, we connected the stimulation coil and the ToF camera module rigidly to simplify the system configuration, so that the proper camera position leads the coil to the correct position (See Figure 3). Reducing the tracking object reduces the error in the total system [15]. The camera position can be monitored by the camera itself by finding the relative position and orientation to the patient's head through the depth view.

The proposed method consists of three major steps, which are also shown in Fig. 2. First, the ToF camera captures 3D depth images, which include all the surface shapes of the objects in the field of view in real time. The face shape is extracted by applying distance and confidence information to mask out unnecessary regions in the depth images. The mask eliminates the low-sensitivity confidence areas, which are possibly noisy. The distance mask excludes improper ranges. Second, the system detects the nose region in the infra-red luminance image, which is another output from the ToF camera. The detected region is applied to the depth image to make the 3D shape data of the nose.

Finally, the transformation between the current nose shape data and the pre-recorded target nose shape is calculated to fit the initial prerecorded shape with the live shape. The geometry of the target shape is recorded for the proper

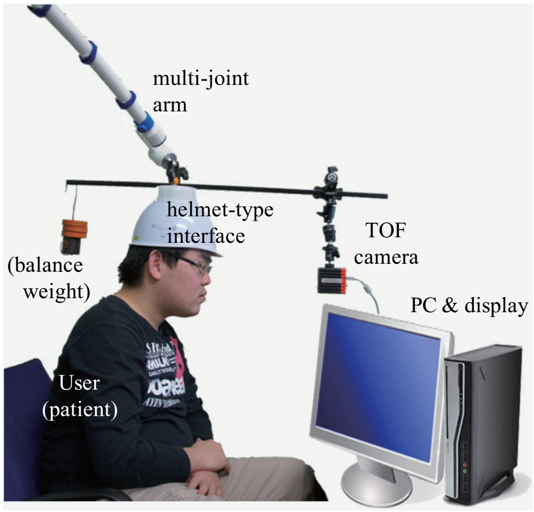

Fig. 3. Prototype system

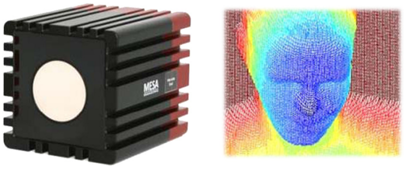

Fig. 4. ToF camera and obtained data [9]

stimulation condition of the coil setup. In this way, the difference of the current and target geometries of the camera setup, which is equivalent to the coil geometry, shows how the user can adjust the coil position to the ideal setup. Figure 3 shows the proto-type of the proposed system. The ToF camera is fixed on a helmet-shaped interface and supported by a joint-arm, so the helmet position can be adjusted easily.

B. Depth Information by ToF Camera

The sensing mechanism of the ToF camera is based on the time-of-flight principle: the time taken for light to travel from an active illumination source to the target objects in the camera's field of view and then back to the sensor is measured to calculate the distance to the target object. The light-receiving sensor receives the number of pixels, each of which measures the phase of modulated light signal independently. Given the speed of light c, we can calculate the distance D corresponding to one full cycle as follows:

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

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 simultaneously with the range images. The confidence image is composed of the numbers coming from the reliability of the phase shift computation for each pixel. All these imaging functionalities can be achieved in a single sensing device, but they are equivalent to the following counterparts in the stereo camera: stereo-vision disparities, intensity images, and stereo-matching confidences.

C. Extracting the ROI from Depth Image

Since the ToF camera is connected to the coil, the proper distance of the target patient from the camera can be assumed. With this assumption, the filter can exclude too far or too near data. The ToF camera data are useful to exclude the data with low confidences. Most of the low-confidence data could be far objects that the distance mask excludes as well. However, a few low-confidence data remain. These data can include shiny objects or too dark parts, whose distances seem proper but their sensing confidences are low.

For effectively narrowing the feature searching area, we apply face-tracking on the luminance image frames. We use a combination of Haar-like features [10] and an Adaboost training algorithm [11]. We prepared 150 gray-scale photos of a human nose from the frontal view as "correct" images and 3000 photos without human noses as "incorrect" images for training the Adaboost classifier using Haar-like features. Since fixed correspondences exist between the luminance image pixels and the depth-image points, the detected ROIs of the nose area in the luminance images extract the shape data of the same area. (See Figure 5.)

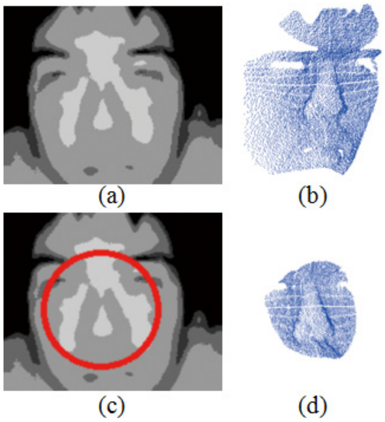

Fig. 5. ROI extraction: filtered face area of luminance (a) and depth (b) images, and detected nose area (c),(d)

D. Ego-motion of the ToF Camera

For fitting the shapes of the depth images, the iterative closest point (ICP) algorithm can be used [12]. ICP is often employed to find rigid-body motion by minimizing the difference between two shape data sets of point sets a and b, as shown in equation (2). Since the human face has a characteristic shape around the nose, the ICP is expected to be applicable for searching the proper corresponding points to fit together the point sets.

$$E = \sum_{i=1}^{N} (Ra_i + t - b_i)^T (Ra_i + t - b_i) \tag{2}$$

The inputs are the two point sets of the patient's face from the initially recorded shape data and the currently obtained shape data. The output is a refined result of the transformation with rotation R and translation t to fit them together, as in the following steps:

1) Associate points by the nearest neighbor criteria.
2) Estimate transformation parameters by a mean square cost function (2).
3) Transform the points by using the estimated parameters.
4) Re-associate the points and iterate.

In every iteration, corresponding pairs of points are sought for finding the best match of all the point sets. The initial shape data are assumed to be recorded in the first clinical treatment and used as the target data for reproducing the stimulation configuration in subsequent treatments.

The ICP result of the transformation is the relative position of the ToF camera for the proper position to set the stimulation coil. Continuously showing the residual gap between the current camera position and that of the proper position is useful for navigating how the coil position should be adjusted, as shown in Figure 6.

TABLE I

DEVICES AND SOFTWARE FOR EXPERIMENTS

ToF camera	SR4000, MESA Imaging AG [9]
	176 x 144 pix
PC	CPU:Core2 Duo, 3.00 GHz, 2.00 GB RAM
Software, Library	MS Visual studio 2010 on Windows 7 32 bit
	OpenCV [13], OpenGL, VTK [14]

IV. EXPERIMENTS

We implemented the proposed method on a prototype system to evaluate the system accuracy. The devices and software used for our current prototype are listed in Table I. We used the library sets in OpenCV [13] for implementing the Adaboost training algorithm with the Haar-Like feature, and the Visualization Tool Kit (VTK) by Kitware Inc. [14] for shape fitting by the ICP algorithm. To verify the precision of the reproducibility of the coil positioning by the proposed system, we employed a marker-based 3D positioning sensor, POLARIS by NDI Inc. [4]. The marker arrangement and corresponding coordinate systems are shown in Figure 7. Based on the sensor coordinates, the geometry between the helmet and the head marker is recorded as the transformation between them. The initial transformation is recorded and we assume that this transformation is specified by a doctor as the ideal situation for rTMS. Then the subject starts the adjustment of the coil position by slight changes of the helmet position. The final transformation is recorded in the experiments. The residual geometrical difference is measured by the distance and the angle between the marker's coordinates of the helmet and the head. The angular residual is calculated through the quaternion expression of the rotational transformation between the marker coordinates. The averaged positioning error was 1.54 mm (1.40 mm STD) in distance and the averaged directional angle error was 2.04 deg (1.02 deg STD) for 10 trials by one subject. The achieved performance is practical, referring to the current clinical rTMS demands; the target diameter is 10 mm [2] and the uncertainty index of the total system is 6.0 mm [15].

V. CONCLUSION

This paper proposed a navigation system for visualizing the rTMS target by a positioning technique of ego-motion monitoring of the ToF camera. By making the most use of shape measurements by a single ToF camera and a compact coil-sensor module, the prototype system showed effective performance for constraints-free rTMS treatment.

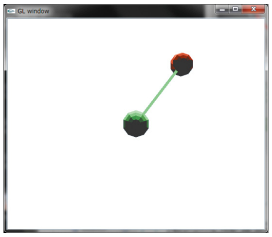

Fig. 6. Helmet adjustment navigation; current camera position from the user's view (left green ball) and target position (right red ball)

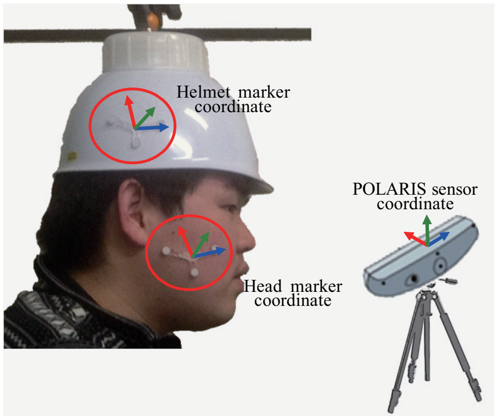

Fig. 7. Coordinate systems

Our next step includes designing the visual user interfaces for easy-to-understand navigation and easy coil attachment for the helmet-shaped physical user interface.

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