Medical Navigation Based on Coloured Markers for Image-guided Surgery

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Abstract

Image-guided Surgery (IGS) is an advanced medical navigation technology that enhances surgical operations and outcomes. The infrared markers have been used in previous years as references to visualize a patient's body part, whether the markers are active or passive. This paper presents a new reference tool of tracking, and develops a new algorithm of tracking an object in real time. Three coloured markers have been used as references of visualizing a patient's body part by providing many advantages, such as an unbounded objects tracking, an inexpensive system compared to the IR-markers system, and an unrestricted working area. This paper shows that using a coloured marker as a reference, a good accuracy of visualization (RMS error 3.78 mm) at the distance of 1000 to 1300 mm can be generated. Image filtering techniques have been used to process the images captured from a stereo camera. As a result, medical navigation based on coloured markers contributes a promising result of Image-Guided Surgery. Moreover, a faster algorithm for a real time tracking of coloured markers has been developed.

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1. Introduction

The Image-guided Surgery (IGS) plays a significant role in surgical operations since it provides a reliable localization and tracking of a human body parts. It describes a surgical concept, which uses computer technology for surgical planning, and for performing or guiding surgical interventions. The significant improvement of the surgical
accuracy has been clinically tested in the fields of neurosurgery, ear, nose and throat (ENT) surgery, knee surgery and orthopedic surgery. The surgeons have recognized the benefits of IGS for patients, doctors and hospitals [1]. The patient parts and precise anatomical information, such as the complete knee joint structure, can be visualized without CT scan in a small incision for every individual surgery, through IGS advance bone morphing technology. The accuracy of the bone cut can be up to 0.1mm to 0.1degree. Consequently, surgeons can make the decision without the estimation of the inner bone structure and where exactly to cut the specific bones. Image-guided Surgery can provide supplementary information that can’t be given with the conventional tools [2].

In IGS, we can define the actual surgical intervention as a surgical navigation. The surgeon will use special instruments in the surgical navigation systems, which are connected to the system to touch the anatomical position of the patient. Therefore, the position will be shown in the images taken from this patient simultaneously. Thus, the surgeon can use the instrument to ‘navigate’ the images of the patient by moving that instrument [3]. IGS systems were introduced when the first clinical test on the navigation system was used in classical surgery as a double of classical tools at Orthopedic Hospital in Otwock, Poland [4]. Accordingly, the infrared markers have been used in the past years as references to visualize patient's body part whether the markers are active marker (IR-source), or passive marker (IR-Reflector) as shown in Fig. 1 (a). The first medical tracking system with infrared data transfer was invented by Günter Goldbach in 2006 [5]. Active IR-markers (wired power source) was used. After that the active IR-marker (Battery) was used. Then, the passive (reflector) IR-marker was used [6].

1.1. IGS System and working mechanism

The Medical Navigation System consists of: 1) Computer system, 2) Screen monitor, 3) Two IR cameras, 4) Patient position, and 5) Surgical instruments in relation to the patient. Which are shown in Fig. 1 (b).

![Fig. 1. (a) Using the surgical needle via passive IR-markers [12]; (b) Medical Navigation System [7].](image)

Target structure (i.e. bones) is visualized together with the tools on the computer screen. Position of the tools and target structure are calculated in real-time. Thus, it becomes easy to compare the actual position with the required position. Therefore, the surgical instruments and the target structures are visualized in their correct relative position [7].

The working mechanism of Image-guided Surgery system is interrelated. In the IR-tracking system there is a camera array, an infrared light source and at least one medical appliance controllable via infrared signals or operative to exchange data via infrared signals. Surgeon uses medical appliance, which is connected to the IGS system to touch a specific position on the patient's body. This position can simultaneously be shown in the images taken from this patient. Thus the surgeon can use the medical instrument to navigate in the images of the patient by moving that medical instrument. IGS can provide extra information that can’t be provided by the conventional tools. With this information, surgeon can make the decision where to cut the bones exactly. Accordingly, the position of the patient's body target and the position of the medical tools are calculated in real-time. Therefore, the comparison between the required position and the actual position becomes attainable [2].
1.2. Related work

In recent years, many researchers have done a lot of work in this area. In [8], Riera, Parrilla and Hueso proposed an experimental analysis of 3D object motion in stationary and rotating system and tracking the object with a stereoscopic camera. They found that the average distance between the experimental points and the simulated points of the object in \((x, y, z)\) is 0.25cm. Smigielski [6] used a cone pattern as a reference marker in his project with a very good result. 3D RMS accuracy was 0.32mm, 79.6% of results have error below 0.35mm and 94.7% of results were below 0.7mm, while Blackman [4] used checkered pattern as a reference marker in his project with an accuracy of 0.3mm. Despite the accuracy found in their works, the medical instrument has limited movement based on the reference used. [16] and [17] are good research studies on three-dimensional tracking objects in a stereo video sequence. There is also extensive literature on [9] and [15] to solve the correspondence problem in stereo-vision camera for the navigation systems. However, none of them used a coloured marker as a reference marker before. In this work, we have proposed coloured reference markers as a new reference tool of tracking with its algorithm for IGS. Accuracy analysis has been presented for the proposed coloured marker. Root mean square errors (RMSE) in positioning of the markers were measured and quantified.

2. Methodology

This section provides a detailed description of the proposed coloured markers tracking method.

2.1. Detection the circular objects in an image

The first step is to detect the circular objects in the image captured by the camera. To achieve this we used "imfindcircles" function from MATLAB to automatically detect circles or circular objects in an image. Also, the function "viscircles" has been used to circularize the detected circles, as shown in Fig. 2.

Fig. 2. (a) The markers before the circular detection. (b) After the circular detection of the three markers.

It should be noted that changing the parameters of "imfindcircles" to be more aggressive in detection, may find unwanted circles. Accordingly, we should choose the suitable parameters to find the true circles we want. The center of each circular object can be found by using the same function "imfindcircles" in MATLAB [13], as shown in Fig. 3 (a).

\[
\text{[centers, radii, metric]} = \text{imfindcircles}(<\text{image}>, <\text{parameters}>); \]

Coordinates of the circles’ centers, will be returned as a \(P\)-by-2 matrix where "\(P\)" is the number of circles detected. The first column is the x-coordinates of the circles centers, while the second column is the y-coordinates of the circles centers.

2.2. Recognition of the color of each marker

After determining the circular objects in the image, and finding the center of each object, we need to recognize the
color of each circular object. For this purpose, Hue, Saturation, Value (HSV) color space has been used to recognize
the specific area of each marker, which is shown in Fig. 3 (b). Consequently, the conditional loops used to match the
coordinates of the circle centers on the correct marker since we do not know which color belongs to which
coordinate. Afterwards, the same method applied to find the markers coordinates of the second camera.

2.3. To determine each coloured marker in space \((x, y, z)\)

After finding the center of each circular coloured object we need to determine each coloured marker in space \((x, y, z)\)
using the concept of motion parallax and trigonometry [8][10]. To better illustrate how the stereo vision works, Fig.
4(a) demonstrates a diagram of a simplified stereo vision setup, where the two cameras are mounted parallel to each
other, and have the same focal length \((f)\) [14]. Three-dimensional (3D) scene is projected onto a two-dimensional
image plane [11]. The projection geometry for two camera system in Fig. 4(b) can be calculated based on the
following equations:
To find \((x, y, z)\) for marker1:

\[
\frac{X_L}{U_L} = \frac{f}{y_1}
\]  

(1)

\[
\frac{X_R}{U_L - B} = \frac{f}{y_1}
\]  

(2)

By solving (1) into (2), we get that,

\[
X_L - X_R = \frac{f \times B}{y_1}
\]  

(3)

By simplifying (3), we obtain the following results,

\[
y_1 = \frac{f \times B}{X_L - X_R}
\]  

(4)

\[
x_1 = \frac{X_L \times B}{X_L - X_R}
\]  

(5)

And since \(Z_L \equiv Z_R\),

\[
z_1 = \frac{Z_L \times B}{X_L - X_R}
\]  

(6)

**Nomenclature**

- \(f\) focal length of the camera.
- \(B\) distance between the two cameras.
- \(y_1\) optical axis of a camera.
- \(U_{LR}\) object displacement of the left or the right camera.
- \(X_{LR}\) projection of the real-world point \((M)\) on an image acquired by the left or the right camera in the X-axis.
- \(Z_{LR}\) projection of the real-world point \((M)\) on an image acquired by the left or the right camera in the Z-axis.
- \(P\) number of circles detected

**3. Result and discussion**

The system is implemented using MATLAB 2012a on a standard PC hardware (Core 2 Duo processor at 1.8GHz with 1GB RAM) and works at 15-25fps. The video image size is 640x480. All the markers have been recognized and determined their coordinates in real time. As shown in Table 1, the root mean square (RMS) of the 3D errors for a marker in space at distance from 1000mm to 1300mm was 3.78mm. Correspondingly, Fig. 5 shows stability of the error points distribution at the distance from 1000mm to 1300mm. Meanwhile, the maximum error point was 20mm at the distance 1800mm, and it is obvious that, if the marker's distance increases the error rate will increase as well.

In summary, the performance of the proposed method is quite good and it demonstrates that optimization of the
performance depends on the choice of the best position (distance) area and the quality of the camera and the capability of the PC hardware used.

Table 1. RMS of 3D errors for a marker in space at distance 1000mm to 1300mm

<table>
<thead>
<tr>
<th>Distance (mm)</th>
<th>3D error (mm) Exp. 1</th>
<th>3D error (mm) Exp. 2</th>
<th>3D error (mm) Exp. 3</th>
<th>3D error (mm) Exp. 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
<td>-1</td>
<td>2</td>
<td>3</td>
<td>-1</td>
</tr>
<tr>
<td>1100</td>
<td>-2</td>
<td>1</td>
<td>-3</td>
<td>4</td>
</tr>
<tr>
<td>1200</td>
<td>3</td>
<td>-5</td>
<td>-6</td>
<td>2</td>
</tr>
<tr>
<td>1300</td>
<td>-4</td>
<td>7</td>
<td>8</td>
<td>-2</td>
</tr>
<tr>
<td>RMS</td>
<td>2.74</td>
<td>4.44</td>
<td>5.43</td>
<td>2.50</td>
</tr>
<tr>
<td>RMS_Total</td>
<td></td>
<td></td>
<td></td>
<td>3.78</td>
</tr>
</tbody>
</table>

Fig. 5. Result of the absolute errors for a marker in space at distance from 1000mm to 1800mm.

After finding the 3-position of the 3-marker, the medical instrument can be visualized either by Simulink® 3D Animation™: The Virtual Reality Modeling Language (VRML) or by controlling Solid Works Animator from MATLAB via CADLab. Accordingly, by converting these three Cartesian coordinates to polar coordinates (translation & rotation), the visualization of the medical instrument becomes simple.

4. Conclusion

In this paper an approach for tracking of coloured reference markers has been presented. The proposed approach has been tested in the context of three coloured markers tracking. Experimental result shows that the method is capable of tracking several coloured reference markers that may move in complex, overlapping trajectories. The target position was measured in \((x, y, z)\) axes. A fast MATLAB algorithm was developed for a real time tracking of coloured markers. The accuracy of the result is affected by the quality of the camera and the capability of the PC hardware used in this experiment.
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