A 3D Registration Method Based on Indoor Positioning Through Networking

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Abstract. The Augmented Reality (AR) technique has been widely used in the academic and industrial community, which integrates virtual data into the real-world environments. However, the key implementation to AR is the 3D registration method because it refers to effectively display object in virtual environment. Most of existing approaches are hard to ensure the quality of 3D registration. Thus, this paper proposes a 3D registration method based on indoor positioning, using gyroscopes, direction sensors and network communications. First, obtain user's line of sight by gyroscopes and direction sensors and send them to server through networking. Second, locate user position by indoor positioning. And then, using these data, calculate the conversion matrix between coordinate systems. Finally, Send data to the client over the network to integrate virtual data into the real-world environments. Our method can avoid the errors which may be impacted by the speed of movement and clearness of objects. Furthermore, experiments are carried out to show the feasibility, accuracy and validity of the proposed method.

Keywords: Network · Augmented Reality · 3D registration
Indoor positioning · Ultra wide-band

1 Introduction

Augmented Reality (AR) is a technique that uses additional graphics or textual information to dynamically enhance the surrounding natural scenes. AR systems allow users to interact with real and computer-generated objects by displaying 3D virtual objects registered in a user's natural environment [1]. 3D registration [2] is the process of positioning virtual object in 3D space, which is one of the most critical technique in AR systems.

At present, 3D registration method at home and abroad is divided into the following three kinds: recognition-based 3D registration, vision-based 3D registration [3] and

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self-tracing 3D registration [4]. Vision-based 3D registration is commonly used for its good overall performance in 3D registration [5, 6]. Though, this method still has a variety of shortcomings [7, 8]: (1) When the mark is blocked or partially blocked, the system cannot calculate 3D transformation matrix, and that will lead to the failure of 3D registration; (2) Marks are actually a kind of pollution to the real scene; (3) The identification of marks will reduce due to light, shadow, abrasion and other issues.

Consider to these shortcomings of existing 3D registration technique, this paper proposes a method to achieve 3D registration through indoor positioning. The application scenarios are mainly buildings, museums, tourist attractions and so on. In this type of application scenario, the disadvantages of current registration methods are particularly acute because of the harsh environment, and long term effective request. Because such scenes is not easy to change position, we can achieve 3D registration by position and direction of sight.

The rest of this paper is structured as follows. We introduce the indoor four-node spatial positioning model in Sect. 2. And Sect. 3 proposes a method using the indoor spatial positioning to complete 3D registration. Section 4 gives the architecture of AR system and analyzes the performance of this 3D registration method through our experiments. Section 5 is the conclusion of this paper.

2 Four-Node Spatial Positioning Model

Ultra wide-band (UWB) technology [9] is a short-range, high-bandwidth radio technology that was first used in military applications. The UWB signal has a bandwidth of gigahertz and a sub-millisecond pulse time width. Thus, its range resolution is extremely high, which even can reach the level of centimeters [10, 11]. In order to obtain the distance between positioning base station and locating tag, first measure the Time of arrival (TOA) [12] of the UWB signal, then multiply it by the known signal propagation speed, which is also mean speed of light. We select the UWB indoor positioning technology [13] for its good real-time performance, strong anti-interference ability and high positioning accuracy.

There are many algorithms based on three-node positioning algorithm in two dimensional plane, such as triangle centroid method [14]. If 2D space algorithm directly extends to 3D space, it will lead to increased time complexity and reduced positioning accuracy [15]. In this paper, we calculate the vertical position at first, and then transform 3D spatial positioning problem into 2D positioning problem.

For a start, place four UWB base stations indoors. To simplify the calculation, the base stations D_1 and D_4 are perpendicular to the horizontal plane, and the spatial coordinate system is established by setting the plane of D_1, D_4, and the unknown coordinate point D to the YOZ plane. The four-node spatial coordinate system is shown in Fig. 1.

The coordinates of point D_1, D_2, D_3 and D_4 are known while the coordinate of point D is unknown. And d1 represent the distance of D and D_1, so as to d_2, d_3 and d_4. Point D' is the projection of D in XOY plane.

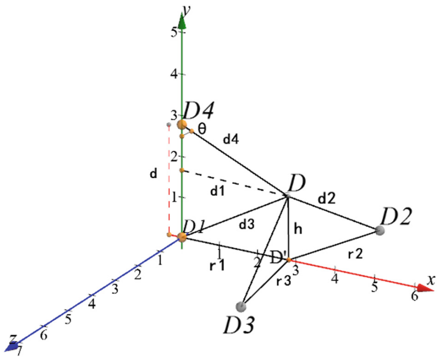

Fig. 1. Four-node spatial coordinate system

Known by Fig. 1:

$$h = d - d_4 \cos\theta \tag{1}$$

$$\begin{aligned} d_4^2 &= d_1^2 - h^2 + (d-h)^2 \\ &= d_1^2 + d^2 - 2dd_1 \cos\theta \end{aligned} \tag{2}$$

By Eq. (2):

$$\cos\theta = \frac{d_1^2 - d_1^2 + d^2}{2dd_1} \tag{3}$$

The vertical height of point D, which set as h, can be obtained from Eqs. (1) and (3):

$$h = d - d_4 \cos\theta = d - \frac{d_4^2 - d_1^2 + d^2}{2d} \tag{4}$$

Then the 3D spatial positioning problem is transformed into a 2D positioning problem by Eq. (5):

$$\begin{cases} r_1 = \sqrt{d_1^2 - h^2} \\ r_2 = \sqrt{d_2^2 - h^2} \\ r_3 = \sqrt{d_3^2 - h^2} \end{cases} \tag{5}$$

In the two dimensional plane XOY, the coordinates of points $D_1(x_1, y_1)$, $D_2(x_2, y_2)$ and $D_3(x_3, y_3)$, and the distances r_1, r_2, r_3 are known.

Using these information, two dimensional coordinates of point D′ can be solved by triangular centroid method. Then, combine it with the Eq. (4) to complete 3D spatial positioning:

$$\begin{cases} x = \dfrac{\frac{x_1}{r_1+r_2} + \frac{x_2}{r_2+r_3} + \frac{x_3}{r_3+r_1}}{\frac{1}{r_1+r_2} + \frac{1}{r_2+r_3} + \frac{1}{r_3+r_1}} \\ y = \dfrac{\frac{y_1}{r_1+r_2} + \frac{y_2}{r_2+r_3} + \frac{y_3}{r_3+r_1}}{\frac{1}{r_1+r_2} + \frac{1}{r_2+r_3} + \frac{1}{r_3+r_1}} \\ z = d - \dfrac{d_4^2 - d_1^2 + d^2}{2d} \end{cases} \tag{6}$$

Due to measurement error, the situation that three circles cannot intersect with one another might happen by using triangle centroid method. Under this situation, ignore the imaginary solution to solve it.

3 3D Registration

To accomplish registration, AR system involves the transformation of four coordinate systems [16] which are shown in Fig. 2.

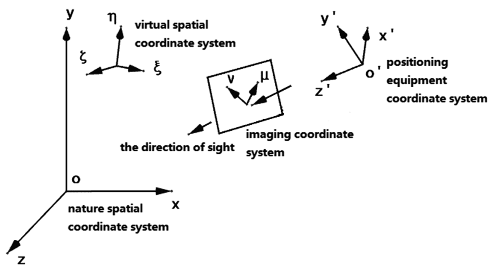

Fig. 2. 3D registered coordinate system

[x, y, z] represents the natural spatial coordinate system, which is the most basic and important one. Select one corner of the house as the origin, and stretch the axis along the intersection of the three planes of the corner. Set the floor plane as XOY plane, and Z axis perpendicular to the XOY plane.

[ξ, η, ζ] represents the virtual spatial coordinate system that is used to describe the virtual space.

[x′, y′, z′] indicates the positioning equipment coordinate system, whose origin is the center point of positioning equipment. Set the direction of sight as the Z axis. The positive direction of Z axis is the direction of sight.

[u, v] represents the imaging coordinate system. Its U, V axis are parallel to X, Y axis in the positioning equipment coordinate system and their positive directions are same.

3.1 Coordinate Transformation

In order to realize the accurate registration of the virtual object to natural scene, need to transform the coordinate of the virtual spatial coordinate system into the coordinate of the imaging coordinate system [17]. So must clarify the following coordinate transformation matrix: the transformation matrix O between the virtual spatial coordinate system and natural spatial coordinate system, the transformation matrix C between the natural spatial coordinate system and the positioning equipment coordinate system, and the transformation matrix P between the positioning equipment coordinate system and imaging coordinate system.

Since the relation between the virtual spatial coordinate system [ξ, η, ζ] and the natural spatial coordinate system [x, y, z] is known, the geometric description [ξ, η, ζ] of 3D object can be transformed into the geometric description [x, y, z]. The homogeneous coordinate is shown as follows:

$$\begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix} = O_{4\times 4} \begin{bmatrix} \xi \\ \eta \\ \zeta \\ 1 \end{bmatrix} \tag{7}$$

In Eq. (7), $O_{4\times4}$ represents the transformation matrix between virtual spatial coordinate system and natural spatial coordinate system.

Similarly, the relation between the positioning equipment coordinate system and the imaging coordinate system is known because of the relative position of display device to the positioning equipment is fixed. Equation (8) shows the conversion relation, where matrix $P_{3\times4}$ represents the transformation matrix.

$$\begin{bmatrix} u \\ v \\ 1 \end{bmatrix} = P_{3\times 4} \begin{bmatrix} x' \\ y' \\ z' \\ 1 \end{bmatrix} \tag{8}$$

The geometric description [x′, y′, z′] in the positioning equipment coordinate system is transformed into the geometric description [x, y, z] in natural spatial coordinate system as follows:

$$\begin{bmatrix} x' \\ y' \\ z' \\ 1 \end{bmatrix} = C_{4\times 4} \begin{bmatrix} \mathrm{x} \\ \mathrm{y} \\ \mathrm{z} \\ 1 \end{bmatrix} \tag{9}$$

In Eq. (9), $C_{4\times4}$ shows the transformation matrix between the positioning equipment coordinate system and natural spatial coordinate system. Therefore, if the transformation matrix $C_{4\times4}$ can be obtained, the geometric description [ξ, η, ζ] in virtual spatial coordinate system is transformed into the geometric description [u, v] in the imaging coordinate system. The equation is shown in Eq. (10).

$$\begin{bmatrix} u \\ v \\ 1 \end{bmatrix} = P_{3\times4}C_{4\times4}O_{4\times4}\begin{bmatrix} \xi \\ \eta \\ \zeta \\ 1 \end{bmatrix} \tag{10}$$

3.2 3D Registration Algorithm

To convert natural spatial coordinate system into positioning equipment coordinate system, matrix $C_{4\times4}$ must be achieved. For convenience, here, use Eq. (11) to express the transformation:

$$\begin{bmatrix} x' \\ y' \\ z' \end{bmatrix} = R \times \begin{bmatrix} \mathrm{x} \\ \mathrm{y} \\ \mathrm{z} \end{bmatrix} + \begin{bmatrix} t_x \\ t_y \\ t_z \end{bmatrix} \tag{11}$$

The matrix R is a 3 × 3 matrix for the rotational transformation, and it reflects the rotation component that the positioning equipment relative to natural spatial coordinate system. The rotation component expresses the three basic rotation of the axis, which can be expressed as follows:

$$R = \begin{bmatrix} r_{xx} & r_{xy} & r_{xz} \\ r_{yx} & r_{yy} & r_{yz} \\ r_{zx} & r_{zy} & r_{zz} \end{bmatrix} \tag{12}$$

Use gyroscopes and direction sensors to attain direction of sight. As shown in Fig. 3, use Euler angle in rectangular coordinate system to describe space angle of the direction of sight. Angle θ is the angle rotated along X axis, and angle ψ is the angle rotated along Y axis while angle Φ for Z axis. The rotation direction is the counter-clockwise rotation direction when viewed from the coordinate system origin in the positive direction of axis. The elements of matrix R are solved by these three angles, shown as follows:

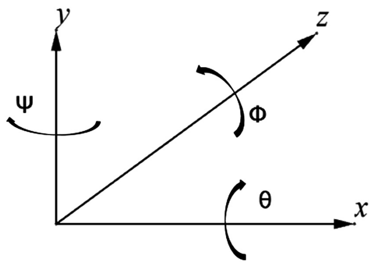

Fig. 3. Euler angles

$$\begin{cases} r_{xx} = \cos\psi\cos\Phi \\ r_{xy} = \sin\theta\sin\psi\cos\Phi - \cos\theta\sin\Phi \\ r_{xz} = \cos\theta\sin\psi\cos\psi + \cos\theta\sin\Phi \\ r_{yx} = \cos\psi\sin\Phi \\ r_{yy} = \sin\theta\sin\psi\sin\Phi + \cos\theta\cos\Phi \\ r_{yz} = \cos\theta\sin\psi\sin\Phi + \sin\theta\cos\Phi \\ r_{zx} = -\sin\psi \\ r_{zy} = \sin\theta\cos\psi \\ r_{zz} = \cos\theta\cos\psi \end{cases} \tag{13}$$

From Eq. (13), according to space angle obtained from positioning sensor, the matrix R is directly attained.

Vector $(t_x, t_y, t_z)^T$ represents translational transformation. And (t_x, t_y, t_z) is the coordinate of positioning equipment in natural spatial coordinate system, which is obtained from Eq. (6).

In summary, obtain the user's direction of sight by gyroscope and direction sensor at first. Then attain the user's positioning data through indoor spatial positioning technology. At last, calculate the conversion matrix $C_{4\times4}$ to achieve 3D registration by using these information. With the transformation relation of Eq. (10), 3D registration is completed.

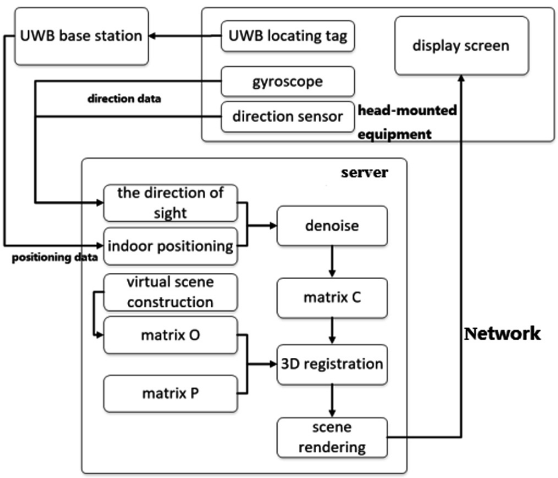

Fig. 4. AR system structure

4 Experiment

4.1 AR System Structure

As shown in Fig. 4, the entire AR system structure is divided into two parts: head-mounted display as the client and the remote 3D registration server. The head-mounted display integrates positioning equipment which includes UWB locating tag, gyroscope and direction sensor. The server collects the positioning data and the direction of sight data to complete the calculation of 3D registration.

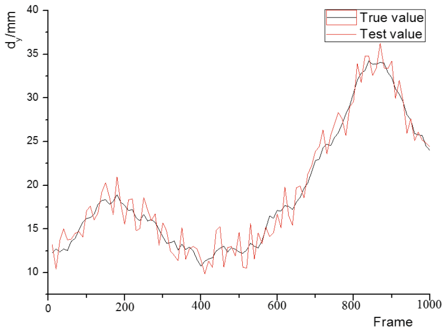

Fig. 5. Experimental error of 3D registration

When the system is running, the UWB positioning base station receives the signal from the integrated UWB locating tag and sends the positioning data to the remote server through network. The 3D registration server calculates the coordinate of the user in the natural coordinate system according to these data. Then it combines the direction of the signal from head-mounted display to calculate the transformation matrix. Since then, 3D registration is completed. As positioning information data acquisition speed is fast, calculate the transformation matrix directly will cause redundant computing. And it will also lead to reduction of real-time performance, picture jitter and other issues. Thus before calculate the transformation matrix C, digitize the positioning data and smooth the data to reduce the calculated frequency and the picture jitter.

The UWB positioning device in AR system called I-UWB positioning module in our experiment. The head-mounted display configuration memory is 4G. The CPU is Qualcomm snapdragon 821. And the operating system is android6.0. The WebGL interface that Html5 published is used to build the virtual scene.

4.2 Experimental Results and Analysis

The accuracy of 3D registration is the most important indicator, and the registration precision is analyzed by taking the d_y of the translation component in 3D registration (as the translation component of Y axis of imaging coordinate system). In experiment, set the moving speed to 1.1 m/s and the longest distance is no more than 6 m, which is

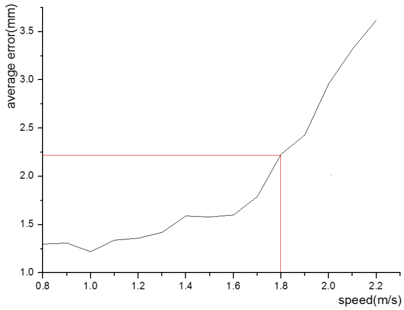

Fig. 6. Error of registration in moving

consistent with the general application environment. Test the accuracy of registration method. Figure 5 shows the change of d_y for 1000 consecutive frames.

In Fig. 5, the horizontal axis represents the frame sequence of virtual display in the experiment while the vertical axis represents the translation component d_y. The black solid line indicates the true value of d_y, and the red solid line represents the measured value of d_y. According to the result, the average difference between measured value and true value is 1.22 mm, and the error range is remained within 3 mm all the time. Because our experimental environment avoids the influence of wall reflection and object reflection, UWB can collect the high-precision positioning data. So the method based on indoor positioning meets high accuracy and small error fluctuation and stable registration precision.

Due to the special requirement of moving speed in large scene application environments, design a experiment to verify the effectiveness of the proposed method in the process of moving. The experiment set translation component d_y as evaluation criteria. The range of moving speed is 0.5 m/s–2.2 m/s, which is conform to reality. The result is shown in Fig. 6, where x axis represents moving speed and y axis represents average error of d_y.

From Fig. 6, with the increase of moving speed, the precision error of registration algorithm increases. When the moving speed is 1.8 m/s, the average error of AR system is less than 2.5 mm. When the moving speed exceeds 1.8 m/s, the error increases rapidly. Figure 7 shows the change of d_y for 300 consecutive frames when the moving speed is 2.2 m/s in experiment.

In Fig. 7, the black solid line indicates the true value of d_y, and the red solid line represents the measured value of d_y using the proposed method when the moving speed is 2.2 m/s. In these 300 consecutive frames, the average error of the measured value is 3.43 mm, where the maximum error is 8.9 mm. From the change curve, the trend of measured value coincides with true value, though it is lagging behind. It is caused by the lagging positioning information for the high-speed movement of users. At the same time, process of smooth positioning data to avoid picture jitter is the second reason for this lagging phenomenon. The blue solid line represents the measured data for vision-based registration method. In the moving speed of 2.2 m/s, this method is unstable to locate mark information, and the positioning matrix calculation fails frequently. The normal walking speed of users is 1.1 m/s–1.6 m/s. According to Fig. 7, the average

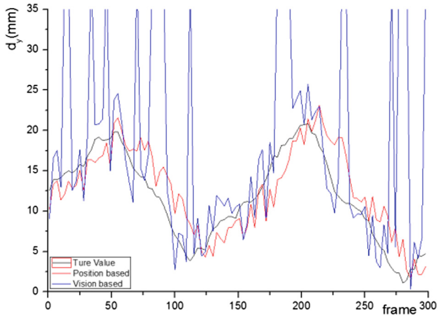

Fig. 7. Accuracy when the moving speed is 2.2 m/s (Color figure online)

error range is controlled below 1.5 mm. This experiment proves that under the moving situation, the proposed method maintain good positioning accuracy at normal pace. So that it is more suitable for large scene application than vision-based registration.

Above experiments prove that, at normal pace, the accuracy of registration method proposed in this paper meets the requirements of AR system. In the large scene, the system maintains good accuracy and stability with the normal pace of movement.

5 Conclusion

AR is gradually applied to all aspects of life, as one of the key techniques to AR, the effect of 3D registration directly affects the user experience. In this paper, a 3D registration method based on indoor positioning technology is proposed, which solves the shortcomings of traditional registration methods. In vision-based AR system, if the marks are not recognized, it will cause the failure of registration. Our method effectively avoids this situation for its no marks. But this method can only be applied to fixed scene. The next step, we will try to combine our method with vision-based registration method to complement each other.

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