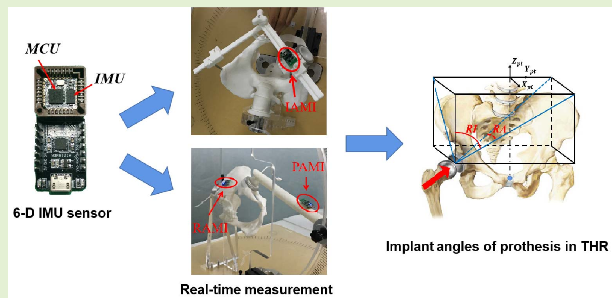
An IMU-Based Real-Time Measuring System for Acetabular Prosthesis Implant Angles in THR Surgeries

Hong Chen, *Senior Member, IEEE*, Zhecheng Yang, Jilin Zhang, Jie Liu, Hao Tang, Yixin Zhou, Binjie Zhu, and Zhihua Wang, *Fellow, IEEE*

***Abstract*—With the aging of population, the number of total hip replacement (THR) surgeries increases year by year. To improve the success rate of THR operation, the measurement of acetabular prosthesis angles should be precise during the surgery. We design an inertial measurement unit based real-time measurement system, which measures the initial attitude of the pelvis coordinate, and traces the real-time attitude of the pelvis coordinate and prosthesis axis. By collecting real-time data of diff- erent pelvic and prosthesis attitudes in quaternion representation through accelerometers and gyroscopes, the relative position between pelvis and prosthesis is calculated in real time. An optimized algorithm is proposed to obtain prosthesis implant angles accurately from the data. The experimental results show that the measured implant angles agree with that calculated by radiographic value, the root mean square errors (RMSE) are less than 3.52 degrees, which is within the safe range of THR requirement. Furthermore, no matter how the implant angles change, the measured values agree with reference values, the RMSE is less than 3.27 degrees. The experimental results show that our system can trace the real-time dislocation of the prosthesis during the THR surgeries.**



***Index Terms*—Total hip replacement (THR), inertial measurement unit (IMU), real-time measurement, acetabular prosthesis implant angles.**

I. Introduction

WITH the aging of society, there is a trend that the number of people suffering from hip joint diseases is increasing year by year. According to the national institute of health (NIH), about 208,600 total hip replacement (THR) surgeries were performed in the United States in 2005, and the growth rate is predicted to reach 572% in 2030 [1]. However, there is still a risk of failure in THR surgeries nowadays, which leads to a series of complications. Among them, the most common one is dislocation [2], [3], which is primarily caused by malposition of the acetabular prosthesis [4]. To avoid dislocation, the prosthesis should be implanted accurately in the surgery. Therefore, a precise and real-time measurement method of implant angles of acetabular prosthesis is necessary.

Many efforts have been made to determine target measurement angles in THR surgeries. In [5], the acetabular prosthesis is expected to be implanted accurately according to two reference angles in radiographic definition, anteversion angle (RA) and inclination angle (RI). Moreover, the authors describe the safe zones of 5° to 25° for RA and 30° to 50° for RI, which are widely recognized in the medical community. For the determination of these two angles, the anterior pelvic plane (APP), and three special planes of the human body, i.e., sagittal plane, coronal plane and transverse plane, as shown in Fig. 1 (a), will be used as a reference. The APP is defined by the left and right anterior-superior iliac spine (ASIS) (① and ② respectively in Fig. 1), and pubic tubercle (③ in Fig. 1) [6]. Because APP is parallel to the coronal plane, we can extract

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Hong Chen, Zhecheng Yang, Jilin Zhang, and Zhihua Wang are with the School of Integrated Circuits, Tsinghua National Laboratory for School of Information Science and Technology, Tsinghua University, Beijing 100084, China (e-mail: hongchen@tsinghua.edu.cn).

Jie Liu is with the Department of Electrical and Computer Engineering, Cornell University, Ithaca, NY 14853 USA.

Hao Tang and Yixin Zhou are with Jishuitan Hospital, Beijing 100035, China.

Binjie Zhu is with Yiemed Company, Beijing 100085, China.

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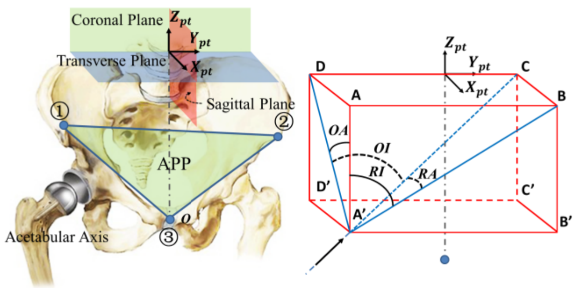


(a) (b)

Fig. 1. Definition of RA, RI, OA, and OI: (a) Definition of APP, sagittal plane, coronal plane and transverse plane; (b) a cuboid extraction from (a).

a cuboid from the pelvis, as shown in Fig. 1 (b). To calculate the implant angles, we first define the coordinate frame of the pelvis (p): X_p is a normal vector vertical to APP, Y_p points horizontally from left to right, and Z_p is defined vertical to X_p and Y_p. Point A′ represents the position of acetabular. Plane ABB′A′ is parallel to APP, and plane ABCD is parallel to the transverse plane.

In radiographic definition, anteversion angle (RA) is the angle between acetabular axis and APP, namely ∠BA′C in Fig. 1(b), and inclination angle (RI) is the angle between the projection of acetabular axis on APP and Z_{pt}, i.e. ∠AA′B in Fig. 1 (b). In operative definition, anteversion angle (OA) is the angle between the projection of acetabular axis on the sagittal plane and Z_{pt}, i.e. ∠ AA'D in Fig. 1 (b), and inclination angle (OI) is the angle between the acetabular axis and the sagittal plane, namely ∠DA′C in Fig. 1 (b).

Researchers have made many efforts to measure the acetabular prosthesis implant angles. With the proper placement for prostheses proposed by Widmer *et al.* [7], the goniometer is first used to determine the positioning angles of the prosthesis [8], but it has been found out that visual measurement is more convenient in practical use [9]. Usually, surgeons use the reconstructed three-dimension (3D) models from computed tomography (CT) and multidetector-row computed tomography (MDCT) images to precisely measure the implant angles of prostheses [10], [11]. However, CT is not the best way to measure implant angles of prostheses because of high cost, long operation time and radiation exposure.

To find a convenient and radiation-less measuring method of acetabular prosthesis implant angles instead of CT, researchers have tried two main approaches: (1) using a visual aided system to improve the accuracy, and (2) using inertial measurement units (IMUs) to obtain the real-time attitude of pelvis and prosthesis. For the visual aided system, a computer-aided visual system consisting of a multi-sensor femoral head trial is introduced in [12] and [13]. However, the system needs complex image analysis, which brings much more power consumption and delay. Therefore, we adopt IMUs to avoid radiation exposure by CT and reduce cost in measuring human motions and joint angles. The accuracy of an IMU-based system for measuring rotations across the hip, knee, and ankle has been discussed in [14]. In [15] and [16], 9-D IMU sensors are used for estimating the orientation of a moving target in surgical applications. To eliminate the uncertainty of magnetometer, 6-D IMU-based systems without magnetometer or gyroscope estimating human body and joint angles are described in [17], [18].

Our previous works in [19] and [20] introduce a measurement instrument based on 9-D IMU sensors to estimate the accurate real-time attitude of APP, and a quaternion-based extended Kalman filter is adopted to fuse the data from IMU and magnetometer to estimate the orientation. Later in [21], the algorithm calculating the attitude of pelvis and relative angles between pelvis and prosthesis is designed, and an acetabular cup angle measurement instrument based on the algorithm in Euler angles is added to the system.

However, two potential problems exist in previous works. The first one is gimbal lock. As we know, when using the heading-pitch-bank convention of Euler angles to describe a rotation, gimbal lock happens inevitably when pitch equals to ±90 degrees, which leads to the coincidence of y axis and z axis in object space and the miss of one freedom degree. In this case, the object's movement is limited in two-dimension space and Euler angles cannot describe arbitrary rotations. Although the experiments in [21] do not encounter gimbal lock, the potential problem still exists. The second problem is the calibration of magnetic field. In general, the powered instruments will influence the magnetic field of the operating room, which leads to positioning errors by magnetometer. Consequently, the experiment results of [21] are subject to potential errors.

To avoid gimbal lock, researchers have tried to use quaternion representation instead of Euler angles in orientation and rotation estimation. In [22], a linear Kalman filter for magnetic angular rate and gravity sensors is presented to obtain an estimation of the orientation in quaternion representation. In [23], a geometrically intuitive 3-degree of freedom (3-DOF) orientation estimation algorithm, which restricts the use of magnetic data, is described. The efforts above have revealed the feasibility of using quaternions instead of Euler angles in orientation estimation.

In this paper, a new real-time system is proposed for measuring acetabular prosthesis implant angles in THR surgeries, and an optimized algorithm based on quaternions of the IMU-based system for implant angles of prosthesis is put forward, which efficiently avoid the problems of gimbal lock and calibration of magnetic field. To verify the system comprehensively, we adopt 41 different reference angles in experiments. The main contributions of this work are: (1) we optimize the algorithm based on quaternions to obtain more accurate and stable measurement results; (2) we improve the system to measure the acetabular prosthesis implant angles. As a result, four advantages can be obtained: (a) easily operate the instruments and obtain the initial attitude of the pelvis coordinate; (b) calculate the real-time attitude of the pelvis coordinate in a reliable way; (c) acquire the real-time reference value more accurately; and (d) acquire the real-time values of prosthesis implant angles no matter how the prosthesis moves; (3) we design a protractor measuring device to obtain all the possible reference angles in real-time when the implant angles are changing. As a result, the system can be fully verified with the device.

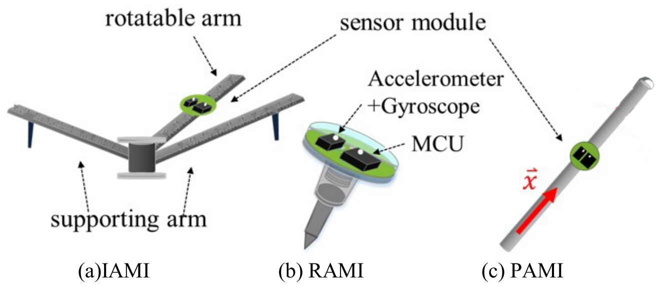


Fig. 2. System Architecture: (a) Initial Attitude Measurement Instrument (IAMI); (b) Real-Time Attitude Measurement Instrument (RAMI); (c) Prosthesis Attitude Measurement Instrument (PAMI).

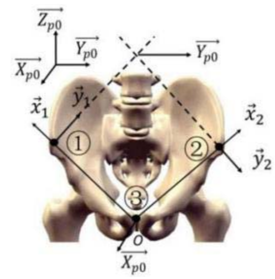


Fig. 3. Determination of initial pelvis coordinate.

The rest of the paper is organized as follows: in Section II, the architecture and algorithms of the IMU-based real-time is escribed. In Section III, the experiment results are discussed and the comparison of system performance is presented. Finally, section IV concludes our work.

II. Methods

A. Architecture of the Measurement System

The proposed architecture of the measuring system without a magnetometer is illustrated in Fig. 2. The system architecture consists 3 parts: the initial attitude measurement instrument (IAMI) (Fig. 2 (a)) is designed to determine the initial parameters of APP as that in [21], the real-time attitude measurement instrument (RAMI) (Fig. 2 (b)) aims to track the real-time attitude of APP, and the prosthesis attitude measurement instrument (PAMI) (Fig. 2 (c)) is designed to measure the real-time implant angles of acetabular prosthesis.

IAMI is comprised of one rotatable arm with a sensor module, and two fixed supporting arms, the angle between which is adjustable. RAMI is a sensor module firmly fixed at the pelvis, and it will change in consistency with the pelvis. And PAMI is a sensor module fixed on the handle of the acetabular prosthesis. We use the 6-axis mode of H1221 wireless networking attitude and heading reference system from Hipnuc company, whose static output precision is 0.8 degree and dynamic output precision is 2.5 degree. The sensor module consists of a micro controller unit (MCU), and a 6-D IMU which is composed of an accelerometer and a gyroscope. The magnetometer is not adopted any more in this system. Extended Kalman filtering and 6-axis fusion algorithms are used to compute the rotation angle on MCU. Real-time data of posture is calculated by IMU sensors, which can be transmitted by the receiver at 100Hz data transmission rate.

The algorithms for the IMU-based system to measure the real-time acetabular prosthesis implant angles include three parts: a) the algorithm calculating the initial pose of APP by IAMI, b) the real-time pose estimation algorithm based on the relationship between the RAMI and the attitude of APP, and c) the algorithm calculating the real-time implant angles of acetabular prosthesis by IMU-based system, which are described in detailed in part B, C, and D respectively.

B. Algorithm for Initial Attitude Measurement

To obtain the real-time pose of the APP, the initial pose of the APP should be calculated first. As said above, the IMU used in this system consists of a triaxial accelerometer and a triaxial gyroscope, the initial quaternion (w,x,y,z) is set to be (1,0,0,0) when it is powered on. Then we use the initial coordinate as a reference to calculate the vector values of the APP. Before the measurement of initial attitude, three sensor modules need to be powered on towards the same direction to guarantee a common reference coordinate.

Then the RAMI is fixed on the pelvis, and the IAMI is placed on the pelvis as shown in Fig. 3, where the supporting arms of IAMI are placed on line ①-③ and line ②-③, forming a triangle that determines APP, and $\overrightarrow{X_{p0}}$, $\overrightarrow{Y_{p0}}$ and $\overrightarrow{Z_{p0}}$ form the coordinate frame of the initial pelvis.

$$\vec{x}_0 = \vec{i} \tag{1}$$

$$\vec{y}_0 = \vec{j} \tag{2}$$

$$\vec{z}_0 = \vec{k} \tag{3}$$

To calculate the x-axis vector of the pelvis coordinate, namely $\overrightarrow{X_{p0}}$, we first place the rotatable arm of IAMI on line ①-③ to obtain the vector $\vec{x}_1$ in reference coordinate, as shown in (4). Then we rotate the rotatable arm to line ②-③ to obtain the vector $\vec{x}_2$, as shown in (5). Compared with the Euler angles to calculate the vectors, our method avoids gimbal lock effectively.

$$\overrightarrow{x_1} = \boldsymbol{q}_1 \cdot \left(\overrightarrow{x_0}\right) \cdot \boldsymbol{q}_1' \tag{4}$$

$$\overrightarrow{x_2} = \boldsymbol{q}_2 \cdot \left(\overrightarrow{x_0}\right) \cdot \boldsymbol{q}_2' \tag{5}$$

$$\overrightarrow{X_{p0}} = \frac{\overrightarrow{x_2} \times \overrightarrow{x_1}}{norm(\overrightarrow{x_2} \times \overrightarrow{x_1})} \tag{6}$$

where quaternions $\boldsymbol{q_1}$ and $\boldsymbol{q_2}$ have the form of $\omega + x\vec{i} + y\vec{j} + z\vec{k}$, $\boldsymbol{q_1'}$ and $\boldsymbol{q_2'}$ represents conjugation of $\boldsymbol{q_1}$ and $\boldsymbol{q_2'}$ respectively. Formula (4) and (5) describe the vector rotation from $\vec{x}_0$ to $\vec{x}_1$ and $\vec{x}_2$ respectively. Formula (6) normalizes the cross product of $\vec{x}_1$ and $\vec{x}_2$, and generates $\overrightarrow{X_{p0}}$.

Similarly, to obtain the y-axis vector of the pelvis coordinate, namely $\overrightarrow{Y_{p0}}$, we use the vector $\overrightarrow{y_1}$ and vector $\overrightarrow{y_2}$ when the rotatable arm of IAMI is on line ①-③ and line ②-③ respectively.

$$\overrightarrow{y_1} = \boldsymbol{q}_1 \cdot \left(\overrightarrow{y_0}\right) \cdot \boldsymbol{q}_1' \tag{7}$$

$$\overrightarrow{y_2} = \boldsymbol{q}_2 \cdot \left(\overrightarrow{y_0}\right) \cdot \boldsymbol{q}_2' \tag{8}$$

$$\overrightarrow{Y_{p0}} = \frac{\overrightarrow{y_2} + \overrightarrow{y_1}}{norm(\overrightarrow{y_2} + \overrightarrow{y_1})} \tag{9}$$

where formula (7) and (8) describe the vector rotation from $\vec{y}_0$ to $\vec{y}_1$ and $\vec{y}_2$ respectively. Since two supporting arms are placed symmetrically on the pelvis, Formula (9) normalizes the sum of $\vec{y}_1$ and $\vec{y}_2$, and generates $\overrightarrow{Y_{p0}}$. This is achieved by rotating the rotatable arm of IAMI. When $\overrightarrow{X_{p0}}$ and $\overrightarrow{Y_{p0}}$ are determined, $\overrightarrow{Z_{p0}}$ can be obtained by (10).

$$\overrightarrow{Z_{p0}} = \frac{\overrightarrow{X_{p0}} \times \overrightarrow{Y_{p0}}}{norm(\overrightarrow{X_{p0}} \times \overrightarrow{Y_{p0}})} \tag{10}$$

C. Algorithm for Real-Time Attitude Measurement

In the first step, as the RAMI is fixed on the pelvis, the direct cosine matrix (DCM) of RAMI, which represents the coordinate of the RAMI, is obtained by the given quaternions at the same time as formula (11).

$$\boldsymbol{R}\left(\boldsymbol{q}_{\boldsymbol{R}_0}\right) = quat2dcm\left(\boldsymbol{q}_{\boldsymbol{R}_0}\right) \tag{11}$$

where $quat2dcm$ is the function calculating the DCM for a given quaternion, and $\mathcal{R}\left(\boldsymbol{q}_{\boldsymbol{R0}}\right)$ stands for the DCM of quaternion $\boldsymbol{q}_{\boldsymbol{R0}}$. Assume that the given quaternion $\boldsymbol{q}$ equals to $\omega + x\vec{i} + y\vec{j} + z\vec{k}$, then according to Rodrigues' rotation formula, the corresponding DCM matrix has the form:

$$DCM\,(q) = \begin{bmatrix} 1-2(y^2+z^2) & 2(xy+z\omega) & 2(xz-y\omega) \\ 2(xy-z\omega) & 1-2(x^2+z^2) & 2(yz+x\omega) \\ 2(xz+y\omega) & 2(yz-x\omega) & 1-2(x^2+y^2) \end{bmatrix} \tag{12}$$

After measuring the initial attitude of the pelvis, the RAMI is applied to track the real-time attitude of the pelvis. Because the relationship between the pelvis coordinate and the RAMI coordinate remains changeless, whenever the attitude of pelvis changes, the absolute coordinate values of pelvis coordinate axes in the RAMI coordinate system remain consistent. To calculate the real-time values of the pelvis axes in the reference initial coordinate, we use the values of the RAMI coordinate, as in (13).

$$\boldsymbol{R}\left(\boldsymbol{q}_{\boldsymbol{Rt}}\right) = quat2dcm\left(\boldsymbol{q}_{\boldsymbol{Rt}}\right) \tag{13}$$

Once we obtain the initial and real-time pelvis coordinate, we need to find the DCM matrix $\boldsymbol{T}$ which symbolizes the rotation from initial to the real-time pelvis coordinate.

$$(1,0,0) = \overrightarrow{x_0} = \boldsymbol{R}\left(\boldsymbol{q}_{\boldsymbol{R0}}\right)^{-1} \cdot \overrightarrow{X_{R0}} \tag{14}$$

$$\overrightarrow{X_{Rt}} = \boldsymbol{R}\left(\boldsymbol{q}_{\boldsymbol{Rt}}\right) \cdot \overrightarrow{x_0} \tag{15}$$

Formula (14) and (15) describe the rotation process from the initial RAMI coordinate to initial ground coordinate, and then to the current RAMI coordinate respectively. Therefore, the rotation from initial RAMI coordinate to current RAMI coordinate can be described as follow:

$$\overrightarrow{X_{Rt}} = \boldsymbol{R}\left(\boldsymbol{q}_{\boldsymbol{R}_t}\right)\boldsymbol{R}\left(\boldsymbol{q}_{\boldsymbol{R0}}\right)^{-1} \cdot \overrightarrow{X_{R0}} = T \cdot \overrightarrow{X_{R0}} \tag{16}$$

As the RAMI is fixed on the pelvis, the rotation of pelvis is the same as that of RAMI. The real-time values of the pelvis axes in the reference initial coordinate can be calculated as:

$$\boldsymbol{T} = \boldsymbol{R}\left(\boldsymbol{q}_{\boldsymbol{Rt}}\right) \cdot \boldsymbol{R}\left(\boldsymbol{q}_{\boldsymbol{R0}}\right)^{-1} = \boldsymbol{R}\left(\boldsymbol{q}_{\boldsymbol{Rt}}\right) \cdot \boldsymbol{R}\left(\boldsymbol{q}_{\boldsymbol{R0}}\right)^{\boldsymbol{T}} \tag{17}$$

$$\overrightarrow{X_{pt}} = T \cdot \overrightarrow{X_{p0}} \tag{18}$$

$$\overrightarrow{Y_{pt}} = T \cdot \overrightarrow{Y_{p0}} \tag{19}$$

$$\overrightarrow{Z_{pt}} = T \cdot \overrightarrow{Z_{p0}} \tag{20}$$

D. Algorithm for Prosthesis Implant Angles Estimated by IMU

The PAMI is designed to measure the real-time implant angles of the acetabular prosthesis. The x-axis of the PAMI, namely $\overrightarrow{X_{PAMI}}$, should be perpendicular to the bottom of the acetabular prosthesis crown. Similarly, the coordinate value of $\overrightarrow{X_{PAMI}}$ in the reference coordinate is described in (21).

$$\overrightarrow{X_{PAMI}} = \boldsymbol{q}_{PAMI} \cdot \overrightarrow{(x_0)} \cdot \boldsymbol{q}'_{PAMI} \tag{21}$$

In total hip replacement surgeries, four angles are important for the judgement of the implants, which are radiographic inclination (RI), radiographic anteversion (RA), operative inclination (OI), and operative anteversion (OA). As mentioned above, the RI, RA, OI, and OA are the angles of ∠AA′B, ∠BA′C, ∠DA′C, and ∠AA′D in Fig. 1 (b) respectively. Note that line A′C in Fig. 1 (b) is in the same direction as $\overrightarrow{X_{PAMI}}$, we can find that angles RA and OI are calculated by scalar multiplication. Because RA (∠BA′C) is the angle between line A′C and surface $A'B'BA$, and OI (∠DA′C) is the angle between line A′C and surface $A'D'DA$, we have

$$RA = arcsin\left(abs\left(\frac{\overrightarrow{X_{PAMI}} \cdot \overrightarrow{X_{pt}}}{\left|\overrightarrow{X_{PAMI}}\right| \cdot \left|\overrightarrow{X_{pt}}\right|}\right)\right) \tag{22}$$

$$OI = arcsin\left(abs\left(\frac{\overrightarrow{X_{PAMI}} \cdot \overrightarrow{Y_{pt}}}{\left|\overrightarrow{X_{PAMI}}\right| \cdot \left|\overrightarrow{Y_{pt}}\right|}\right)\right) \tag{23}$$

To calculate RI (∠AA′B) and OA (∠AA′D), we adopt the lemma that the cosine value of the angle between a vector not in plane and a vector in plane is the product of the cosine value of the angle between the vector not in plane and its projection, and the cosine value of the angle between the vector in plane. Therefore, we calculate angle RA and angle OI as follows:

$$RI = arccos\left(abs\left(\frac{\overrightarrow{X_{PAMI}} \cdot \overrightarrow{Z_{pt}}}{\left|\overrightarrow{X_{PAMI}}\right| \cdot \left|\overrightarrow{Z_{pt}}\right|}\right)/cos(RA)\right) \tag{24}$$

$$OA = arccos\left(abs\left(\frac{\overrightarrow{X_{PAMI}} \cdot \overrightarrow{Z_{pt}}}{\left|\overrightarrow{X_{PAMI}}\right| \cdot \left|\overrightarrow{Z_{pt}}\right|}\right)/cos(OI)\right) \tag{25}$$

E. Designed Measuring Device Based on Protractors

To carry on more comprehensive experiments with different reference angles, we design a measuring device (in Fig. 4), which is comprised of two semi-circular protractors to help to get the precise implant angles of the prosthesis adopted as reference values.

As shown in Fig. 4 (a), protractor A, which is precisely perpendicular to the horizontal plane (in Fig. 1), is designed to

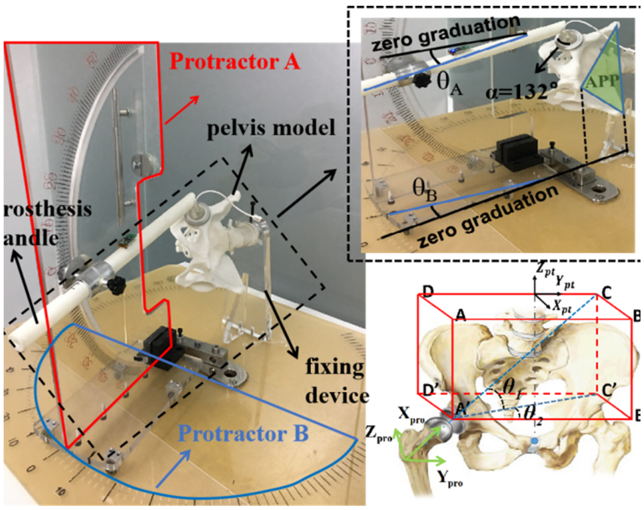


Fig. 4. Customized measuring device and its measurement angles: (a) Measuring device with customized protractors; (b) Measurement angles derived by the customized device.

measure the real-time angle between prosthesis and horizontal plane. And protractor B, which is parallel to the horizontal plane, is used to reflect the projection of prosthesis on horizontal plane. The pelvis model is equipped on a fixator, where it can rotate around the fixed axis. The prosthesis handle is equipped on protractor A, which can rotate with the vertical protractor A on the horizontal plane. The angle between the handle and prosthesis itself, namely $\boldsymbol{\alpha}$, is 132° accurately. The angle between the handle and zero graduation of protractor A and B is named $\boldsymbol{\theta_A}$ and $\boldsymbol{\theta_B}$ respectively as shown Fig. 4 (a).

F. Algorithm for Prosthesis Implant Angles Measured by Protractors

To obtain various angles between the femoral head and acetabular cup implants, that is, the reference values of target angles RA and RI in real-time, we propose an algorithm based on the customized protractor measuring device. In the measurement experiments, the pelvis is rotated to the position where the APP plane of the pelvis is precisely perpendicular to protractor B, and the customized device makes sure the zero graduation of protractor B is on the APP plane. With protractor A and B, we can obtain the value of $\boldsymbol{\theta_A}$ and $\boldsymbol{\theta_B}$ (in Fig. 4 (a)). When the prosthesis handle is lower to the zero graduation of protractor A, or on the left of protractor B, the measurement angles $\boldsymbol{\theta_A}$ and $\boldsymbol{\theta_B}$ are negative. As shown in Fig. 4 (b), the angle between the prosthesis axis and transverse plane $\boldsymbol{\theta_1}$ ($\angle CAC'$), and the angle between the prosthesis axis' projection on the transverse plane and the APP plane $\boldsymbol{\theta_2}$ ($\angle BAC'$), can be derived by formulas below.

$$\theta_1 = \theta_A + 48° \tag{26}$$

$$\theta_2 = \theta_B \tag{27}$$

We assume the unit vector of prosthesis is $\overrightarrow{X_{pro}}$ (in Fig. 4 (b)) in the real-time pelvis coordinate, its x, y and z values can be calculated by the cosine and sine values of $\boldsymbol{\theta_1}$ and $\boldsymbol{\theta_2}$. Let the point A' in Fig. 4 (b) be the origin

Fig. 5. Experimental platform where angles between femoral head and acetabular cup prosthesis are fixed.

point, we have:

$$\overrightarrow{X_{pro}} = (-\cos\theta_1 \sin\theta_2, \cos\theta_1 \cos\theta_2, \sin\theta_1) \tag{28}$$

Obviously, the coordinate in Fig. 4 (b) is the same as the pelvis coordinate shown in Fig. 1 (b). Note that line A′C is in the same direction as that of $\overrightarrow{X_{pro}}$, angle RA in Fig. 1 (b) is calculated by the dot product. Because RA ($\angle BA'C$) is the complementary angle of $\angle BCA'$, it can be calculated by (29):

$$RA = \arcsin\left(\frac{\left|\overrightarrow{A'C}\cdot\overrightarrow{X_{pt}}\right|}{\left|\overrightarrow{A'C}\right|\cdot\left|\overrightarrow{X_{pt}}\right|}\right) = \arcsin\left(\left|\cos\theta_1 \sin\theta_2\right|\right) \tag{29}$$

Similarly, the RI ($\angle AA'B$) can be calculated by the same lemma adopted in formula (24) and (25).

$$RI = \arccos\left(\left|\sin\theta_1\right| / \cos RA\right) \tag{30}$$

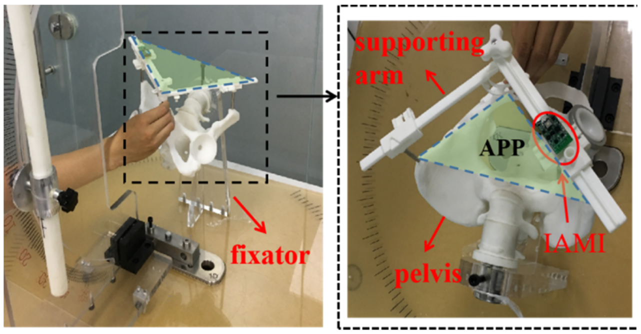
III. Results and Discussions

A. Experimental Results and Discussion

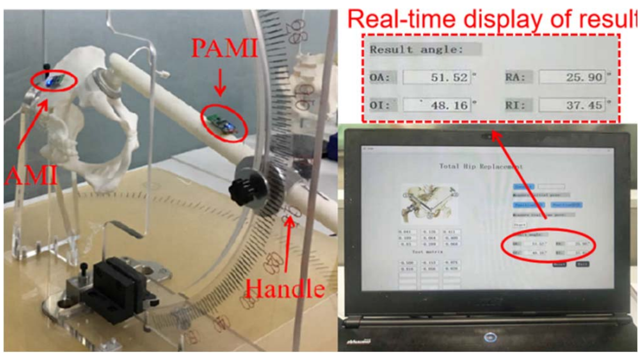
To conduct a comprehensive verification of our system, we carry out two groups of experiments: the first one aims to verify the system when the angles between the femoral head and acetabular cup prosthesis are fixed, where the stable pelvis model is shown in Fig. 5. The second one is to prove that when the target angles change, our system can trace them in real time. As shown in Fig. 6, the pelvis model is equipped on the fixator in two postures. One is flat posture (in Fig. 6 (a)), in which the initial attitude of APP could be obtained by IAMI. The other one is vertical posture (in Fig. 6 (b)), in which the APP plane is perpendicular to protractor B at the zero graduation of protractor B.

During the experiments, the pelvis model remains stable at vertical attitude and the IMU has a delay no more than 2.5ms. The data collected by accelerometers and gyroscopes are transmitted to the computer wirelessly through UART. To implement our algorithms, a computation program on PC (in Fig. 6 (b)) is designed by C++ for data analysis, and the calculated values of target angles are displayed on the screen in real time.

The four measurement steps of the system are as follows. Firstly, we place the three sensor modules in the same direction and power them on, which takes about five seconds. Secondly, we fix the RAMI unit firmly on the pelvis model. Then we put the pelvis model in flat posture to obtain the initial attitude of the pelvis by IAMI as shown in Fig. 6 (a). The second step takes less than 30 seconds. Thirdly, we place the pelvis

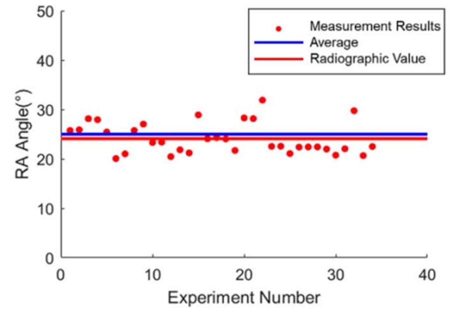


(a) Flat posture of pelvis model to obtain the initial attitude of APP.

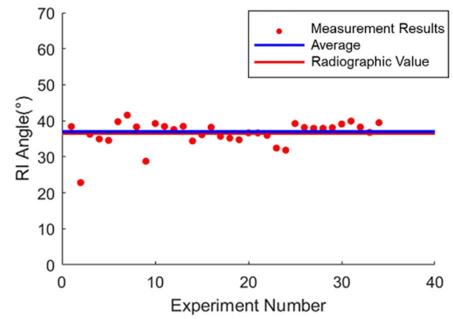


(b) Vertical posture of pelvis model to trace the real-time attitude of APP and the computation program designed by C++ on PC.

Fig. 6. Experimental platform where angles between femoral head and acetabular cup prosthesis are variable.



(a) Plot view of RA measurement



(b) Plot view of RI measurement

Fig. 7. Results of fixing implant angles (RA and RI) measurement experiment on one pelvis model.

model in vertical attitude, and put the femoral head prosthesis with the handle correctly into the pelvis model as shown in Fig. 6 (b), which takes about 20 seconds. Finally, with data from RAMI and PAMI, the values of RA and RI can be calculated. Meanwhile, the reference values can be obtained by the customized protractor device. To verify the system with different reference angles, we modify the implant angles of prosthesis by changing the position of protractor A and B gradually, and compare the measured values and reference values.

As mentioned above, during surgery the surgeons concern themselves with two important angles: RA and RI. We first carry out 34 experiments with the pelvis model and instrument placement shown in Fig. 5. With the help of surgeons, we obtain the radiographic value of RA and RI of the bone model in the experiments measured by computed tomography (CT), which are about 25° and 37° respectively and considered as the real angles of the pelvis model. The experiment results are shown in Fig. 7. From the results we can find that the measured angles are around the average line, only a few points deviate from the average line, caused by hand-hold shaking in the process of IAMI. Moreover, the shape change of the pelvis model may contribute some fluctuation to the measured value in the experiments.

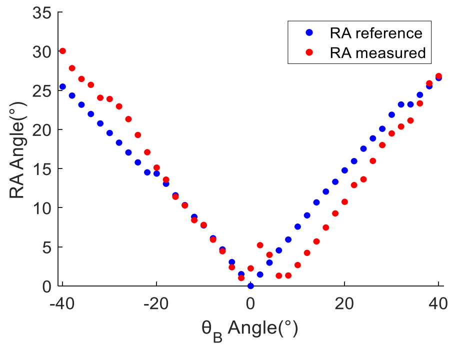
The average values, root mean square (RMS), root mean square error (RMSE), and standard deviation of RA and RI are shown in Table I, from which we can see that the RMSE is less than 3.52 degrees. Besides, the standard uncertainties of RA and RI measurements are 2.62 degrees and 2.79 degrees respectively with a level of confidence of 95% according to [24]. Moreover, RA and RI maintain their stability and reliability regardless of how the pelvis changes its attitude, which demonstrates that our system is more effective and stable than that in previous work [21].

TABLE I
AVERAGE, RMS, RMSE AND STANDARD DEVIATION OF FIXING IMPLANT ANGLES

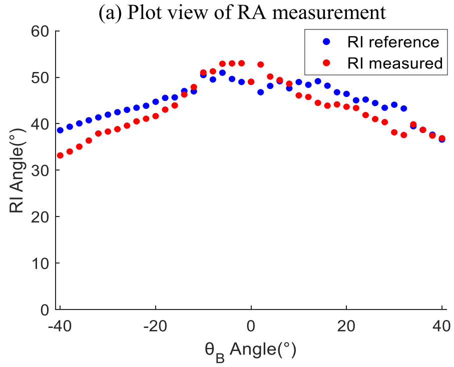
Measured Angles	Average	RMS	RMSE	Standard Deviation
RA	24.1085°	24.3006°	3.1770°	3.0493°
RI	36.5209°	36.6860°	3.5101°	3.4773°

Furthermore, to verify the system with different reference angles of RA and RI, we change the angle of θ_B in the range of -40 to 40 with the step of 2 degrees and conduct 41 experiments using the same experimental platform in Fig. 6. The experiment results are shown in Fig. 8. From the results, we find that the measured values agree with the reference values, and only a few measured values deviate from their reference values. The errors in the experiments are mainly caused by three reasons: (1) the three IMU sensors in the experiments may have static drift over time; (2) the measuring device (in Fig. 4) to obtain the reference values of implant angles has the accuracy of 1 degree and the uncertainty of 0.0995 degree, which means the reference values may have errors relative to the real values; (3) small shifts of the pelvis may be produced when changing the angles between the femoral head and acetabular cup prosthesis manually in experiments.

The IMU sensors of the system has a maximal drift of 1.5° over 5 minutes duration, which is acceptable for clinic application. As we measured, the drifts of the IMU sensor in IAMI, RAMI and PAMI are less than 0.005°/s, 0.003°/s and 0.002°/s



(a) Plot view of RA measurement



(b) Plot view of RI measurement

Fig. 8. Results of variable implant angles (RA and RI) obtained by IMU-based system and protractor system.

TABLE II
MEAN ABSOLUTE ERROR AND RMSE OF THE RESULTS OF VARIABLE IMPLANT ANGLES

Measured Angles	MAE	RMSE
RA	2.5450°	3.0506°
RI	2.7752°	3.2649°

respectively. Drift in the IAMI is higher than that in other parts, which is mainly caused by IMU sensors' poorer accuracy in 'z' axis. Hence, to reduce the influence of static drift on the accuracy of measuring system, the shorter the using time of the system during the surgery, the more accurate of the results.

The mean absolute error (MAE) and RMSE between the reference and measured values of RA and RI in the experiment are shown in Table II, from which we can see that MAE is less than 2.78 degrees, while RMSE is less than 3.27 degrees, which meet the requirement of THR surgery. Since the changes of θ_B do not affect the measuring uncertainty of our IMU-based system, the standard uncertainties of RA and RI are the same with the experiments when the implant angles are fixed. From the experiments, it is observed that no matter how the prosthesis changes its posture, the implant angles of prosthesis calculated by the system agree with the reference angles, which verifies the validity of our algorithm and the reliability of the system. Besides, the results show our system can provide the RA and RI in real time and detect the real-time dislocation of the prosthesis during THR surgeries.

B. Comparison of System Performance

Table III compares the performances of measuring systems used in THR surgery. Compared with the IMU-based systems

TABLE III
PERFORMANCE SUMMARY OF POSTURE MEASURING SYSTEM FOR THR

	NEWCAS 2014[25]	TIM 2018[21]	J Biomech 2019[26]	This work
Sensor type	camera	9-axis IMU	9-axis IMU	6-axis IMU
Measurement error	8%(rotating error)	3°(RSME)	≤4.5° (MAE)	3.52°(RSME) ≤2.78°(MAE)
Algorithm	EPNP	Euler angles	Quaternions	Quaternions
Gimbal lock	No	Yes	No	No
Affected by magnetic field	No	Yes	Yes	No
Data transmission	Wired	Wireless	Wired	Wireless
Target angles	Camera rotation	AA, AI	Euler angles of stem	RA, RI
Reference values	Protractor	Protractor	Protractor	CT and protractor
Radiation	No	No	No	No

in [21] and [26], our system improves adaptability of magnetic environment by using 6-axis IMU without magnetometer. Moreover, we use quaternions to avoid potential risk of gimbal lock, which may happen in [21]. Compared with [26], whose algorithm is also based on quaternions, our system is wireless and therefore has better magnetic field adaptability. Besides, the experiments of our system are more comprehensive, as our experiments are conducted with both fixed and various reference angles for system verification. Compared with the systems in [25], our system is wireless and non-radiative with higher accuracy and is more convenient for surgeons due to shorter operating time.

IV. CONCLUSION

This paper proposes a magnetometer-free IMU-based system with a quaternion-based algorithm for real-time measurement of the acetabular prosthesis implant angle during THR surgery. The system consists of 3 parts: IAMI, RAMI, and PAMI. The attitude data of the pelvis is obtained in quaternion representation by a 6-D IMU. The initial attitude and real-time attitude of the pelvis coordinate is measured by IAMI and RAMI respectively, and PAMI obtains the direction of acetabular prosthesis. The reference values are obtained by a customized protractor device. Experimental results show that the RMSE of RA and RI are less than 3.52 degrees when the implant angles are fixed, and less than 3.27 degrees when changing the angles between femoral head and acetabular cup prosthesis. The comprehensive experiments verify that our system can trace the real-time dislocation of prosthesis no matter how the prosthesis moves. Our system is more reliable and stable to meet the requirement of THR without any potential risk of gimbal lock, which will lead to better success rate. More clinic experiments will be carried out in future.

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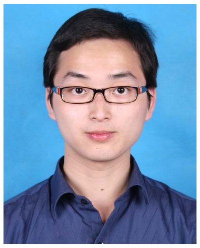
Hong Chen (Senior Member, IEEE) received the Ph.D. degree from the Department of Electronic Engineering, Tsinghua University, in 2005. From 2005 to 2007, she worked as a Postdoctoral Fellow with the Institute of Microelectronics, Tsinghua University. Since 2007, she has been working with the School of Integrated Circuits, where she is currently an Associate Professor. She worked as a Visiting Scholar with the Medical Center, Nebraska University, in 2006, and the Department of Electronics and Computer Engineering, Georgia Tech, in 2016. Her research interests include monitoring-system design for TKR/THR surgery, low-power digital integrated-circuit design, asynchronous circuit design, and low-power mixed-signal SoC design.

Zhecheng Yang received the B.S. degree in microelectronics from Tsinghua University, Beijing, China, where he is pursuing the master's degree with the School of Integrated Circuits. His current research interests include IMU-based real-time measuring system for anterior pelvic plane and implantation angles, and 3D image processing.

Jilin Zhang received the B.S. degree in microelectron engineering from Lanzhou University, China, in 2019. He is currently pursuing the master's degree with the School of Integrated Circuits, Tsinghua University, China. His current research interests include asynchronous circuit design and spiking neural network for biomedical applications.

Jie Liu received the B.S. degree from the Institute of Microelectronics, Tsinghua University, China, in 2019. She is pursuing the Ph.D. degree with the Department of Electrical and Computer Engineering, Cornell University, USA. Her research interest includes system-based on inertial sensors for pose measurement of implantation angles.



Hao Tang received the M.D. degree in clinical medicine from Peking University in 2014. Since 2014, he has been an Orthopaedic Surgeon with the Beijing Jishuitan Hospital. His research interests include computer/robot assisted surgery, biomechanics of primary and revision hip and knee arthroplasty, smart surgical tools, and periprosthetic imaging.

Yixin Zhou received the M.D. degree in clinical medicine from Peking University in 2004. He is the Chief of the Department of Adult Joint Reconstruction, Beijing Jishuitan Hospital, and a Professor with Peking University. His research interests include surgical accuracy in adult joint reconstruction, computer/robot assisted surgery, and complex primary and revision hip and knee arthroplasty. He is a member of the International Hip Society.

Binjie Zhu received the B.S. degree from Tsinghua University, Beijing, China, in 2008, and the M.S. degree from the Tsinghua University, and University of Leuven, Belgium, in 2011. He worked with Tsinghua Tongfang and participated in the development of metro and airport security equipment. He is currently the Founder and the CEO of the Institute of Microelectronics and in charge of research and development and product commercialization with Yiemed Company.

Zhihua Wang (Fellow, IEEE) received the B.S., M.S., and Ph.D. degrees in electronic engineering from Tsinghua University, Beijing, China, in 1983, 1985 and 1990, respectively. Since 1997, he has been working as a Full Professor and the Deputy Director of the Institute of Microelectronics in 2000. He was a Visiting Scholar with CMU from 1992 to 1993 and KU Leuven from 1993 to 1994, and was a Visiting Professor with HKUST from September 2014 to March 2015. His current research interests include CMOS RFIC and biomedical applications, involving RFID, PLL, low-power wireless transceivers, and smart clinic equipment. He has served as the Chairman of the IEEE SSCS Beijing Chapter from 1999 to 2009, an AdCom Member of the IEEE SSCS from 2016 to 2019, a Technology Program Committee Member of the IEEE ISSCC from 2005 to 2011, a Steering Committee Member of the IEEE A-SSCC since 2005, a Guest Editor for IEEE JSSC Special Issues in December 2006, December 2009, and November 2014, and an Associate Editor of IEEE TRANSACTIONS ON CIRCUITS AND SYSTEMS—I: REGULAR PAPERS, IEEE TRANSACTIONS ON CIRCUITS AND SYSTEMS—II: EXPRESS BRIEFS, and IEEE TRANSACTIONS ON BIOMEDICAL CIRCUITS AND SYSTEMS.