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An Estimation Method of Skeleton Proportion for Hand's Motion Capture

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Abstract

Hand motion capture systems usually use the anatomical skeleton statistics size as the skeleton length of the virtual hand. The difference in user hands leads to error in the delicate hand tracking process. By analyzing the skeleton structure and movement characteristics of the hand, a three-dimensional hand skeleton model is constructed. Based on two specific gestures, the virtual hand model is calibrated. A skeleton proportion estimation algorithm based on specific attitudes is proposed. It can estimate the exact proportion of hand bone and realize the initial deviation correction of sensor data. In the meantime, the attitudes and positions of the virtual hand skeleton is calculated based on kinematics. Hand movement tracking is realized with accurate reduction. Using this method, a hand tracking and interaction system works fine.

Keywords: virtual hand; motion capture; calibration; skeleton proportion

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1. Introduction

Virtual hand interaction based on hand motion capture system is a hotspot of current VR / AR research. The calibration of the hand movement posture refers to converting the hand movement information obtained in the hand tracking and capturing system into the motion attitude information of the hand model built in the system. MEMS-based hand motion capture system transforms real-time hand movement data collected by the sensors into attitude data of the three-dimensional hand skeleton model, thereby achieving hand motion tracking.

In the process of wearing MEMS inertial sensors, the initial posture and the human body joints are not fully consistent. Calibration and initial attitude calculation are performed when the sensors are initialized. Liu Xin, a researcher at Tianjin University, proposed a dynamic calibration algorithm based on data gloves, which can reflect the real movement of hands based on joint constraints and forward kinematics [4]. Wang Weidong from Shanghai Jiaotong University solved the initial attitude with MAGR algorithm using micro inertial sensors to measure the Euler angle of the entire palm [7]. Liu Bo of Beijing University of Technology used the MEMS sensor to calibrate the arm bone, the thigh bone and the head bone to realize the accurate posture positioning of the human body motion data to the human skeleton model [3]. Tannous Halim [2] and others have realized a method to improve the accuracy of human body motion attitude measurement based on the Kalman filter method. Eric Foxlin [1] and others use sensors composed of a gyroscope and accelerometer as an attitude tracking acquisition unit and propose a method for head tracking and neck movement of the human body.

In today's MEMS-based hand motion capture system, sensors use the skeleton length statistics in the anatomy as the skeleton length of the virtual hand to calculate the joint position. The effect of the difference in the proportions of individual hands of users results in the error of delicate activities reduction of the hand. In this paper, a skeleton proportion calculation algorithm using specific gestures is proposed by analyzing the skeletal structure and motion characteristics of the hand and

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calibrates the two specific gestures respectively. This algorithm can calculate the precise proportion of the hand bones while achieving the initial deviation correction of the sensor data, so as to realize the accurate reduction of the individual hand movement.

2. MEMS-based Hand Motion Capture System

2.1. The composition of the hand motion capture system

The hand motion capture system is mainly composed of a hand sensor module, data collection module and data receiving processing module on PC, as shown in Figure 1.

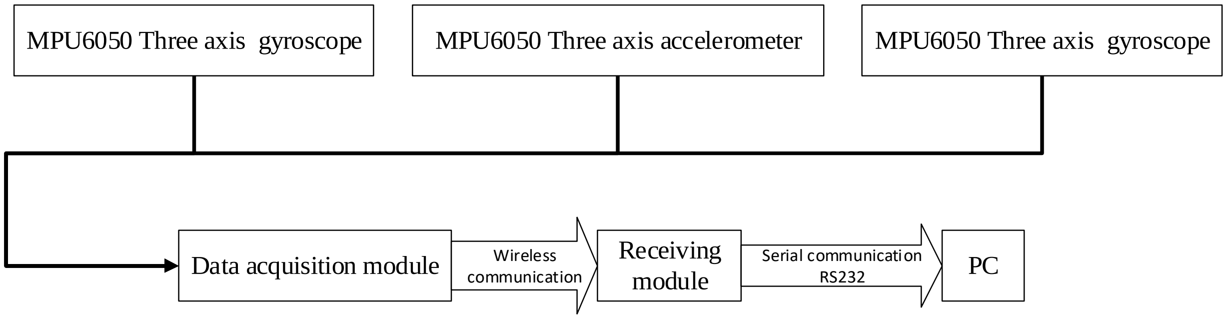

Figure 1. Motion capture system

MEMS inertial sensor is a nine-axis sensor composed of a three-axis accelerometer, three-axis gyroscope and three-axis magnetometer. In the hand tracking system, 11 inertial sensors are used to collect the motion data of the main joints of the hand, and the sensors are connected to the data collection circuit board through the data transmission line. Through wireless communication, the receiver receives the data from the data collection board, transmits the data to the computer at about 30 frames per second, and realizes virtual hand joint position resolution, hand model reconstruction and motion tracking.

2.2. Calibration algorithm workflow

At present, most of the virtual hand calibration algorithms use an anatomical standard skeleton model to deal with the proportion of the hand bone, resulting in the hand capture system virtual hand as a "standard hand", rather than the user's "real hand". Hand size distortion will lead to errors in the reduction of precise hand movements. In this paper, two specific hand gestures are studied, and the calculation of the proportion of the hand bone is achieved in the process of calibration. On the basis of the different hand structures of the users, the skeleton proportion of the virtual hand is adaptively changed. According to the sensor attitude data, the virtual hand realized the reduction of the user’s delicate activities. The specific algorithm flow is shown in Figure 2.

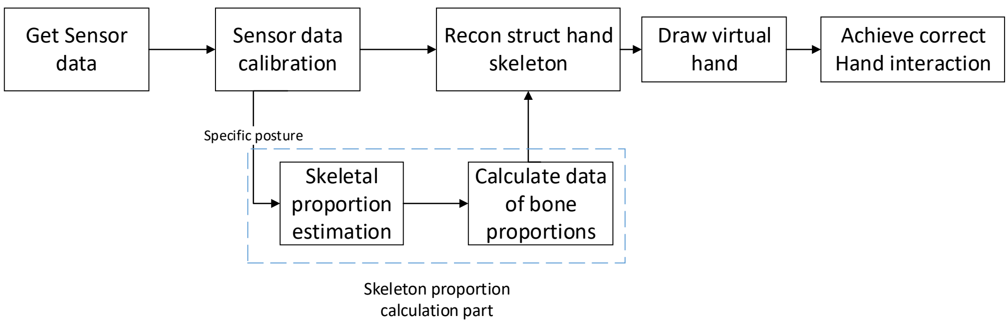

Figure 2. Hand tracking process

3. Analysis of hand structure and movement characteristics

The hand is an important part of the interaction between man and the outside world. Fingers have a high degree of sensitivity and flexibility, and can cooperate with people's thinking for fine and complex behaviors. Using kinematics for hand skeletal structure analysis [6] is shown in Figure 3.

Bones of the human hand are mainly metacarpals and phalanxes. In the five fingers of the hand, the thumb joint has only the distal interphalangeal joint DIP (Distal Interphalangeal Joint) and the metacarpal joint MP (Metacarpophalangeal Joint), while the palm wrist joint has a strong athletic ability. Each finger in the other four fingers has three joints: the metacarpophalangeal joint MP, the proximal interphalangeal joint PIP (Proximal Interphalangeal Joint), and the distal interphalangeal joint DIP. Joint movements of hands are mainly divided into two forms: stretching and bending, as well as outreach and adduction.

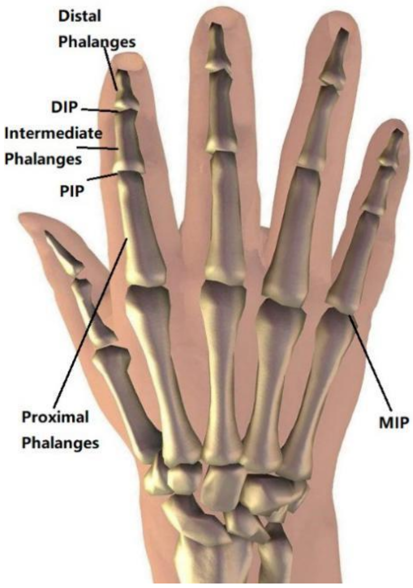

Figure 3. Skeleton structure of hand

The four-finger movements of the hand are determined by the metacarpophalangeal joint MP, the proximal interphalangeal joint PIP, and the distal interphalangeal joint DIP. The metacarpophalangeal joints can be stretched, bent or outreached, and adducted, giving two degrees of freedom; the PIP and DIP can only stretch or bend, giving only one degree of freedom. The thumb is slightly different from the four-finger movement, and the palm wrist has two degrees of freedom. Studies have confirmed that there is a constraint between the proximal interphalangeal joint and the distal interphalangeal joint of the same finger [5]. In the normal motion, the bending angle of DIP has a linear relationship with the bending angle of the PIP:

$$\theta_{DIP} = (2/3)\theta_{PIP} \tag{1}$$

So, the hand structure can be simplified, and only two knuckles of the finger and 11 joints of the hand are selected as the object of study. By using 11 sensors to collect the hand gesture data, the hierarchical structure of the hand and method of wearing sensors was established, as shown in Figure 4.

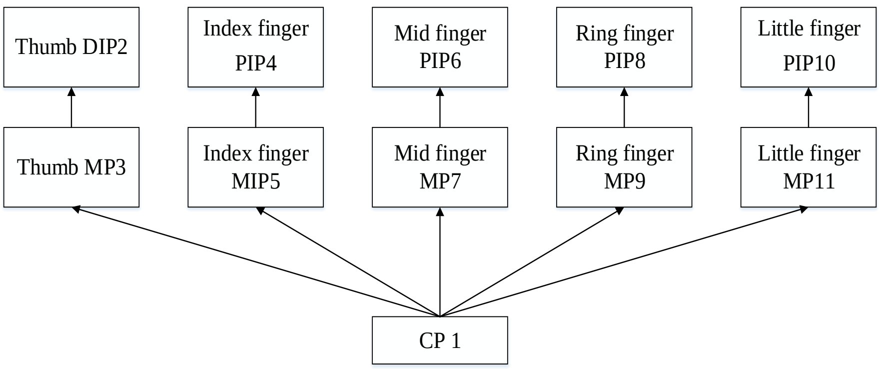

Figure 4. The hierarchical structure of the hand and method of wearing sensors

The hand model is divided into three layers: the first layer is the root node and the palm joint, the second layer is the metacarpophalangeal joint, and the third layer refers to the distal interphalangeal joint of the thumb and the remaining fingers' proximal interphalangeal joint. According to the motion characteristics of the hand, the movement of each finger is attached to the palm wrist joint, and for a single finger, the movement of the third layer node attaches to the movement of the second layer node; they are regarded as parent and child nodes. In Figure 4, the relationship between the joints is indicated by arrows, and if two nodes are linked by arrows, there is a parent-child relationship between the two nodes. The beginning of the arrow indicates the parent node, which is pointed by the arrow, and the direction is irreversible.

4. Bone Estimation Based on Specific Gestures

4.1. Specific hand gestures selection

In the initial stage of the virtual hand, in order to achieve accurate motion tracking, it is necessary to initialize and calibrate based on a specific attitude to compensate for the error in the sensor wear process. In this paper, we design a calibration method based on two specific gestures to achieve the correction of the initial error of the sensor-wearing process and calculate the proportion of the main bones of the hand.

First of all, the first gesture is flat hand, palm down, fingers close together, as shown in Figure 5. The purpose of this gesture calibration is to calculate the error offset matrix caused by the wearing process and achieve the conversion between the sensor coordinate system and the hand skeleton coordinate system.

Figure 5. Calibration gesture 1

Figure 6. Calibration1 gesture 2

4.2. Bone Proportional Calculation Algorithm

In most of the hand motion capture system, the length of each hand bone is initially fixed while establishing the virtual hand model. Under these circumstances, it is difficult to measure the actual finger metacarpal joint length of the user, which affects the position of each joint in the virtual hand. Therefore, this paper presents a bone proportional calculation algorithm in the calibration process. The basic flow is shown in Figure 7.

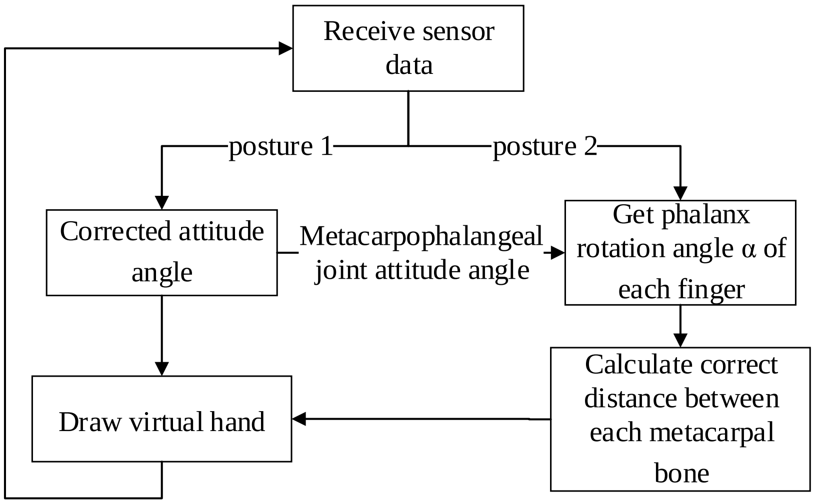

Figure 7. Process of a hand skeleton proportion calculation algorithm

By analyzing the sensor data, the difference between the first posture rotation matrix T and the reference yaw matrix base is the offset matrix M. See equation (2), indicating that during the motion initialization phase, the sensor attitude data projected to the agreed plane, making the sensor's yaw angle to the agreed value. The corresponding roll angle and pitch angle are the deviation between the sensor coordinate system and the hand skeleton coordinate system.

$$M = T * base^{-1} \tag{2}$$

$Base^{-1}$ represents the inverse of base. After that, the correct data after calibration can be obtained by multiplying each frame of data with this error offset matrix, as shown in equation (3)

$$R = R * M^{-1} \tag{3}$$

The first R is the posture matrix after calibration, the second R is the attitude matrix of the sensor, $M^{-1}$is the inverse matrix of M.

Under normal circumstances, the real hand has some shape restrictions, and these parameters can be used to calculate the proportion of the hand bone. Each finger is composed of metacarpal and phalanx. The length of each bone of the fingers conforms to the golden section theory [8]. That is to say, the length proportion of the proximal bone and the metacarpal bone is close to 0.618.

Take the index finger and the middle finger as an example. For the middle finger, assume the length of its metacarpal is L1, then the length of the proximal bone is 0.618 L1, and the length of the middle phalanges is 0.618-2*L1 $\approx$0.382 L1. The index finger can also be handled in the same way.

Use the first gesture to correct the initial error. At this point the finger is in a straight state, as shown in Figure 8.

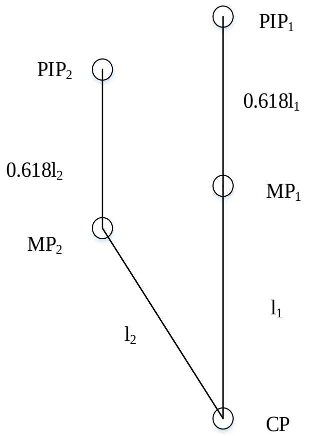

Figure 8. Schematic diagram of Posture 1

In gesture two, when the five fingers naturally expand to the maximum, we can assume that the middle finger does not move, and assume that the knuckles and metacarpals of the rest of the fingers are in a straight line, as shown in Figure 9.

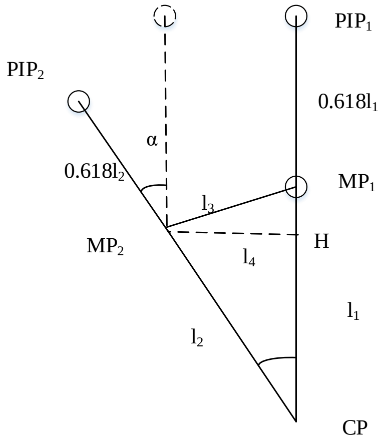

Figure 9. Schematic diagram of Posture 2

When the hand turned from gesture one to gesture two, the relative position and angle of index finger metacarpal bone and middle finger metacarpal bone did not change. But, the phalanx of the index finger has been rotated compared to gesture 1. The rotation angle of the index finger and the middle finger can be captured by the inertial sensor. The angle α between them can be calculated by the rotation matrix. A line segment MP2H is perpendicular to the line segment MP1PIP1 parallel lines, and the angle formed by MP2, CP, and MP1 is α. The length of the line segment HMP2 is expressed as:

$$l_4 = l_2 * \sin\alpha \tag{4}$$

The length of the line segment MP2MP1 is expressed as:

$$l_3 = \sqrt{(l_2 \sin\alpha)^2 + (l_1 - l_2 \cos\alpha)^2} \tag{5}$$

$$l_3 = \sqrt{{l_2}^2 + {l_1}^2 - 2 l_1 l_2 \cos\alpha} \tag{6}$$

According to this method, the length relationship of the remaining fingers (except the thumb) can be calculated during the calibration phase. According to the mature human hand bone length ratio [7]: thumb metacarpal length = 0.673 * index finger metacarpal length = 0.701 * midfielder metacarpal length = 0.778 * ring finger metacarpal length = 0.847 *little finger metacarpal length. Combine the proportion of palm metacarpal with calculation results of the distance between the fingers so that the virtual hand can be more conformed to aesthetics and ergonomics.

5. **Calibration Algorithm Experimental Results**

The MEMS inertial sensors are worn on the right hand and the length of the hand bone is preset to the Statistics. Then, the hand was horizontally placed, palm down, fingers stretched as open as possible, as shown in Figure 10. At this time, according to the calculation method of the proportion of the hand bone in the calibration process, it is assumed that the length of the middle finger palm is L, and according to the ratio of the length of metacarpal bone, the length of the thumb metacarpal bone is 0.701L, the index finger palm length is 1.04L, ring finger metacarpal length is 0.9L and small finger metacarpal length is 0.83L. According to the hand expansion state, using the calculating method of the proportion of the hand bone in the calibration process, we can obtain the length between the fingers.

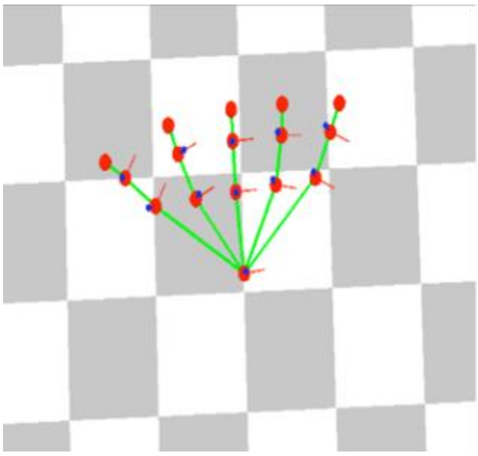

Figure 10. Stretched hand model

In the calibration process, the angles between the thumb, index finger, ring finger, little finger metacarpals and middle finger metacarpal are 48.85 o, 20.10 o, 16.05 o, 30.46 o. Then in the solving process, we can find that the distance between these fingers' MP and the index finger's MP are 1.051L, 1.051L, 0.972L and 0.987L. Keep the middle finger metacarpal value unchanged, and update the length of the remaining bones, as shown in Figure 11.

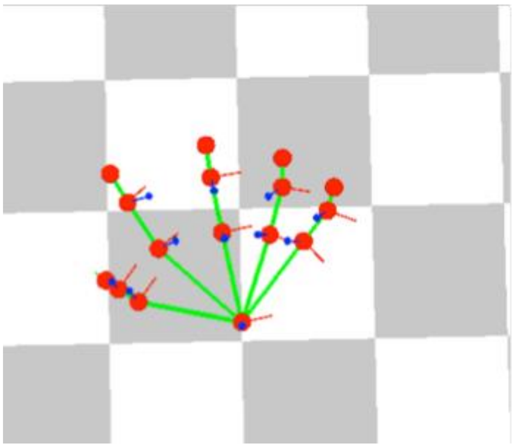

Figure 11. Hand model after calibration

Analysis of the nine sets of experimental data shows that the average error of the pitch angle after calibration is 1.47 o. This error includes random noise and measurement error. It can be found that these errors are within a reasonable range, verifying the reliability and accuracy of the data.

Table 1. Pitch angle before and after calibration

Standard Angle	Standard Angle After Roll Angle Changed	Measured Value	Measured Value After Roll Angle Changed	Angle After Calibration
(0,-30,0)	(0,-30,-30)	(4.92,-30.68,2.91)	(-3.10,-32.80,-28.12)	(-4.00,30.80,-0.46)
(0,-30,0)	(0,-30,-45)	(-0.50,-29.95,1.77)	(2.70,-32.08,-48.92)	(1.60, 29.92, -2.33)
(0,-30,0)	(0,-30,-60)	(-1.70,-26.63,-1.70)	(-1.08,-26.92,-59.39)	(1.05,26.66,1.05)
(0,-45,0)	(0,-45,-30)	(2.04,-42.60,-1.32)	(0.36,-45.91,-29.54)	(-4.00,42.49,3.66)
(0,-45,0)	(0,-45,-45)	(-1.92,-44.95,-0.22)	(1.69,-43.52,-47.46)	(2.92,44.93,-1.61)
(0,-45,0)	(0,-45,-60)	(3.25,-43.56,2.34)	(2.1,-42.87,-58.78)	(-2.26,43.61,-0.14)
(0,-60,0)	(0,-60,-30)	(1.32,-62.34,2.56)	(1.43,-61.09,-28.45)	(2.04,62.33,-3.00)
(0,-60,0)	(0,-60,-45)	(2.34,-58.56,-1.56)	(1.67,-59.34,-44.68)	(-7.00,58.33,6.78)
(0,-60,0)	(0,-60,-60)	(-2.45,-58.32,-2.36)	(-1.62,-57.32,-62.45)	(0.84,58.35,0.52)

Personalized hand proportion calculation method can achieve high-precision gesture recognition and interaction in the virtual hand movement tracking process. Figure 12 shows the interactions in a simulation system that uses virtual hands to carry objects, clicking the navigation map hot area and operating small parts. At present, the method of this paper has been well applied in this system.

(a) carrying objects (b) clicking hot area (c) operating small parts

Figure 12. Virtual hand interaction

Acknowledgements

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