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An IMU-based robotic manipulator for versatile applications

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Abstract. With the development of sensory technologies, the inertial measurement unit (IMU) has been emerging widely. In this paper, the IMU sensor is used to facilitate the versatile applications of robotic manipulators. The Kalman filter fuses the raw measurements of an IMU mounted on human hands to obtain the real-time attitude information. The contribution is to manipulate the robotic arm dexterously by the motion guidance of human hands, to achieve human-robot interaction. The experimental results evaluate the attitude preciseness and associated manipulator's locomotion. In the future work, the proposed interaction method will be applied in manipulation tasks such as grasping, inspection and so on.

Keywords: IMU, Kalman filter, robotic manipulator.

1. Introduction

With the development of robotic technology, the advantages of automated manipulator in various industrial application scenarios asymptotically appear. Recently, robotic manipulators are far more efficient than human beings when conducting simple and repetitive tasks. However, in the face of relatively complicated unstructured environments, existing robotic technologies are difficult to tackle effectively [1]. Therefore, the man-machine collaboration has become an important research hotpot at present. This research field, an emerging research field that aims to complementarily combine the intelligence of the human brain with the repeatability, robustness and applicability of robots [2]. Man-machine coordinated solutions under the environment of complex or high-risk operations, such as fire rescue, are able to ensure the safety of human and mechanical system's ability to adapt to the environment. The method breaks out human physiological limits, while human decision-making ability can also make the system more intelligent. Therefore, the establishment of human-machine cooperative system can effectively improve the mechanical performance. The existing human-machine collaboration technology is usually implemented by using a series of equipment to detect the signals issued by the human body, such as the muscle electrical signals [3], or the coordination of camera and machine vision. These methods have high accuracy [4], but a lot of computing resources are consumed, and there are other problems such as low sampling rate, complex configuration, long calibration time and so on.

With the development of chip manufacturing technology in recent years, high-precision lightweight sensors can be manufactured massively, so wearable devices have increasingly attracted researchers. In this case, the detection of human movements is biased towards wearing these smart sensors. The Inertial Measurement Unit (IMU) is one of them. IMU is a sensor which can measure the three-axis angular velocity and acceleration of an object. Currently, it has been widely used in automatic driving, robot control and other fields, as well as in situations requiring high-precision posture data [5] [6], such as inertial navigation equipment of aircraft. In the actual robot control system, IMU is often used to detect the movement of human limbs thanks to the high-precision real-time detection of posture. By employing the IMU on different places of the human body, such as the large arm, forearm, palm, etc., accurate estimation of human movements can be achieved [7].

Different from the exoskeleton which is a type of mechanical device directly strengthening the human body [8], the robotic manipulator does not need human beings to enter the operating environment in person. It ensures enough safety for human to operate and play a better role in operation process. Therefore, the design of the robotic manipulator is very important. The design of the robotic manipulator requires kinematic analysis of it, so as to implement the control algorithm of the robotic arm. There are two general ways to analyze the kinematics of the manipulator: one is to analyze the posture of the end-effector so as to calculate the orientation of each joint through the inverse kinematics; the other one is to calculate the orientation of each joint through the forward kinematics so as to obtain the pose of the end-effector of the robotic manipulator. Above all, the forward kinematics analysis has the advantages of low complexity of the control algorithm and high efficiency under the premise of knowing the orientation of each joint, which is more associated with the requirements of this work.

2. Contributions

The purpose of this study is to use the angular velocity and linear acceleration obtained by IMU to calculate the Euler angle of the current pose through Kalman filter, and to verify the feasibility of man-machine collaboration by designing a robot arm which is tele-controlled by human beings.

3. Experiment setup

This experiment uses two types of IMUs: MPU6050 and MPU9250, and a robotic arm controlled by Arduino. The MPU6050 (6-DoF) consists of a triaxial accelerometer and a triaxial gyroscope. Among them, the measurement range of the accelerometer is ±16g, and the Euler angle measured by the gyroscope is ±180^° on the X-axis and ±90^° on the Y-axis. The sampling rate of the MPU6050 is approximately 200Hz. The MPU9250(9-DoF) consists of a triaxial accelerometer, a triaxial gyroscope and a triaxial magnetometer. Among them, the measurement range of accelerometer is ±16g, and the Euler angle measured by the gyroscope is ±180^° in X-axis and Z-axis, and ±90^° in Y-axis. The sampling rate is 200Hz.

In order to imitate the motion of the human arm, the robot arm selected in this experiment has five degrees of freedom. In this experiment, only four degrees of freedom were used because the degree of freedom of the wrist in the pitch direction was not considered.

4. Method

As shown in Fig. 1, the IMU is placed on the finger (MPU9250), palm (MPU9250) and forearm (MPU6050). Two different models of IMUs were used because more accurate measurements and higher sampling rates are needed for the degree of freedom of a person's arm near the finger. In addition, since the rotation on the Z-axis needs to be detected, the IMU on the finger also uses nine degrees of freedom, in which the triaxial magnetometer is used to measure the change of yaw. In addition, an IMU (MPU9250) was placed on the end-effector of the robotic arm and used to detect the posture changes of the end-effector of the robotic arm.

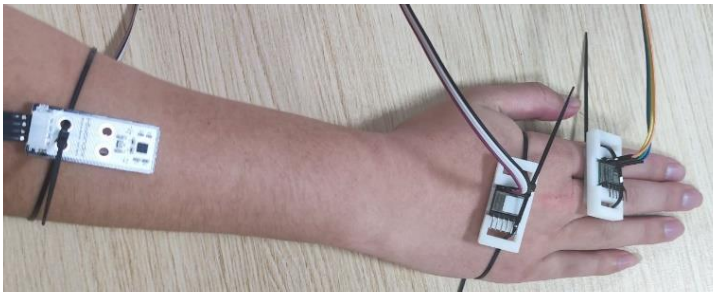

Figure 1. IMU on human arm.

Since the requirement for calculation speed is not very high, the experiment uses Arduino uno as the microcontroller to control the robotic arm, and the control code is written in C language.

As for the communication between various devices, due to the limited interface provided by Arduino uno, a modem is used between the three IMUs to detect human arm movement and Arduino uno. The three IMUs are mounted on the IIC bus of Arduino uno, and the communication speed is about 15Hz. The communication between the IMU to detect the movement of the robotic arm and PC utilizes serial port communication, and the communication speed is about 200Hz. The soft serial communication is used between Arduino and the robotic arm, two digital pins (D8, D9) are simulated as serial ports for communication. Finally, the serial communication is used between the Arduino and the PC.

For the test platform, the starting position of an object is 13 cm away from the robot arm, at a 45° angle to the edge of table. The target position of the object was 13 cm away from the robot arm and at a 50° angle to the edge of the table. In the process of the experiment, the operator needs to wear the IMU on the forearm, palm and finger successively, and control the robot arm with the movement of the arm to implement the grasping operation. Then, the operator moves the object from the starting position to the target position, repeats for ten times and records the data returned from the IMU and Arduino.

5. Data processing

IMU Data processing: The Inertial Measurement Unit (IMU) is a type of sensor that can measure triaxial angular velocity and acceleration. Typically, the IMU consists of a triaxial accelerometer and a triaxial gyroscope. Due to the need to measure the change of yaw in this experiment, the IMU also includes a triaxial magnetometer.

The accelerometer can directly measure the acceleration component on the three axes, but the attitude of the object is unknown, the simple use of the triaxial accelerometer cannot distinguish the gravitational acceleration from the linear acceleration. Although gyroscope can measure the rotation of the object's own coordinate system, the gyroscope cannot directly measure the rotation of the object in the world coordinate system due to the lack of reference. Because the integration process needs to calculate the angle through angular velocity, it will inevitably drift due to the existence of zero deviation and noise.

The usual solution to these problems is to combine a triaxial accelerometer with a gyroscope. In this case, the reference for the static horizontal plane is provided by the direction of gravity measured by the accelerometer, while the gyroscope is used to measure the rotation of the object. In this experiment, the Kalman filter will be used to fuse the data of the two sensors [9]. By applying Kalman filter on accelerometer and gyroscope, the angle changes of IMU on X-axis and Y-axis can be accurately obtained. However, the Z-axis Angle change cannot be corrected by the accelerometer, so it is necessary to add a magnetometer to correct the Z-axis Angle change.

Consequently, the formula of magnetometer to calculate yaw deviation Angle is as follows:

$$mag_x = magRead_X * \cos(pitch) + magRead_Y * \sin(roll) * \sin(pitch) + magRead_Z * \cos(roll) * \sin(pitch) \tag{1}$$

$$mag_y = magRead_Y * \cos(roll) - magRead_Z * \sin(roll) \tag{2}$$

$$yaw = 180 * atan2(-mag_y, mag_x)/\pi \tag{3}$$

In the following, the Kalman filter will be used to estimate the IMU state at time k:

Prediction stage:

The Kalman filter first estimates the current state of the system based on the previous state of the system and the measured value of the gyroscope. The prior state estimate of the system estimation at time k is:

$$\hat{x}_{k|k-1} = F\hat{x}_{k-1|k-1} + B\grave{\theta}_k \tag{4}$$

Estimate the prior error covariance matrix based on the previous error covariance matrix:

$$P_{k|k-1} = FP_{k-1|k-1}F^T + Q_k \tag{5}$$

The above equation shows that the error covariance increases with the last predicted state of the system, so the prior error covariance matrix $P_{k|k-1}$ can be obtained by multiplying the error covariance matrix with the state transition model and the transpose matrix of the state transition model matrix and adding the result to the process noise Q_k at the current time k. For the IMU system, the error covariance matrix is:

$$P = \begin{bmatrix} P_{00} & P_{01} \\ P_{10} & P_{11} \end{bmatrix} \tag{6}$$

Renewal stage:

First, calculate the difference between the actual measured value and the prior state, that is, the residual, which represents the degree of deviation between the measured value and the predicted value:

$$\widetilde{y_k} = z_k - H\hat{x}_{k|k-1} \tag{7}$$

The observation model H is used to map the prior states to the observation space, that is, the measurement of the acceleration.

Calculate the residual covariance:

$$S_K = HP_{k|k-1}H^T + R \tag{8}$$

The observation model is used to map the prior error covariance matrix to the observation space.

The Kalman gain is used to represent the confidence of the residual:

$$K_k = P_{k|k-1}H^T S_k^{-1} \tag{9}$$

For the IMU system, the starting angle is determined and the starting gyroscope deviation can also be corrected, so the initial state of the system is determined. Therefore, the initial error covariance matrix is:

$$P = \begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix} \tag{10}$$

Update the posterior estimate of the current state:

$$\hat{x}_{k|k} = \hat{x}_{k|k-1} + K_k\widetilde{y_k} \tag{11}$$

Finally, update the posterior covariance matrix:

$$P_{k|k} = (I - K_kH)P_{k|k-1} \tag{12}$$

Where I is the identity matrix. Through the Kalman filter of the above steps, relatively accurate accelerometer readings and Euler Angle readings can be estimated.

The rotation order needs to be defined when the Euler angle is used to measure the offset of the IMU coordinate system and the world coordinate system. In this experiment, the northeast celestial coordinate system is used for the attitude angle settlement, and the rotation order is defined as z-y-x when the Euler angle represents the attitude, where the range of the roll Angle is +-180° and the range of the pitch Angle is +-90°.

Due to the coupling of three axes, only the small angle change will show independent changes. When the large angle rotation occurs, the attitude angle will have coupled changes, which is the inevitable problem of Euler angle representation. Therefore, when the IMU is used to control the robotic arm, the angles of all joints are designed to rotate within ± 90 degrees. In order to avoid the occurrence of motor direction mutation caused by Euler angle computational mutation, we have to avoid the damage to the motor.

6. DH modeling of robotic arm

DH parameter modeling is a systematic method proposed by Jacques Denavit and Richard Hartenberg in 1995 to describe the relationship between position and orientation and the system of adjacent coordinates, which requires four parameters in total [10]. In this paper, the standard DH method is used to conduct kinematic modeling for the used 5-DOF robotic arm. The DH parameters of the robotic arm are shown in the following table:

Table 1. DH parameters.

i	α_{i-1} (mm)	a_{i-1} (°)	d_i (mm)	θ_i (°)
1	0	0	0	θ1
2	17	90	0	θ2
3	103	0	0	θ3
4	88	0	0	θ4
5	65	0	0	θ5

The principle of DH method to represent rotation is given by the following formula:

$$ {}^{i-1}P = {}^{i-1}_{i}T\,{}^{i}P \tag{13}$$

$$ {}^{i-1}P = {}^{i-1}_{R}T\,{}^{R}_{Q}T\,{}^{Q}_{P}T\,{}^{P}_{i}T\,{}^{i}P \tag{14}$$

$$ {}^{i-1}_{i}T = {}^{i-1}_{R}T\,{}^{R}_{Q}T\,{}^{Q}_{P}T\,{}^{P}_{i}T = T_{\hat{X}_{i-1}}(a_{i-1})T_{\hat{X}_R}(a_{i-1})T_{\hat{Z}_Q}(\theta_i)T_{\hat{Z}_P}(d_i) \tag{15}$$

$$ {}^{i-1}_{i}T = \begin{bmatrix} \cos(\theta_i) & -\sin(\theta_i) & 0 & a_{i-1} \\ \sin(\theta_i)\cos(a_{i-1}) & \cos(\theta_i)\cos(a_{i-1}) & -\sin(a_{i-1}) & -\sin(a_{i-1})d_i \\ \sin(\theta_i)\sin(a_{i-1}) & \cos(\theta_i)\sin(a_{i-1}) & \cos(a_{i-1}) & cos(a_{i-1})d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{16}$$

The above formula represents the rotation matrix from $i-1$ to i, and the posture of the end-effector can be obtained by multiplying the rotation matrices:

$$ {}^{0}_{n}T = {}^{0}_{1}T\,{}^{1}_{2}T\,{}^{2}_{3}T \ldots {}^{n-2}_{n-1}T\,{}^{n-1}_{n}T \tag{17}$$

7. Results

This experiment first tries to use the IMU after Kalman filter to output the image of Euler angle and acceleration changes with time. The following image shows the measurements of IMUs when the human hand rotates in the direction of roll, pitch and yaw in turn:

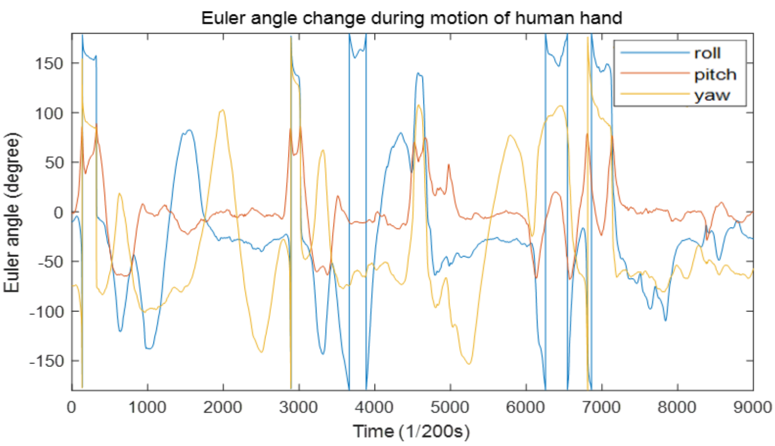

Figure 2. Euler angle change during motion of human hand.

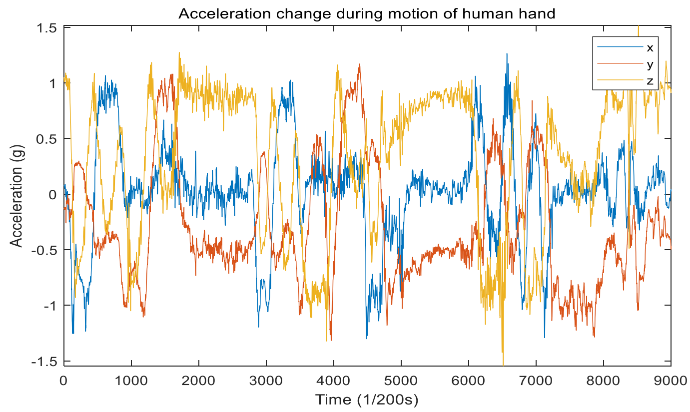

Figure 3. Acceleration changes during motion of human hand.

It can be found that IMU can accurately obtain the Euler angle and acceleration of human arm movement when the posture of human arm changes rapidly, indicating that the effect of Kalman filter is acceptable.

By measuring the movement of the robotic arm during the grasping process, the image of the Euler angle and acceleration as a function of time obtained by the IMU is plotted and shown in the following figure:

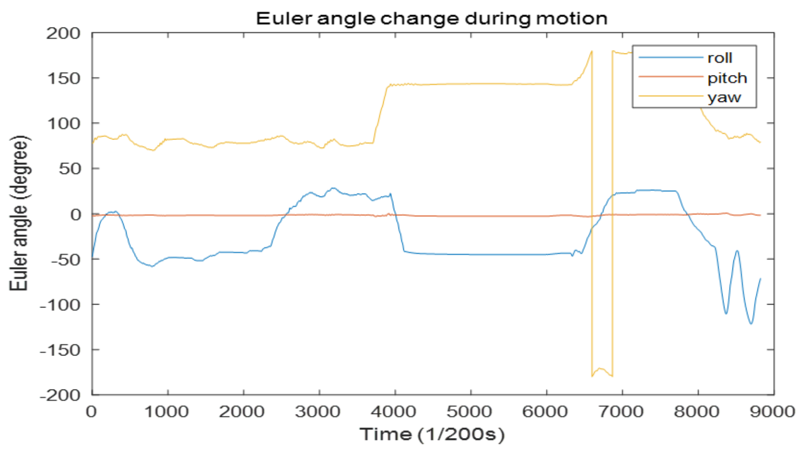

Figure 4. Euler angle change during motion.

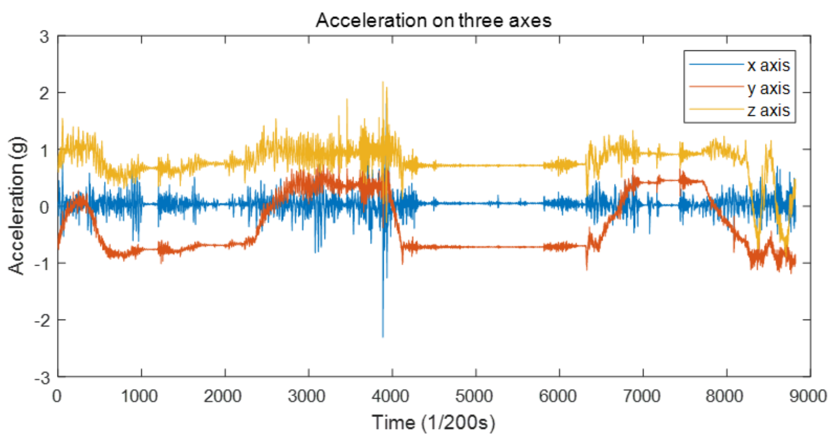

Figure 5. Acceleration on three axes.

It can be found that IMUs can precisely output the changes of Euler angles in motion and accurately record the changes of triaxial acceleration. However, it can be seen from the image that the acceleration oscillations from the accelerometer are quite distinct. This indicates that the ability of the accelerometer to resist high-frequency vibration is poor, so the actual motion trajectory of the end-effector of the manipulator cannot be obtained by integrating the accelerometer twice. The data recorded by the IMU on the human finger and the IMU on the end-effector of the robotic arm can be used to detect the situation of the robot arm to simulate the motion of the human arm, as shown in the figure below:

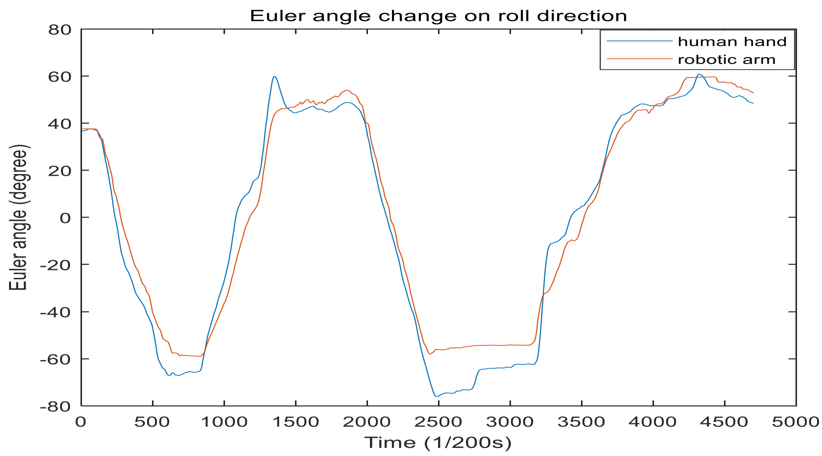

Figure 6. Euler angle change on roll direction.

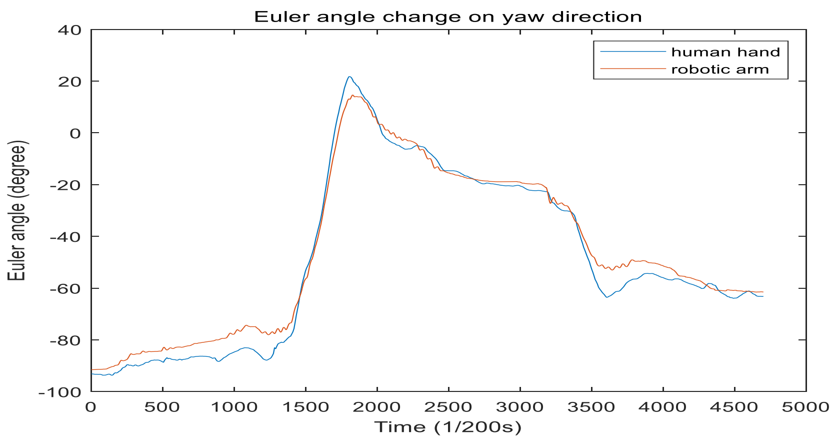

Figure 7. Euler angle change on yaw direction.

It can be found that the simulation of human arm movement by the robot arm is basically accurate, but there are some deviations in the control of relatively fine angle changes, due to the differences in the structure of the robot arm and the human arm. And because the rotation of the motor takes time, the overall movement of the robot arm has a certain degree of delay compared with the human arm. Moreover, due to the poor control accuracy of the motor, the control accuracy of the motor will further decrease for some positions with large angle mutations. This problem can be seen from the large angle errors at several wave peaks and troughs in the image.

Although the trajectory of the robotic arm cannot be visually displayed by the accelerometer, the theoretical trajectory of the end-effector of the manipulator in the three-dimensional space can be obtained by recording the rotation angle of each motor of the manipulator:

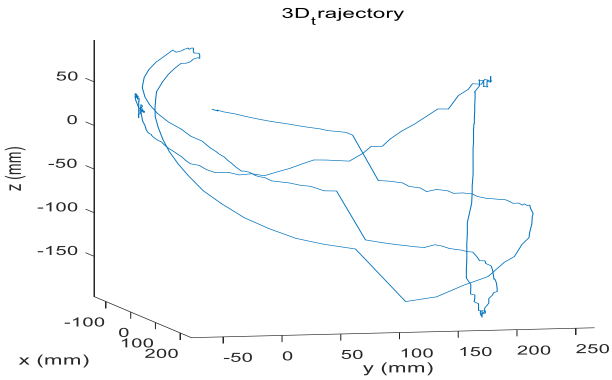

Figure 8. 3D trajectory.

8. Discussion

Because the motor rotation command can only be transmitted to the robotic arm in one direction, the actual operation of the motor is not clear. In the actual experiment, it can be found that after several times of experiments, when the instruction input of the same rotation angle is faced, the actual rotation angle of the motor will be deviated within five degrees.

In addition, since the MPU6050 needs to be calibrated by the direction of gravity [11], the Y-axis and X-axis of the MPU6050 should be kept perpendicular to the gravity direction when the whole system is started, so as to avoid the problem of posture solving error. As a result, the robotic arm must be in a recumbent position when starting, which has a certain impact on the convenience of use.

During the experiment, when the weight of the object to be grasped is greater than 200g, the robotic arm will not operate normally in some postures, because the torque generated by the motor is not enough to drive the operation in some postures due to the lever action.

Because the mechanical claw will elongate on the mechanical mechanism when grasping the object, it has a certain influence on the control of grasping distance. In the experiment process, there appears a phenomenon that the mechanical claw overpasses the object during the grasping process.

9. Conclusion

In this paper, the Euler angle of the current posture is obtained by using the angular velocity and linear acceleration obtained by IMU through Kalman filter calculation, and the simulation of the motion of the robot arm to the human arm is successfully realized by placing the IMU on the human arm and collecting the motion data of the human arm in a robotic arm control system. It is proved that it is feasible to collect human motion data by IMU to realize man-machine cooperation. In the experiment process, due to the inherent characteristics of the posture represented by the Euler angle, the manipulation of the robotic arm still has problems such as insufficient accuracy and data mutation. It may be better to use quaternion or rotation matrix to represent the pose.

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