Inertial Sensor-based Knee Angle Estimation for Gait Analysis Using the Ant Colony Algorithm to Find the Optimal Parameters for Kalman Filter

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Abstract. This paper describes a new method for human joint angle calculation based on inertial measurement data. By exploiting kinematic constraints based on anatomical knowledge, a method is developed that avoids the assumption that the sensors must be mounted in certain orientations towards the body segments. The joint axis is identified by calculating the inertial measurement units’ (IMUs’) quaternion, and then the joint angle is calculated from segment acceleration and angular velocity data according to the joint axis, respectively. As a tool for sensor fusion, a Kalman filter is used to combine both angles. There are two parameters in the Kalman filter that are always assigned to experiential values. In this paper, a standard subject experiment is designed to optimize the parameter combination in two dimensions by using the ant colony algorithm. The results showed that the root-mean-square error (RMSE) between the estimated rotation angles and the programmed angles was less than 1 degree after the optimal parameters’ values were found by the ant colony algorithm.

Introduction

Gait analysis is crucial to the application of rehabilitation exercises and sports training etc. Since the 1970s, gait analysis has growing popularity and attracted a lot of attention from the researchers and clinicians. In the 1980s, a video camera system was developed to track the human movements for gait analysis, which has been the primary method for gait analysis for a long time[1]. Typically, this kind of system is expensive and limited to indoor environments, such as laboratories or clinics. With the development of micro-electromechanical systems (MEMS) technology, a series of lightweight, low power, MEMS inertial sensors were developed, which are known as inertial measurement units (IMUs)[2]. These inertial sensors, such as accelerometers, gyroscopes and magnetometers, measure the acceleration, angular velocity and magnetic field vector in their own local coordinate system. By using some appropriate algorithms, the orientation of the sensors can be estimated.

One of the main factors in gait analysis is the angle of the lower extremity, such as the knee angle and hip angle etc. Lots of algorithms have been proposed for IMU-based knee angle estimation. There are two major challenges to this estimation. First, converting the coordinate system of the IMUs to the coordinate system of the body segments is problematic. Previous scholars have avoided this problem by assuming that the IMUs can be precisely mounted in an expected orientation towards the joint in some publications[3, 4]. However, unlike robotic devices, the human body lacks even surfaces and right angles, which makes this assumption unrealistic. To solve this problem, many methods have been proposed. The most common approach is to apply a calibration procedure. Some researchers use calibration postures[5-7], they make the subject stand upright for a few seconds with the segment’s longitudinal axis parallel to the gravitational acceleration vector, which can be measured by an accelerometer. Besides the upstanding calibration procedure, additional sitting calibration posture is also applied in [5-7]. Calibration motions can also be useful in coordinate system conversion[8, 9]. Another method that exploits kinematic constraints is proposed. It identifies the knee joint axis coordinates from arbitrary motion data rather than predefined postures or motions data[10], but, this method is more complicated and hard to apply to real-time situations.

The other major challenge is the inertial sensors’ offset, which results in accumulated drift after integration. The calibration of the IMUs is necessary to minimize the offset. Even a precise
calibration, however, yields a non-zero bias. Several methods have been studied and proposed to eliminate this effect. In some papers, the cyclic properties of gait were used to compensate for the drift. They identified the beginning and the end of the walking cycle and made the signals at these two moments equal. This method is restricted to the measurements of cyclic gait. In other methods, additional information like acceleration and the magnetic field are used to compensate for the drift. Some researchers take advantage of the magnetic field, which provides information on azimuth to remove the drift. However, the magnetic field is heterogeneous inside buildings. Although some researchers have attempted to solve the heterogeneity, it’s still difficult to measure the orientation in typical indoor environments. Therefore, methods focused on acceleration have attracted the most attention. A high-pass filter was used to remove the drift, and the complementary filter was used to fuse the inertial sensors’ data. Other filters, such as least mean squares (LMS) and recursive least squares (RLS) filters, are also studied. Most of the proposed methods use the Kalman filter because of its better response. There are researchers who designed an extended Kalman filter for real-time estimation of the orientation of human limb segments. Some other researchers proposed an algorithm where the Kalman filter was used to correct the shank inclination measured by the gyroscope. The extended Kalman filter and the Gaussian particle filter were used to evaluate the hip angle in a walking cycle. The Kalman filter’s result is highly dependent on its progress of parameters tuning. In most papers, the parameters are determined by experiments, which is inconvenient in some situations. We chose the Kalman filter to compensate for the drift in this paper. Furthermore, we use a new method to search for the optimal combination of parameters.

To solve the problems mentioned above, the paper proposes a new method to calculate the knee angle. First, a new calibration motion is introduced. Unlike the calibration procedure mentioned before, the subject doesn’t need to perform any predefined postures or motions. They just need to walk naturally and the algorithm based on the quaternion will find the rotation axis automatically. In addition, unlike the method presented in, which uses the Gauss-Newton algorithm to find the joint axis, this method is more convenient to implement and can be used in both off-line and real-time situations. In order to achieve the best filtering effect, the ant colony algorithm is applied to find the optimal values of the parameters in the Kalman filter.

Methods

As described before, it is difficult to attach IMUs on the leg in such a way that one of the local coordinate axes coincides exactly with the knee joint axis. To achieve arbitrary mounting orientation, this paper considers the knee joint as a one dimensional hinge joint, which has one rotational degree of freedom. Each segment is equipped with an IMU that is attached to the segment in an arbitrary orientation. This paper defines the knee joint axis vector with respect to the local coordinate system of the IMUs attached to both segments as $j_1$ and $j_2$, respectively.

After the local joint axis coordinates, $j_1$ and $j_2$, have been successfully identified, which is crucial for IMU-based joint angle measurement, the identified values of and can now be used to calculate the flexion/extension angle of the knee joint with one major degree of freedom.

In the Kalman filter, the variance of the state noise and the measurement noise, $Q_k$ and $R_k$, are always assigned to experiential values. For example, in most applications of quad copters, the variance yields of the state noise and the measurement noise have always been assigned to 0.001 and 0.003, respectively. In this paper, however, the ant colony algorithm based on grid partitioning was used to search the optimal combination of these two parameters in the two-dimension space. First, the search criteria should be defined. In the proposed method, a simulation experiment based on a servo motor is designed to obtain the reference angle data. The search criteria minimizes the bias between the reference angles and the angles calculated by the IMUs.
Experiment

The Simulation Experiment

In this paper, a servo motor with an additional 3D print prosthesis is used as the standard subject. The servo motor is used to simulate the human thigh segment and the shank is assumed to be stationary. A 9-axis IMU (MPU 9150) with an IIC protocol is attached to the 3D printed prosthesis model in an arbitrary orientation to acquire the angular velocity and acceleration data, which are stored in a SD-card. The main controller of the entire data acquisition system is an ARM Cortex-M3 architecture MCU (STM32F405). The rotation angles of the servo motor are programmed according to the actual walking situation that is treated as the reference results, as depicted in Figure 1.

First, the servo motor rotates for 5 seconds in order to find the rotation axis with respect to the local coordinate system of the IMU. However, we should note that if the application is used in an off-line situation, this step will not be necessary. By processing a part of the actual experimental data, the rotation axis can also be found. Then, the servo motor rotates with the programmed angles. During the rotation, the IMU collects the 3D print prosthesis’s angular velocity and acceleration data. For comparison, the angles calculated from the IMU data based on the proposed method are obtained. According to the bias between the programmed angles and the angles calculated from the IMU, the optimal combination of parameters in the Kalman filter can be found by the ant colony algorithm.

The Human Experiment

After the optimal parameters in the Kalman filter are found by the simulation experiment, a basketball player of Xiamen University was selected as the test subject to carry out a human experiment. His information is shown in Table 1. However, in this experiment, there is no reference system. The purpose is just to have a look at the results of the real knee angle when the IMUs are mounted on the human segments.

Table 1. Test subject anthropometric data.

<table>
<thead>
<tr>
<th>Gender</th>
<th>Age</th>
<th>Height [cm]</th>
<th>Weight [Kg]</th>
<th>Thigh length [cm]</th>
<th>Shank length [cm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>male</td>
<td>21</td>
<td>203</td>
<td>100</td>
<td>58</td>
<td>50</td>
</tr>
</tbody>
</table>

First, the subject is asked to stand upright in order to keep the lower limbs vertical to make the initial knee angle zero. Then, he walks in a normal speed along the edge of the basketball court. During the whole time, the IMUs’ data are acquired by the acquisition electrical circuit board whose sampling frequency is 85 Hz.

Results

The rotation angles are estimated by processing the IMUs’ data by the methods proposed in this paper. The overall estimation performance in the simulation experiment is determined through comparison with the reference results, which are programmed. The parameters’ search results and the root-mean-square error (RMSE) between the estimate rotation angles and the programmed angles are showed in Table 2.
According to the search results, the optimal combination of the parameters are chosen as the average of three searches. By using the chosen values, the knee angles estimated from IMU data and the programmed data are compared in Figure 2. Figure 3 shows the estimator errors for the same sample times. As we can see from the figures, the knee angles estimated from IMU data are mostly consistent with the original data. The maximum estimator errors are less than 2.5°, which justify the feasibility of the proposed algorithm.

Table 2. The initial values or sources of the parameters used in the methods.

<table>
<thead>
<tr>
<th>Numbers of Searching</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>( Q_k )</td>
<td>[ 0.0057 \ 0 ]</td>
<td>[ 0.0045 \ 0 ]</td>
<td>[ 0.0055 \ 0 ]</td>
<td>[ 0.0052 \ 0 ]</td>
</tr>
<tr>
<td>( R_k )</td>
<td>0.9889</td>
<td>0.8057</td>
<td>0.7843</td>
<td>0.8596</td>
</tr>
<tr>
<td>RMSE(degrees)</td>
<td>0.7839</td>
<td>0.7827</td>
<td>0.7983</td>
<td>0.7878</td>
</tr>
</tbody>
</table>

Figure 2. Comparison of thigh angle estimates using the IMU data and the programmed data.

Figure 3. Rotation angle estimation error from IMU data and programmed data.

After the simulation experiment, the proposed methods are used in a human experiment. In order to look at the performance of the knee angle estimation when the IMUs are mounted on human segments, the knee angles estimated only from the angular velocity and the knee angles estimated by the proposed methods are compared in Figure 4.

Figure 4. Comparison of knee angles estimated from the angular velocity and the proposed methods.

**Conclusions**

This study has proposed a new method to estimate the flexion/extension knee angle based on two IMUs (attached to the thigh and shank). Each IMU consists of a three-axis accelerometer and three-axis gyroscope, which provide data on acceleration and angular velocity. The offset of the
gyroscope is eliminated by the Kalman filter, and the optimal values of two parameters, system noise and measurement noise in the Kalman filter, are searched by the ant colony algorithm. The experiments’ results showed that wearable sensors like accelerometers and gyroscopes can provide quantitative measurements of human gait motion with high accuracy as expressed by joint angles like knee angles.

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References

