A Wearable Human Movement Measurement System: 
~ Sensor Fusion and Signal Processing Method ~

Achmad Arifin§, Fauzan Arrofiqi, Rachmad Setiawan, Bambang Supeno, 
Tasripan, Pujiono

Biomedical Electronic Engineering Research Group B205 
Department of Electrical Engineering 
Institut Teknologi Sepuluh Nopember (ITS) 
Jl. Arief Rahman Hakim, Surabaya 60111 INDONESIA 
§Email: arifin@ee.its.ac.id

Abstract

We studied a method of joint angle measurement during movements using wearable sensor for rehabilitation purpose. The method utilized fusion of two types of inertial sensors, gyroscope and accelerometer-based tilt angle sensor. In order to remove measurement error due to bias error of the gyroscope and fluctuation of tilt sensor, Kalman filter was used to estimate true joint angle. The method was tested experimentally in measuring knee joint angle during cyclic movements using a physical model of knee joint. The measured joint angle data in 24 trials were assessed statistically comparing to the joint angle data measured by the electronic goniometer instrumented in the physical knee joint model. The designed Kalman filter reduced measurement error significantly. The method of sensor fusion and Kalman filtering showed high accuracy reflected by low RMSE: 2.66±0.64 degree, and high correlation coefficient: 0.97±0.05. By utilizing the Kalman filter, fusion of the gyroscope and tilt sensor would be applicable as a wearable, low-cost human movement measurement system, or in realizing a wearable control system for human movement rehabilitation.

1. Introduction

Human movement measurement is an important research cluster. Sensor system for measuring human limb motion is very important in the field of human movement measurement. Advancements of electronic sensors and instrumentations stimulate research efforts in the cluster. High accuracy human movement data are important for that are useful for diagnosis, rehabilitation, and control of human movement restoration. Therefore, effective measurement method to produce high accuracy human movement data is one of actual research interest. Availability of a wearable sensor system for human movement will improve readiness of measurement as well as the acceptability of the measurement system by human subject.

Our previous research effort has been focused in studies of control method of human movement restoration using functional electrical stimulation (FES) [1]-[3]. In order to apply our control method in clinical use, availability of a portable FES control system including a wearable human movement sensor system is absolutely important. Clinical application of FES requires wearable movement sensor system with simple set up procedure and easy for operated by medical rehabilitation staffs.

Electronic goniometer has utilized in our previous studies of human gait measurement [1] and FES control [4]-[7] could generated high precision gait data. However, it remains problems of calibration procedure, attachment position, and patient acceptability. A commercially available human movement measurement system, such as NDI OPTOTRACK can provide accurate human movement data. However, its set-up methods are difficult for medical rehabilitation staff in clinical use.

Gyroscope sensor was considered to realize wearable human movement sensor system. With small size, simplicity in analog signal conditioning, and easiness in attachment, the gyroscope can be applicable as a wearable sensor for human movement measurement that can be operated easily. However, the gyroscope sensor is sensitive to vibration. The measured velocity is fluctuated by the vibration of its attached location. Offset voltage drift also causes significant error. In order to eliminate the problems stated above, we developed a powerful signal processing method to estimate true measured joint angle in a Kalman filter with additional information from an accelerometer-based tilt sensor.
2. Method
2.1. Design of Joint Angle Measurement System

The joint angle measurement system was realized in the form of fusion of two wearable inertial sensors, gyroscope (IDG 5000, Invensense, USA) and accelerometer (ADXL 335, Analog Device, USA). The sensor system was attached to shank and thigh segment of physical model of knee in Biomedical Electronic Engineering Laboratory, Department of Electrical Engineering, ITS.

Two accelerometers were used to measure knee joint angle by measuring tilt angle of shank and thigh segments. A gyroscope was attached to shank segment to measured movement. In this study, only one gyroscope was used. The design was aimed to test possibility of measuring knee joint angle using single gyroscope attached at shank segment. Analog outputs of the sensors were digitized using 10 bits internal analog to digital converter (ADC) of AT Mega 16 microcontroller unit. Design of the system diagram is shown in Figure 1. Digital data of the sensors outputs were sent to a laptop computer using serial data communication standard RS-232. Prototype of the sensor system with experimental set up is shown in Figure 2.

Value of the shank angle in sagittal plane measured by the gyroscope was determined by integrating the sagittal plane shank velocity (\( \omega \)) produced by the gyroscope. This value was calibrated by initial angle measured by accelerometer attached at the shank. The knee joint angle was determined by difference of the shank and thigh tilt angles measured by accelerometers. Definition of the measured shank angle by the gyroscope (\( \theta_{\text{gyro}} \)) and the knee joint angle by the accelerometers (\( \theta_{\text{tilt}} \)) are expressed in Equations (1) and (2), respectively.

\[
\theta_{\text{gyro}} = \int \omega \ dt + \theta_{\text{accel_shank}} \tag{1}
\]

\[
\theta_{\text{tilt}} = \theta_{\text{accel_shank}} - \theta_{\text{accel_thigh}} \tag{2}
\]

2.2. Kalman Filter

Kalman filter is a method of estimation of a signal under noisy condition based on recursive least square error (LSE). As an estimation approach, the Kalman filter is usually used for estimating both time-invariant and time-variant signals [8]. The estimation method of Kalman filter utilized generation and observation models of signal based on state-space approach. Basic structure of the Kalman filter is shown in Figure 3. A state space equation in Equation (3) represents the dynamics of signal process of an
input signal. An observation equation in Equation (4) models noisy observation signal,
\[ y_n = H x_n + \epsilon \quad (4) \]
where \( x \) is vector of the input signal, \( y \) is vector of the observed signal including observation noise, \( A, H, \eta, \) and \( \epsilon \) are the matrix of signal model, the matrix of observation model, noise excitation model, and measurement noise model, respectively. Estimation of true value of the signal determined by the Kalman filter using Equation (5),
\[ \hat{x}_n = \hat{x}_{n|n-1} + K(\hat{y}_{n|n-1} - H\hat{x}_{n|n-1}) \quad (5) \]
where \( K \) is a vector of Gain of Kalman filter.

Structure of the designed fusion sensor system with Kalman filter is shown in Figure 4. Input signal of the Kalman filter \( \theta_r \) was difference of \( \theta \) gyro and \( \theta \) tilt.

The models of the signal generation, the error and the observation error of the joint angle were represented as in Eqs. (6)-(8), respectively,
\[ \begin{bmatrix} \theta_n \\ b_n \\ \Delta \theta_n \\ \Delta b_n \end{bmatrix} = \begin{bmatrix} 1 \\ 0 \\ 0 \\ 0 \end{bmatrix} \begin{bmatrix} \theta_{n-1} \\ b_{n-1} \\ \Delta \theta_{n-1} \\ \Delta b_{n-1} \end{bmatrix} + \begin{bmatrix} \omega \\ 0 \\ 0 \\ 0 \end{bmatrix} \begin{bmatrix} B_1 \\ B_2 \end{bmatrix} \eta \quad (6) \]
\[ \Delta \theta = [1 \ 0] \begin{bmatrix} \Delta \theta_n \\ \Delta b_n \end{bmatrix} + \delta \quad (7) \]

where \( \theta, \omega, b,\) and \( \delta \) are the joint angle, joint velocity, bias offset, and integration error. Estimation of the error of measured joint angle was performed by the Kalman filter as in Eq. (9), and the true joint angle was determined by Eq. (10), respectively.
\[ \begin{bmatrix} \Delta \theta_n \\ \Delta b_n \end{bmatrix} = \begin{bmatrix} \Delta \theta_{n|n-1} \\ \Delta b_{n|n-1} \end{bmatrix} + \begin{bmatrix} K^1_s \\ K^2_s \end{bmatrix} (\Delta \theta_n - \Delta \hat{\theta}_{n|n-1}) \quad (9) \]
\[ \hat{\theta}_n = \theta_{gyro} - \Delta \hat{\theta}_n \quad (10) \]

2.3. Experimental Method

We performed measurement experiment to test measurement performance of the designed sensor system. The designed sensor system was attached to shank and thigh segment of physical model of knee joint motion. The experimental set up is shown in Figure 2. The knee joint movements were generated by moving the segment model manually in sagittal plane. The movements consist of knee extension and knee flexion. The recorded movement data were sent to a laptop computer using RS-232 serial communication supervised by a real-time data acquisition and processing system developed in this study. In the program, the Kalman filter estimated the true joint angle value in real-time.

The measurement experiment was performed in 24 trials, which duration of each trial was one minute. The measured joint angle data were assessed statistically comparing to the joint angle data measured by the electronic goniometer. The root mean squared error (RMSE) and the correlation coefficient (\( \rho \)) were calculated for each trial for evaluation purpose.

3. Results

An example of experimental measurement result is presented in Figure 5. In the figure, the measurement data is posed in first 30 second. The knee joint angle measured by the accelerometer showed many fluctuation values. As seen in Figure 5 (a), the accelerometer sensor could not measure smooth joint angle movements. On the other hand, the joint angle measured by the gyroscope show the smooth values as well as the measured value by the electronic goniometer. However, inherent bias drift caused obviously very measurement deviation.

The fusion of the accelerometer and the gyroscope sensors with the Kalman filter could estimate the measurement error. The estimated measurement error caused by the bias voltage drift estimated by the Kalman filter is presented in Figure 5 (b). The estimated error was used to calculate the true joint angle value by Equation (10). An example of the estimated trajectory of the knee joint angle compared to the measured by electronic goniometer is presented in Figure 5 (c).
Performance evaluation of the 24 measurement trials is summarized in Table 1. Low RMSE was resulted in each trial with correlation coefficient. Overall RMES and correlation coefficient were 2.66±0.64 degree and 0.97±0.05, respectively. The small values of the RMSE and the high correlation coefficient show that the estimated joint angle by the Kalman filter was very close to the joint angle measured by the electronic goniometer.

4. Discussions

In single operation, both accelerometer and gyroscope showed deterioration in measuring knee joint movements. The accelerometer measurement performance was pointed by noisy measurement values. On the other hand, the gyroscope was with bias drift error. Fusion of the two small movement sensors with Kalman filter, the bias drift error could be estimated and the true joint angle was estimated well.

The designed Kalman filter used the both measurement data with each own errors. By utilizing error model of the measured joint angle data, the
Kalman filter could estimate the true joint angle value, although measurement data of the accelerometer noisy.

The method of sensor fusion with the Kalman filter presented in this paper estimated the true joint angle value. The presented method could overcome deterioration of the gyroscope sensor, made the gyroscope sensor possible to be an alternative to high cost portable human movement measurement systems. The advancement of the presented method is using single gyroscope to measure the knee joint angle. It was considered to be superior to other study that used a couple of gyroscopes [9]. Additionally, the system could produce the true human movement data in real-time. Therefore, this method would be applicable for sensing of human movement in a wearable human movement measurement system, assistive device, or control of FES-induced limb movements.

Real applications in human movement measurement and control of FES-induced limb movements require measurements of multi-joint movements. Expansion the tested design with the method for multi-joint movements will be addressed.

5. Conclusions

The method of sensor fusion with the Kalman filter presented in this paper estimated the true joint angle value using simple hardware system and minimized sensor number in real-time. The presented method would be applicable for sensing of human movement in a wearable human movement measurement system, assistive device, or control of FES-induced limb movements. Application of the method for multi-joint movements will be performed in the next research step.

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References


Corresponding Author:
Dr. Achmad ARIFIN
Biomedical Electronic Engineering Research Group B205
Department of Electrical Engineering
InstitutTeknologiSepuluhNopember (ITS)
JlAriefRahman Hakim, Surabaya 60111 INDONESIA
Telp. +621-31-5947302 Ext 132, Fax. +62-31-5931237
Email: arifin@ee.its.ac.id