Journal of Scientific & Industrial Research
Vol. 79, March 2020, pp. 213-215

# Real-Time Feedback Control for Knee Prosthesis using Motion Fusion Algorithm in 6-DOF IMU

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*Received 12 July 2018; revised 13 August 2019; accepted 14 December 2019*

Stump angle measurement (SAM) system was developed and tested for its use in the development of a low cost electronic knee prosthesis using an accelerometer to measure "tilt" angle of the residual stump during various phases of gait. This system provided real time feedback to control the actuator position for covering a wide range of mobility for the above knee amputees. However, this system is prone to high frequency noise resulting from gait events. These "noise" spikes triggered false threshold values resulting in incorrect operation of the actuator. In the proposed design, a 6-degree of freedom (6-DOF) sensor replaces the accelerometer from previous design. The modified algorithm uses complimentary filter to process the data from inertial measurement units (IMU). This new system produces sensitive yet smoother output, removing the drawbacks of the earlier system. This paper reports the comparative analysis of the SAM system using 6-DOF and accelerometer. These results using 6-DOF sensor will assist in the further development of an intelligent feedback system for low cost active prosthetic leg.

**Keywords:** Knee prosthesis, Microcontroller, Sensors, IMU

## Introduction

Trans femoral prosthesis are classified into two groups, passive prosthesis (which do not require power supply for their operation) and active/powered prosthesis. Passive prostheses are less adaptive and have limitations while performing non-conservative positive knee work as well as have to spend more energy compared to healthy subjects[1,2]. Powered prosthesis provide a wider mobility because of its real time feedback through sensors and the employment of complex algorithms. Current approaches focus on the sensors, algorithm and actuator design for smoother transitions (allowing variable damping of the knee). The power consumption in such devices is high as the actuators are directly coupled to knee joint and lack the natural tendency of elastic energy storage and return as compared to passive devices[2,3]. Low cost electronic knee prototype design focuses on developing a robust and reliable feedback system with few sensors that can be coupled with any mechanical actuator. Stump angle measurement (SAM) system uses feedback from the accelerometer (tilt) sensor to measure thigh movement to predict the knee angle[4]. The output of SAM system is continuously compared with the output from the stance detector (SD) sensors and a corrective action is taken. SAM system, however produced high frequency noise resulting from stance phase of the gait event leads to false feedback signals. The proposed system overcomes this drawback using a 6-DOF sensor instead of an accelerometer. A complementary filter is used for the motion fusion algorithm. This paper presents a comparative analysis of the output of SAM system using accelerometer and 6-DOF sensor.

## Methodology

### *Human Gait*

The human gait consists of two phases, Stance and Swing Phase. Stance phase comprises of 60%, while swing phase is remaining 40% of one gait cycle. Stance phase begins at heel strike(HS) and ends at Toe-Off(TO). During the stance phase, the foot is in contact with the ground, while in swing phase, the foot has no contact with the ground. During swing, the knee tends to extend post flexion for ground clearance and initiates the heel strike marking of the next gait cycle. The stump angle is the angle between the perpendicular to the ground and the thigh movement.

### *System Architecture*

The point of focus for the development of a low cost electronic knee prototype is on minimal

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hardware, along with reliable sensory feedback system. For the same, IMU (for angle/tilt measurement) and Pressure sensors are used. Inertial measurement units(IMU) with various sensor fusion algorithm have been found useful in accurate detection of gait movement[5-7]. This updated version of earlier SAM system uses IMU to evaluate lower limb motion. Earlier system used accelerometer sensor and LPC2148 microcontroller for its processing. This proposed update uses programmable system on chip (PSoC 4), 042-BLE, low-cost rapid prototyping kit with integrated Bluetooth. The sensor, ADXL 335 accelerometer is replaced by MPU6050. This low-cost IMU consists of a 3-axis gyroscope and a 3-axis accelerometer. It is capable of processing complex 9-axis motion fusion algorithms. Bluetooth was chosen as the preferred mode of communication for its direct connectivity with mobile phones, PDA's and Laptops.

The placement of the sensor for stump angle measurement and the stance detection is shown in figure 2(a). Sensor can be placed anywhere along the axis passing through hip and knee joint. The system is programmed to communicate with the sensor using I2C protocol and sends the data to a laptop over Bluetooth. The feedback from the stance detector and SAM system is used for controlling the linear actuator in the low cost electronic knee, thereby providing a wider mobility range for the amputee. The processing algorithm is explained in the next section.

**Algorithm**

MPU6050 consists of a 3-axis accelerometer and a 3-axis gyroscope. The output of the gyroscope is subjected to "gyroscopic" drift resulting due to the addition of the noise component, especially as the ambient temperature changes. Assuming that the accelerometer output is dominated by gravity under the normal conditions, by tracking the direction of the gravity, the orientation of the sensor frame can be calculated. The use of IMU allowed using sensor fusion algorithms, resulting in better accuracy as well as reliability. Kalman filter or Complimentary Filter are few popular math filters that can be used for sensor fusion algorithm. To keep the algorithm simple and faster, Complimentary filtering is used for sensor fusion. The complementary filter fuses the accelerometer data and the gyroscope data by passing the accelerometer data through a 1$^{st}$-order low pass filter and the gyroscope data through a 1$^{st}$-order high pass filter and adding the inputs. Where Low pass filter (Filters the accelerometer output) and its response is given by (i):

$$y_a[n]=(1-\alpha)*x_a[n]+\alpha*y_a[n=1] \quad \ldots (1)$$

$x_a[n]$ is X/Y/Z axis angle values from the accelerometer; $y_a[n]$ is filtered final angle values for further processing;

High Pass filter (Filters the Gyroscope output) and its response is given by (ii):

$$y_g[n]=(1-\alpha)*y_g[n-1]+(1-\alpha)*(x_g[n]-x_g[n-1]) \quad \ldots (2)$$

$x_g[n]$ is pitch/roll/yaw from gyroscopes; $y_g[n]$ is filtered final pitch/roll/yaw for further processing; n is the current sample value.The value of alpha ($\alpha$) is chosen using equation (iii)

$$\alpha=(\tau/\tau+\Delta t) \quad \ldots (3)$$

$\tau$ is desired time constant; $\Delta t$ is sampling frequency; Value of "$\alpha$" is usually chosen such that $\alpha > 0.5$.

The complementary filter thus has the equation:

$$\theta = (1- \alpha)*( \theta +y_g[n]*\Delta t) + \alpha* y_a[n] \quad \ldots (4)$$

The sensitivity of gyroscope is set to 20mV/°/s and the sampling time is set at 0.01. The output is free from gyroscopic drift and can be used as a feedback signal for the microcontroller.

**Comparative Analysis**

The SAM system using IMU was tested on 6 healthy subjects with normal walking abilities and 14 above-knee amputees with passive hydraulic prosthesis. They were made to walk on a level ground (for ~5mtr to ~10mtr) at slow and fast walking speeds. Stair ascend and descend readings were also acquired from the module and compared with the older SAM system output. The data was collected at a prosthesis laboratory via Bluetooth communication from the module. Table 1 shows the output of SAM system tested on one such subject, which used accelerometer for tilt angle measurement and the new version of same SAM system with IMU sensor, for the measured hip angle and gait event associated with it.

Table 1 — Result Analysis of stump angle (in degrees)

| Level of Walking | Gait Event | Video Analysis | SAM system o/p | SAM system (with IMU) |
|---|---|---|---|---|
| Slow Walking | Heel Strike | 27.14° | 29.3 ° | 28.2 ° |
| | Toe Off | -3.2 ° | -4.7 ° | -3.8 ° |
| Fast Walking | Heel Strike | 33.87 ° | 36.8 ° | 34.25 ° |
| | Toe Off | -5.8 ° | -4.75 ° | -5.64 ° |

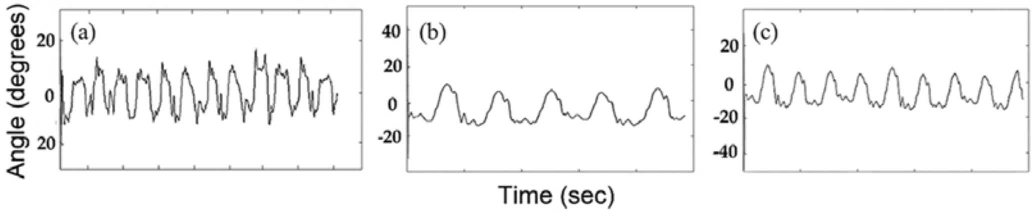


Fig. 1 — (a) Output of earlier SAM system on sound subject with accelerometer (b) Output with 6DOF IMU: straight walk on ground plane (c) straight fast walking on ground plane

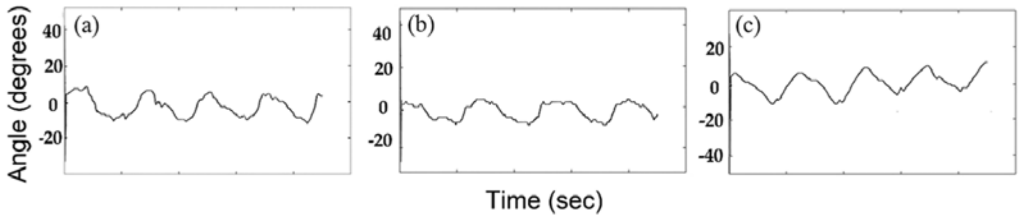


Fig. 2 — Output: (a) Stair descend (b) stair ascend (c) Amputee using a passive hydraulic knee during a straight walk. Notice the change in the hip angles (2a and 2c). This results due to the distinctive limp action of the amputee.

## Results and Discussion

The module was tested on the above subjects and data was recorded for various trials of ground and staircase walking. Few graphical results of the sensor output in various gait phases are shown in Figure 1 and Figure 2. The output of the accelerometer in earlier SAM system often generated false feedback at heel strike resulting in mis-triggering of the actuator [Figure 1(a)]. Whereas the output of the same system using IMU provided reliable feedback signal, especially without any high frequency noise component. Successful detection rate of gait events was above 93% for the IMU readings. Real time processing and machine learning nature of the algorithm helps to overcome the above problem. Following graph shows the response of the sensor measuring the thigh angle. The vertical axis shows the angle (in degrees) and horizontal axis denotes the time frame, where each division is equal to one second. The cost of this module stays approximate around 40$(~INR 2700).

## Conclusion

Developing of machine learning algorithms and their evaluation for extensive analysis of the human gait using minimal hardware is the key for developing low cost active prosthesis. By using the IMU sensor in the SAM system, we were able to identify the thigh angle that can be used as a feedback signal for developing a low cost electronic knee. 6DOF sensor and Complementary filtering eliminated false triggering of the feedback signal that was seen in the earlier SAM system. Feedback is obtained wirelessly and this module alone can be used for diagnostics of gait pattern of an amputee. Future work aims in synching this output with foot pressure sensor module and build a low cost active knee which would cover wider mobility and allows stair ascent, descent, level ground as well as slope walking.

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