

## Chapter 5

# Methods for Improving Foot Displacement Measurements Calculated from Inertial Sensors

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### **ABSTRACT**

*The use of inertial sensors to measure human movement has recently gained momentum with the advent of low cost micro-electro-mechanical systems (MEMS) technology. These sensors comprise accelerometer and gyroscopes which measure accelerations and angular velocities respectively. Secondary quantities such as displacement can be obtained by integration of these quantities, a method which presents challenging issues due to the problem of accumulative sensor errors. This chapter investigates the spectral evaluation of individual sensor errors and looks at the effectiveness of minimizing these errors using static digital filters. The primary focus is on the derivation of foot displacement data from inertial sensor measurements. The importance of foot, in particular toe displacement measurements is evident in the context of tripping and falling which are serious health concerns for the elderly. The Minimum Toe Clearance (MTC) as an important gait variable for falls-risk prediction and assessment, and therefore the measurement variable of interest. A brief sketch of the current devices employing accelerometers and gyroscopes is presented, highlighting the problems and difficulties reported in literature to achieve good precision. These have been mainly due to the presence of sensor errors and the error accumulative process employed in obtaining displacement measurements. The investigation first proceeds to identify the location of these sensor errors in the frequency domain using the Fast Fourier Transform (FFT) on raw inertial sensor data. The frequency content of velocity and displacement measurements obtained from integrating the inertial data using a well known strap-down method is then explored. These investigations*

DOI: 10.4018/978-1-61692-004-3.ch005

*revealed that large sensor errors occurred mainly in the low frequency spectrum while white noise exists in all frequency spectra. The efficacy of employing a band-pass filter to remove a large portion of these errors and their effect on the derived displacements is elaborated on. The cross-correlation of the FFT power spectra from a highly accurate optical measurement system and processed sensor data is used as a metric to evaluate the performance of the band-pass filter at several stages of the processing stage. The motivation is that a more fundamental method would require less computational demand and could lead to more efficient implementations in low-power and systems with limited resources, so that portable sensor based motion measurement system would provide a good degree of measurement accuracy.*

## **INTRODUCTION**

Gait is one of the most essential and common form of human movement, as it allows the movement from one destination to another. This entails the quasiperiodic movement of the limbs and the appropriate positioning of the feet on the floor. Depending on the walking style, terrain conditions and speed, gait can have different forms and features. Excluding the evident linkage between this activity to the effects on public health risks such as obesity, diabetes and cardiac disease, the analysis of these features in a biomechanical context has also provided answers to pathological aspects related to the task of walking. This can also include the research of gait functionality deviations, such as musculoskeletal disorders (amputation and osteoarthritis), and neurological disorders such as cerebral palsy and stroke, that may considerably affect gait functionality. Many hospitals and research institutions now possess gait laboratories, where patients with pathological diseases are examined with statistical methods that provide means for further understanding and identifying causes and effects of these deviations. This is where progress in gait analysis has the greatest impact, in deciding on overall treatments, preventive measures and also modified surgery procedures (Begg et al., 2007)

Recent research of human motion has turn to the developments of low-cost and small sensor devices, set to replace the current reliance on bulky, laboratory constraining optical video systems such as Vicon and Optotrak NDI. These low powered

sensors can be used to develop portable systems which would extend motion analysis to the outdoor environment as opposed to the optical systems. Secondary quantities such as limb velocity and displacement and joint instantaneous angles can be inferred by numerically integrating the primary signals. Early work directly used the raw inertial signals to track physical quantities such as limb or upper body accelerations, and joint orientations and inclinations. Baten et al. (1996) assessed accelerometers and gyroscopes to compute low-back angles against a 3D video system with errors around  $\pm 10\%$ . These results were extended to using EMG signals to track trunk muscle activities during lifting, achieving estimation errors below  $5^\circ$  (Baten et al., 2000). Gyroscopes have been used by Najafi et al. (2002) to detect postural transitions and hence determine potential elderly fallers. A Discrete Wavelet Transform (DWT) successfully denoised the signal and left the integrated trunk tilt, which is the angle between the vertical axis and the thorax wall, reasonably intact to measure transitions, such as sit-stand or stand-sit. Zijlstra et al. (2003) also measured lower trunk acceleration to detect spatio-temporal gait events such as walking speed, foot contact and step length. Using Ground Reaction Forces (GRF) to compare, it was shown that accelerometry had small biases but reasonable accuracy to estimate mean step length and walking speed. Bourke et al. (2008) extended this work by using Vertical Velocity Thresholding (VVT) to detect potential falls in the elderly. The authors used tri-axis accelerometers and gyroscopes to monitor vertical

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