A Clip-on Shoe-Mounted Wearable System for Gait Analysis

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***Abstract*—In this work, we present a low-cost miniature foot-mounted positioning system and its potential for gait analysis. The system includes an inertial measurement unit and three time-of-flight proximity sensors. The addition of proximity sensors can provide an absolute measure for real-time vertical reference for the inertial sensor fusion. An extended Kalman filter is used for sensor fusion which uses the proximity sensor measurements and zero velocity updates to correct for the inertial integration drift. Monitoring of orientation of foot and vertical distance is used to enhance detection of zero velocity periods. The steps are segmented based on the zero velocity periods, and different measures such as foot hight, vertical and horizontal speeds are depicted in graphs.**

INTRODUCTION

A common method of gait analysis is using optical motion capture systems which is very accurate, but due to its high cost and space requirements, it is not available in many clinics. Furthermore, it has limited workspace and cannot be used for monitoring the subject in everyday life.

Today, micro-electromechanical (MEMS) inertial measurement units (IMU) are widely available in a single-package and single-chip form that integrate both the sensors and interface electronic components. With proper integration of acceleration and angular rate acquired by such sensors, a complete Attitude and Heading Reference System (AHRS) can be formed to be used for gait analysis. One of the most suitable locations for IMU for gait analysis is foot since it can be used to recalibrate the speed at every stance phase, foot motion can provide characteristic information about the gait and it can be considered a minimally obtrusive location for a sensor specially if it is clipped on the foot-ware. Gait analysis using IMUs have been extensively studied in the literature [1]. Using an IMU, many characteristics of gait such as stride length, stride speed, attitude, acceleration, speed and angular rate of foot at different stages of the gait can be acquired.

Many research groups have made progress towards foot-worn IMU attaching IMUs to one or both feet [2], [3], [4], [5]. The process of acquiring position from an IMU involves two main steps. First, estimating the orientation of the unit to compensate the effect of gravity on accelerometers. Second, double integration of the linear acceleration to get position information. These two processes are prone to exponential drift due to sensor imperfections and numerical errors which are magnified by double integration. Many methods exist to compensate for these errors using external information, such as data fusion with Zero Velocity Updates (ZVU) [3], [4], [6], [7]. However, the accuracy of positioning without relying on pre-installed setup in the environment is still limited for position tracking over long periods of time.

Due to inherent drift of IMU integration, to increase accuracy over long periods of time, for a self-contained system, addition of other type of sensors is the only option. For example atmospheric pressure sensor can be used to estimate the approximate height from the sea level [8]. However local air pressure is very dependent on the daily weather, wind, temperature and momentary changes and thus it is more suitable for only rough height approximations. Tactile sensors can also be used under the foot for increasing the accuracy of foot stationary periods for zero velocity detection [9]. However a force sensor should be under the shoe (either inside or outside) which may limit the application.

Mobile optical sensors when fused with IMU, seem to be the most precise and robust measurement methods which rely on feature extraction and estimation of relative motion at sampling each frame which is commonly used for drones [10], [11]. Optical proximity sensors have been also used on foot to increase vertical positioning accuracy. Arami et al [12] have used analog IR proximity sensors for foot clearance measurement which need calibration using an absolute reference data. Duong et al [13] have suggested estimating foot pose using digital infrared (IR) time-of-flight (ToF) proximity sensors. These off-the-shelf low-cost miniature proximity sensors are much less sensitive to environmental lighting as they operate based on measuring the time it takes the light signal to travel from sensor to the target and back. Due to precise time measurement and noise rejection these sensors provide a sub-millimeter accuracy however limited to a few meters range, which is sufficient for most foot mounted applications.

Here, we focus on using a custom wearable system using an IMU and the ToF proximity sensors for gait analysis purposes. By using ToF sensors the foot clearance can be measured more precisely when fused with IMU information which on the other hand further enhances the 3D positioning and attitude estimation accuracy in real-time.

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I. Methods

A. Hardware

We use a proprietary low-cost miniature shoe-mounted motion capture system which integrates an IMU and several ToF proximity sensors as well as high frequency logging mechanism, USB and Bluetooth communication. The device is encapsulated in a $3 \times 2 \times 1cm$ 3D printed package and weighs less than 13 grams and it can be easily clipped on to any shoe (Fig. 1).

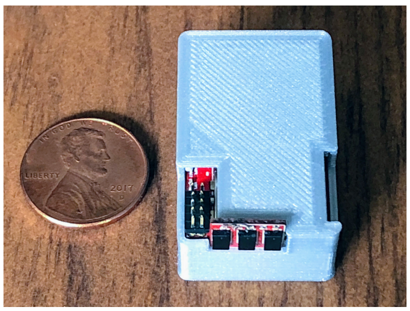

Fig. 1. The in-house self-contained system including an IMU, three time-of-flight (ToF) proximity sensors, SD card, Bluetooth and a powerful processor

An example of data acquired from the device is shown in Fig. 2 during a normal walk.

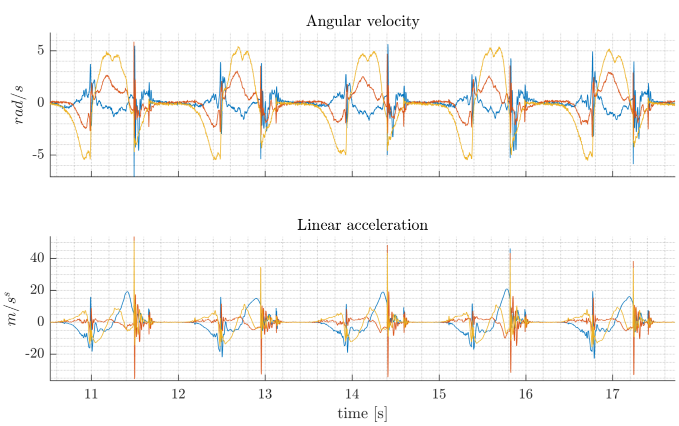

Fig. 2. Angular velocity and linear acceleration relating to 5 steps.

B. EKF

An Extended Kalman filter (EKF) is used to fuse the predicted model which is based on IMU data integration and is updated on each step when the foot is stationary. The height estimations based on ToF proximity readings and device orientation, are fed to EKF at each sensor reading (33Hz). The addition of ToF proximity sensors serves two main advantages: 1: removal of vertical drift and 2: reduction in vertical as well as horizontal errors due to correlation of errors through EKF. EKF consists of two update events; zero-velocity updates (ZVU) and vertical height updates. The height measurement is estimated from the ToF sensor reading and the orientation of device. The states of the system are the 3D position, velocity and Euler angles. The details and formulation of EKF is presented in [14]. An example of EKF performance is shown in Fig. 3.

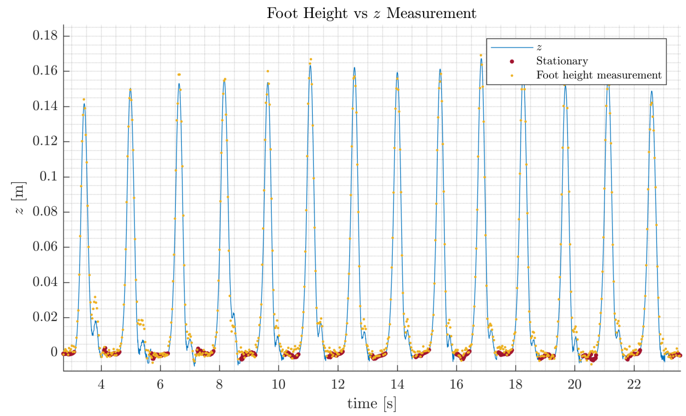

Fig. 3. Vertical EKF height estimation and ToF proximity updates

C. Step Events

Using the angular velocity in sagital plane for example it is possible to segment the steps [15] and detect the heel strike and toe-off. Similarly, here we use foot inclination in sagital plane as well as the vertical distance from proximity sensors to detect three consequent events: toe-off, mid-air, about-to-land and stance. Each must follow previous one. The time between any of these events including the stance phase will form four different phases. A time-out is considered for each of these phases to avoid getting locked in any phase. The events are defined as below:

1) Toe-off: is a possible event only right after a stance event when the foot inclination is less than $-8°$.
2) Mid-air: is an event after toe-off when the foot inclination reaches $5°$.
3) About-to-land: is an event at least $0.15seconds$ after mid-air when the foot inclination reaches $5°$.
4) Stance: After about-to-land and when the angular energy is less than $0.2rads^2/s^2$.

An example of events can be seen in Fig. 4. Attachment of coordinate system is also shown in Fig. 5.

The About-to-land event enables a more accurate zero velocity detection by removing the chance of false detections between a stance and about-to-land events.

D. Step Segmentation

The steps are segmented from the end of the last stance phase to the start of next stance phase, for this reason the three middle phases of toe-off, mid-air and about-to-land only exist to ensure that a step has happened between the two stance phases. Therefore, the limitation are less strict on all of these intermediary phases.

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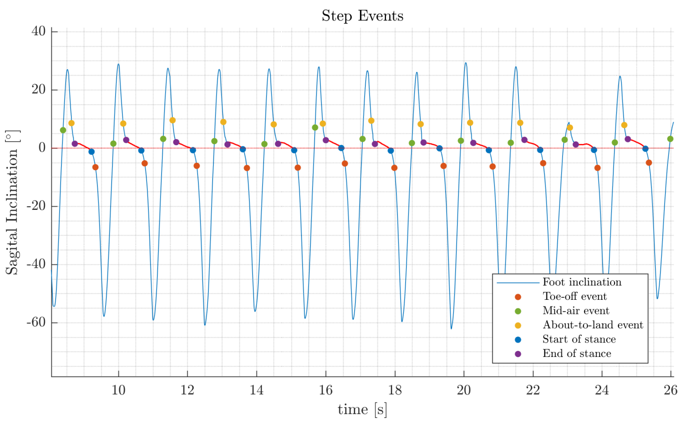

Fig. 4. Event steps shown on foot inclination during normal walk.

Fig. 5. Coordinate system attached to sensor and shoe. In neutral stance phase the device is calibrated so that z is facing upward. After the first few steps the x axis is aligned with the forward direction of motion.

II. Results

The data is collected by clipping the sensor to the back of the foot as seen in Fig. 6.

Five trials of an individual (female 29) on a flat floor within a building is presented here. Vertical position, horizontal speed and angular velocity around y axis is presented in Fig. 7, Fig. 8 and Fig. 9.

III. Discussion

The results show that our system can be used for step detection and analysis. However since the tests are performed at an S-shaped path, the length, heading and speed of steps vary. In a future work the data will be collected by walking on a treadmill to be able to verify the calculated speed ans stride length.

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TABLE I
Test Summary

Test	Duration [s]
Test-1	34
Test-2	42
Test-3	45
Test-4	49
Test-5	52

Fig. 6. Sensor attachment

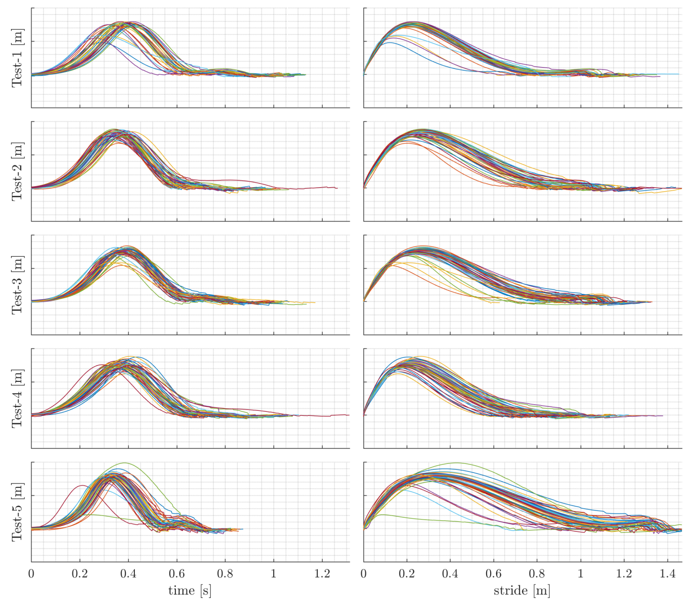

Fig. 7. Vertical height according to 5 tests, walking in an S shaped path for 2 to 4 times per test resulting in a 34m to 48m walk. The Angular velocity is presented over time and stride length

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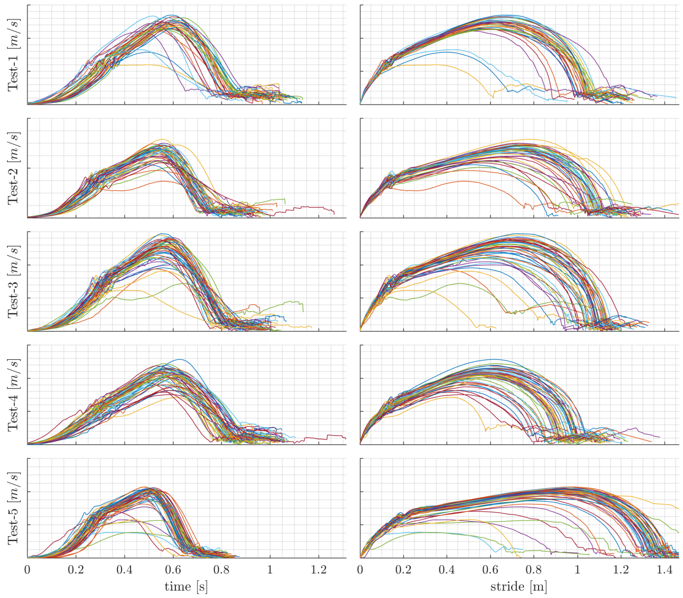

Fig. 8. Horizontal speed according to 5 tests, walking in an S shaped path for 2 to 4 times per test resulting in a 34m to 48m walk. The Angular velocity is presented over time and stride length

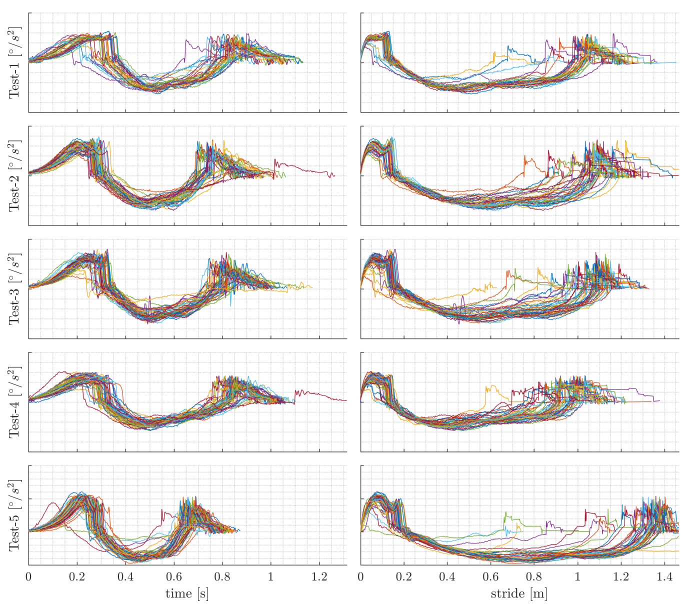

Fig. 9. Angular velocity according to 5 tests, walking in an S shaped path for 2 to 4 times per test resulting in a 34m to 48m walk. The Angular velocity is presented over time and stride length

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