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Multisensor Approach to Walking Distance Estimation with Foot Inertial Sensing

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Abstract— **Walking distance estimation is an important issue in areas such as gait analysis, sport training or pedestrian localization. A natural location for portable inertial sensors for gait monitoring is to attach them to the user shoes. Step length can be computed by means of a biaxial accelerometer and a gyroscope on the sagital plane. But estimations based on the direct signal integration are prone to error. This paper shows the results achieved by using a multisensor model approach to reduce uncertainty. Unbounded growth of error is reduced by means of sensor fusion techniques. The method has been tested, and early experimental results show that it provides an estimation of the walking distance with a standard deviation smaller than with single IMU similar systems.**

I. Introduction

STEP length estimation by means of inertial sensors has applications in several fields where wearable devices are necessary. Especially in gait analysis, it has been detected the convenience of such portable systems. Inertial sensors provide a good trade-off between portability, cost and precision; compared to other sensors such as foot switches, force sensitive resistors, etc. Recently, events and phases in normal human gait have been characterized with inertial sensors [1-7].

A natural location for portable inertial sensors for gait analysis is to attach them to the user shoes, someplace close to the instep of the foot [8-12]. The estimation algorithms look for invariant signal features related to the step-to-step walking cycle. Then, the stride length can be obtained by direct double integration of the accelometric signals. The task is difficult because the unbounded growth of the estimation error associated with such integrations. Another uncertainty source comes from the integration of a gyroscope signal, necessary to define the distance integration limits when no additional contact sensors are used [10].

Sabatini et al [8] has proved, for treadmill walking, the feasibility of a single IMU (inertial measurement unit, that includes triaxial accelerometers and gyroscopes) solution for the estimation of spatio-temporal parameters. Further, it is possible to reduce the gait events detection part from the gyro signal, as Svensson and Holmberg proposed [13], allowing to use the system for analysis of gait disorders and stairs. These works report an standard deviation of around 10% [14].

The previous approach has been extended here, both in hardware and software, in order to increase the precision of the estimation. The system consists of two IMUs located at the front of each foot. Estimation of each stride length is combined, by data fusion based on geometrical biomechanical limits. This paper shows the results achieved by using this multisensor approach to uncertainty reduction.

Section II of the paper describes the model and the algorithms used to produce the estimations. Experimental setup and results are shown in Section III. These results are discussed in Section IV. It will be shown that this method provides an estimation of the actual displacement with a reduced growth of uncertainty when compared to its monosensor counterpart.

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II. Methods

A. Model description.

Motion is computed, at every stride, by estimating the distance traveled by the foot that swings forward on the air, that is, the antero-posterior displacement of the swinging foot during the single stance phase. The measurement phase begins and ends with the foot-flat (FF) of the reference foot. The body swings forward using the opposite foot as an anchor to the floor. Forward displacement of the foot can be computed by a direct double integration of the horizontal acceleration:

$$l(t) = \iint A_x(t) \cdot dt \tag{1}$$

being $A_x(t)$ the horizontal acceleration measured in the floor fixed frame.

The foot orientation while swinging, on the sagital plane, can be obtained by integrating the gyroscope signal:

$$\theta(t) = \int_{ta}^{tc} \omega(\tau) \cdot d\tau + \theta_{init} \tag{2}$$

which has an initial value that depends on the specific location of the sensor over the shoe, which can be calculated off-line during the initial setup.

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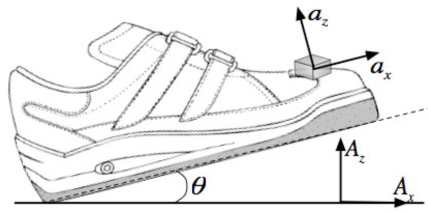

Fig. 1. The inertial measurement unit is attached over the fifth metatarsal, and a gyroscope measures orientations of the foot on the sagital plane (positive when counter-clockwise). Measured horizontal and vertical accelerations, $(a_x(t),a_z(t))$ have to be corrected to the floor fixed frame $(A_x(t),A_z(t))$ and the effect of gravity eliminated, using the gyroscope measure.

By using this orientation, we can calculate the foot accelerations on the fixed frame, $A_x(t)$ and $A_z(t)$, from the raw values given by a biaxial accelerometer placed close to the fifth metatarsal, $a_x(t)$ and $a_z(t)$, see Figure 1. The transformation is:

$$\begin{aligned} A_x &= a_x \cos\theta - a_z sen\theta \\ A_z &= a_x sen\theta + a_z \cos\theta - g \end{aligned} \tag{3}$$

Accelerometer data is prone to drift problems. We make the assumption that the speed and orientation of the foot in successive FFs is zero when the subject is walking regularly, over a flat surface and at constant forward speed. As a consequence, both contour conditions are used to correct the drift effect in the double integral.

B. Angle Estimation and Event Detection

The integration period begins with the push-off or heel-off (HO) of the reference foot, see Figure 2. The angular velocity reaches a (negative) peak and then a sign change that makes the foot to be in parallel with the floor while in the air. The orientation reaches a positive peak before the heel-strike event, and then the foot-flat (FF) position is reached again. When in FF the three magnitudes have zero value.

This method requires that HO and FF can be determined for each step. It is possible to detect these events with en IMU located in the COG, with the vertical acceleration or the acceleration in the antero-posterior direction. According to Zijlstra et al [1], the initial contact coincides with the peak forward acceleration preceding a change of sign, while the final contact of the contralateral foot [15] is associated with the minimum preceding an increase in forward acceleration.

We selected the detection with the gyro signal in the sagital plane. The signal is low-pass filtered using a fourth order, zero-lag low-pass Butterworh filter. Heel off and Foot flat points are selected by threshold levels when the signal leaves the zero level, see Figure 3. From that, equations (1), (2) and (3) can be applied to the accelerometer signals, as shown in the stride represented in Figure 4.

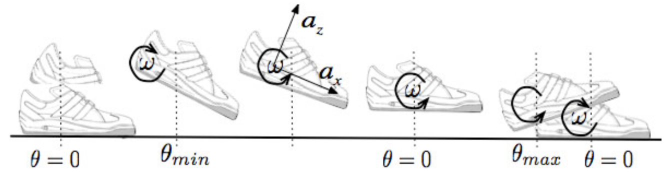

Fig. 2. The integration period begins with the push-off or heel-off (HO) of the reference foot. The angular velocity reaches a (negative) peak and then a change in the sign that makes the foot to be in parallel with the floor while in the air. The orientation reaches a positive peak before the heel-strike event, and then the foot-flat (FF) position is reached again. When in FF the three magnitudes have zero value.

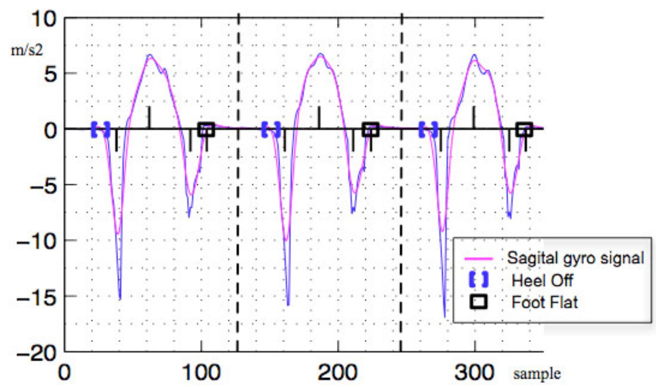

Fig. 3. Three steps in the gyro signal (fm=100Hz). The integration limits of the step length estimator are obtained by integrating the gyroscope signal of the sagital plane. The Heel-Off point corresponds to the sudden change of the gyro signal derivate, previous to the signal minimum. The Foot Flat state is reached when the signal goes to zero after the maximum.

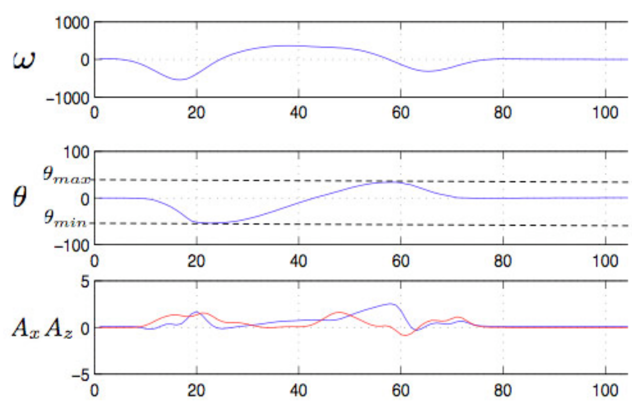

Fig. 4. One foot displacement, signals from the gyroscope (up), its integration (middle) and the corrected accelerations (down). Computations are made with equations (2) and (3).

C. Sensor Fusion

The previous estimator can be computed independently if we mount one IMU at each foot. Then, the estimation at each stride can be compared with the correspondent of the opposite foot. With anthropometric considerations specific to the user biomechanics –leg length and usual stride length- it is possible to limit the uncertainty growth, see Figure 4. To mix that information a simplified version of the extended kalman filter is applied [16].

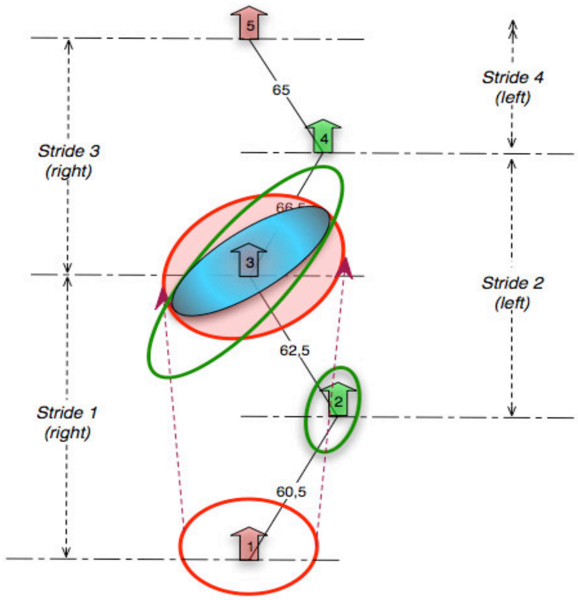

Fig. 5. Sensor fusion procedure. The four steps correspond to two stride length estimations of the right foot, and one stride length estimation of the left foot. The position of the third step (footprint 3) is computed by two ways: the right foot IMU allows us to propagate the initial uncertainty (footprint 1), see red ellipse; on the other side, the previous estimation of step 2 (footprint 2) defines an area of possible locations of the next step, green ellipse. Both estimations can be mixed with an extended kalman filter.

III. Experiments and Results

A. Experimental Setup

Preliminary tests have been done in the Electrical Eng. Department at the Oviedo University. Measurements were taken from one healthy man, with no footwear requirements for the experiment. The procedure is being currently extended to a number of volunteers to get statistically significant results. During test procedures, subject were asked to walk 10 meters following a straight path. The first and last two steps were discarded for the analysis, since gait is not stable during the initial and final phases. The subject completed 4 independent excursions, and he was asked to maintain a constant velocity for each walk. Subjects were allowed to turn freely between each excursion.

One camcorder was placed at the beginning of the 15m segments, at the floor level. The HO event of every step was visually identified in the records, with a maximum error of 2 video frames (0.08s). Floor marks were placed each centimeter, and the actual distance was visually measured for each excursion. Total time was also measured, as the difference between these two events. Velocity and the total length and excursion duration are computed.

Acceleration data were gathered by means of a triaxial accelerometer placed close to the fifth metatarsal, see Figure 1. The device is fixed to the shoe spine by means of a tight adhesive tape to avoid movement artifacts.

The accelerometer is an XSens MTx sensor. Measurement range is ±2g, being *g* the gravity acceleration. Data were gathered at 100Hz by using a 12bit A/D conversion. MTx sensor is wired to an Xsens Xbus Master, placed in the subject's belt. All data are stored in a PC, where the Xbus Master device transfers them in real time by means of a bluetooth communication link for further processing.

Syncronization between the camcorder and the IMU was done inserting a special mark in both systems. Final syncronization error was less than a video frame (0.04s).

Two ink adhesive markers of different colors were added to the sole of the shoe, one at the heel and the other near the toe-off point. This way, every step was recorded and its length measured by hand. For example, Figure 5 is made from real data of one trip.

B. Experimental Results

Since the proposed estimator depends on the correct identification of two gait events, HO and FF, the performance of the detection algorithm has been visually examined, and no one step were missed.

In order to facilitate comparison, all estimations were refereed to the real measured length, that is, estimation minus real length. Therefore a percent change of 0% means an exact estimation.

The mean estimation for a single IMU was 10.069% (±6.167) considering all the experiments together. These results are consistent with what is reported in the literature. Estimations ranged from -14.87% to +9.12%.

The estimation for two IMUs presented is able to reduce the errors and to bound the uncertainty growth with distance. Estimations range means decrease in around three per cent points and reduction level are obtained in the standard deviation. Ongoing experiments are aimed to validate these results.

IV. Conclusion

We have presented a method to estimate the step length based on inertial feet attached sensors. Contrary to similar works, a multisensor approach is applied in order to reduce uncertainty and to produce better estimations. An adapted kalman filter based sensor fusion system is proposed. Initial results are encouraging. Ongoing extended field experiments have been designed to validate and generalize the results for a heterogeneous populations and walking conditions.

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