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Estimation of traversed distance in level walking using a single Inertial Measurement Unit attached to the waist

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Abstract— **A method for estimating step length during level walking using a single inertial measurement unit is proposed. A combination of an optimally filtered direct and reverse integration technique and a velocity update technique for the initial velocity values identification was implemented to reduce the effects of the acceleration signals drift. The method takes advantage of the cyclic nature of gait. The inertial measurement unit was placed at waist level on the right side and the method was validated on eight subjects walking for 75 m while varying their speed. The traversed distance was estimated with an average error equal to 0.8% of the total walking distance.**

I. INTRODUCTION

MEASURING pedestrian displacements and temporal and spatial features of gait, both outdoor and indoor, with no space limitation and for prolonged periods of time is useful for a variety of applications including rescue operations, movement activity monitoring [1] and functional evaluations of gait disorders [2]. These goals can be conveniently pursued by using wearable inertial measurement units (IMU). Recently, the use of IMUs for estimating spatial gait parameters has been investigated with great interest since IMUs have become low-cost and small sized [3]. IMUs often include accelerometers and gyroscopes [4]. Linear displacements can be obtained by double integrating the IMU linear coordinate acceleration (i.e. IMU acceleration components in the global reference frame). IMU coordinate acceleration can be obtained by removing the gravitational contribution from the accelerometer signals (i.e. specific force). To this purpose an estimate of the IMU orientation in the global reference frame is needed [3, 5].

However, the implementation of the procedure described above requires the solution of a number of critical issues:

a) the compensation of the drift affecting the recorded accelerometer and gyroscope signals, which introduces errors in the displacement estimations non-linearly related to the integration time [6, 7],

b) the determination of the IMU orientation with respect to the global reference frame from gyroscopic and accelerometer data [8], and

c) the estimation of the initial velocity values for the integration of the coordinate acceleration components.

The detrimental effects of the drift are typically reduced by exploiting the cyclical nature of gait. This allows reducing the integration time to a single gait cycle but requires the identification of an instant of known velocity to be used as initial velocity in the integration process [3, 9, 10, 11].

When the primary goal is the estimation of the temporal and spatial gait parameters, the preferred IMU location is on the foot, since in such case the velocity and the orientation can be set to zero at the beginning of the integration interval (zero velocity update technique) [3, 4, 5, 9, 10, 12, 13, 14, 15, 16].

Unfortunately, positioning a single IMU on a foot does not allow gathering information about the events of the contra-lateral foot and therefore about the gait symmetry, (comparison of ipsilateral and contra-lateral step length, double support durations etc.). When such information is of interest, the most straightforward solution would be to place a single IMU on each foot. However, when the requirement of a simple low-cost setup is of primary importance (e.g. monitoring of daily activities in a large number of subjects), it would be desirable to obtain the same information using a single IMU. Zijlstra and Hof proposed a method that uses a single IMU to estimate right and left spatial-temporal parameters of gait from trunk accelerations [17]. The IMU was placed on the back at the S2 level. The method used zero crossing of the forward accelerations for detecting foot contact instances and an inverted pendulum model to estimate the stride length. However, in their method, left and right foot contacts identification failed for 6 out of 15 subjects, 12 % of the times and step lengths were underestimated in all subjects and at all speeds [17]. Moreover, the location of the IMU at the dorsal side of the trunk limits the use of the method for monitoring daily activities (e.g. during sitting, laying, etc.).

Recently, Kose and colleagues [18, 19], proposed a method for the estimation of spatial and temporal parameters of both sides during walking using a single IMU attached to the right side at the waist level using an optimally filtered direct and reverse integration (OFDRI) [20] technique for correcting the effects of the drift. The OFDRI can be applied when both initial and final velocity of the gait cycle are known. The method presented in that study required a gait at constant known speed. However, in traversing distances in daily life, gait speed may often change, limiting the usability

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of the above mentioned method.

To address such limitation, we developed an improved version of the original method. The accuracy of the method was evaluated for a fix distance traversed (75 m) for variable walking speed.

II. Material and Methods

The method presented here can be applied to any IMU featuring a tri-axial accelerometer and three axial gyroscope and it can be decomposed in the following steps:

a) segmentation in the gait cycles;

b) estimation of the coordinate acceleration in the direction of progression (AP);

c) integration technique.

2.1a Segmentation in gait cycles

The segmentation in gait cycles required the identification of the instances of the heel strikes (HS) on a chosen side. These instances were obtained using an approach based on a wavelet decomposition technique [21].

A preliminary visual investigation was performed in order to correlate the distinctive features in the IMU signals with the gait events extracted from the footswitches data (Fig. 1).

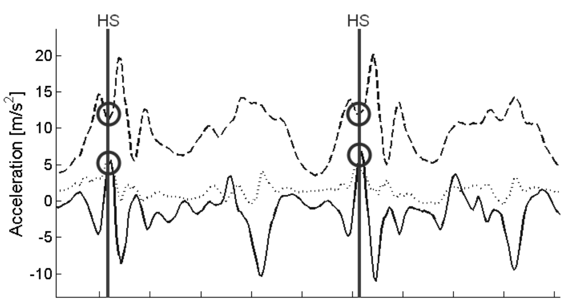

Fig 1 Vertical (dashed line), anterior-posterior (solid line) and medio-lateral specific force (dot-dashed line) with footswitch events superimposed (vertical lines). Circles show the reference points on the specific force components in correspondence of the gait events. X-axis divided in intervals of 0.2 seconds.

In order to identify the candidate time instances from the specific forces time series measured by the accelerometers, a wavelet-based method was applied to the IMU signals. In this method, all signals were decomposed in ten levels of detail with “Stationary wavelet decomposition” [21]. Daubechies level 5 (“db5”) mother wavelet was used, since it is similar to the signals in the intervals of interest. Following the decomposition, thresholds were applied to the first three detail levels and the other detail levels were discarded.

Thresholds for these levels were 1/5, 1/4 and 1/3 of its magnitude for the first, second and third level, respectively. The reconstructed signal is shown in figure 2. The HSs were detected as the midpoint of the time of the maximum of the wavelet filtered anterior-posterior acceleration and the time of the first minimum of the vertical acceleration in the interval of interest.

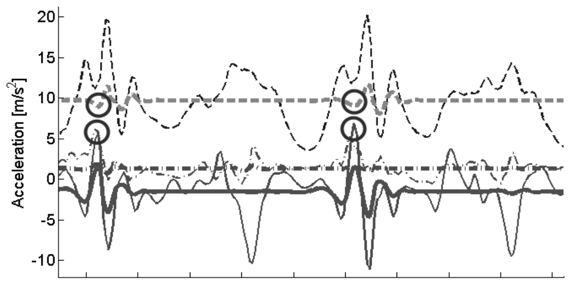

Fig. 2. Accelerometric signals after wavelet decomposition (in bold), superimposed to the raw signals. X-axis divided in intervals of 0.2 seconds.

2.1b Estimation of the IMU acceleration AP coordinate component

In order to compute the IMU coordinate acceleration components, the orientation of the reference frame embedded with the IMU (L_{IMU}) with respect to the global frame (G_{IMU}), was estimated using a specifically designed Kalman Filter [22]. The orientation of L_{IMU} with respect to G_{IMU} at the i[th] instant of time can be expressed using the orientation matrix notation:

$$^{G_{IMU}}\mathbf{R}_{L_{IMU},i} = \begin{pmatrix} c\phi & -s\phi & 0 \\ s\phi & c\phi & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} c\theta & 0 & s\theta \\ 0 & 1 & 0 \\ -s\theta & 0 & c\theta \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & c\psi & -s\psi \\ 0 & s\psi & c\psi \end{pmatrix} \quad (1)$$

Where ψ is the rotation about the $\mathbf{x}_{G_{IMU}}$ axis (roll), θ is the rotation about the $\mathbf{y}_{G_{IMU}}$ axis (pitch) and ϕ is the rotation about the axis $\mathbf{z}_{G_{IMU}}$ (yaw).

Let $^{L_{IMU}}\mathbf{f}_i$ be the specific force vector measured by the IMU expressed in L_{IMU} at time *i*, then the coordinate acceleration vector expressed in the G_{IMU} ($^{G_{IMU}}\mathbf{a}_i$), including, in particular, its AP component ($a_{x,i}$) can be computed as:

$$^{G_{IMU}}\mathbf{a}_i = {}^{G_{IMU}}\begin{bmatrix} a_{x,i} \\ a_{y,i} \\ a_{z,i} \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ -g \end{bmatrix} + {}^{G_{IMU}}\mathbf{R}_{L_{IMU},i}\, {}^{G_{IMU}}\mathbf{f}_i \quad (2)$$

2.1c Integration technique

In order to obtain the velocity and position time series, two different integration techniques were used: Optimally Filtered Integration (OFI) and Optimally Filtered Direct and Reverse Integration (OFDRI) [20]. The OFDRI can be applied only when both initial and final values of the integral are known. Given an arbitrary gait cycle *j*, let be v_{x,ih_j} , the AP velocity component expressed in the G_{IMU} at the initial heel strike which is supposed to be known. The velocity component at the heel strike at the end of the gait cycle

v_{x,fh_j} is first computed by integrating the acceleration $a_{x,i}$ using the OFI. Then, if the difference $v_{x,fh_j} - v_{x,ih_j}$ is lower than a selected threshold ($\varepsilon = 0.3 m/s$), the OFDRI technique is used to compute $v_{x,i}$ otherwise the velocity is estimated using OFI and $v_{x,ih_{j+1}} = v_{x,fh_j}$ (velocity update, VUT). The values of velocity at the first three initial heel strikes were estimated by integrating the acceleration throughout the first three gait cycles using the OFI technique. The AP displacement $d_{x,i}$ was computed by integrating $v_{x,i}$ using the OFI.

2.2 Method validation

The method proposed was validated in two different experimental conditions (dataset A and B) on eight healthy subjects (31 ± 6 yrs) for dataset A and nine subjects (34 ± 8 yrs) for dataset B.

2.2a IMU specifications

Gait data were acquired using an IMU (FreeSense, Sensorize®) featuring a tri-axial accelerometer and two bi-axial gyroscopes (acceleration resolution 0.0096 m/s^2, angular rate resolution 0.2441 deg/s, unit weight 93 g, unit size 85 mm × 49 mm × 21 mm). The IMU was mounted on the right side of the body at the waist level with its x-axis pointing downwards, the y-axis pointing forward and the z-axis pointing to the right (Fig. 3). Acquisitions were sampled at 100 Hz.

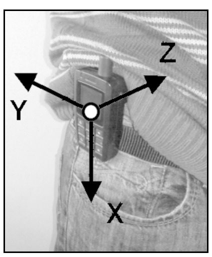

Fig. 3. IMU positioned to the right side of the subject at waist level.

2.2b Experimental acquisitions

Dataset A - This experimental setup was aimed at validating the heel strike events detection method Footswitches (BTS® FreeEMG) were placed under each heel and big toe. Subjects were asked to walk at a self-selected speed three times along a closed loop track delimiting an area of approximately 10 by 3 meters.

Dataset B – The subjects walked straight for 75 m starting at their self selected speed and increasing it every 25 m. The heels of the subjects were aligned at the start line and when they stopped in the proximity of the finish line, the distance between the finish line and their heels was then measured with a ruler.

2.2c Data analysis

Dataset A - The estimations of HS events were compared to those obtained from footswitches. The errors were determined as the absolute time difference of the events detected using the IMU and the events identified with the footswitches.

Dataset B – The traversed distances were estimated using the method presented in this study. The error associated to the IMU displacement estimates was determined as the difference between the actual distance traversed and the distance estimated with the IMU.

III. RESULTS

3.1 Heel strikes detection

The 96% of the right HS (RHS) instances were successfully detected using a single IMU placed at waist level. The undetected events occurred at the beginning and at the end of the acquisitions when the signals were characterized by small amplitude. Errors in detecting the gait events using the proposed method are reported in Table I.

3.2 Traversed distance

The difference between the distance marked on the walkway (75 m) and the IMU-based estimates are reported in Table II. The average of the absolute values of the errors over the subjects was 0.66 m, i.e. 0.8% of the total walking distance.

TABLE I
ERRORS IN DETECTING RHS

subject	RHS	
	mean [s]	s.d. [s]
A1	0.03	0.04
A2	0.04	0.03
A3	0.03	0.04
A4	0.02	0.04
A5	0.02	0.03
A6	0.04	0.02
A7	0.05	0.04
A8	0.04	0.03
average	**0.03**	**0.04**

TABLE II
ERRORS IN TOTAL DISTANCE ESTIMATION

	actual distance [m]	estimated distance [m]	difference [m]	% difference
B1	74.99	74.16	-0.83	-1.11
B2	74.94	75.76	0.82	1.09
B3	74.94	74.41	-0.53	-0.71
B4	74.94	74.59	-0.34	-0.46
B5	75.03	74.45	-0.58	-0.77
B6	75.05	75.62	0.57	0.76
B7	75.00	75.66	0.66	0.88
B8	74.97	74.20	-0.77	-1.03
B9	75.05	75.89	0.84	1.12
	average		**-0.02**	**-0.02**

As an example, in figure 4 the AP component of: the coordinate acceleration ($a_{x,i}$), the velocity ($v_{x,i}$) and the displacement ($d_{x,i}$) as a function of time are reported for one subject.

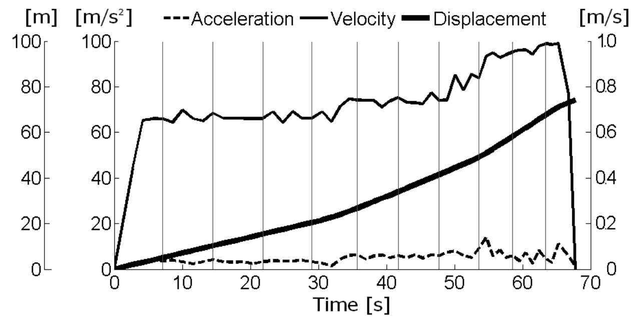

Fig. 4. Time series of AP component of: coordinate acceleration, velocity and displacement estimated during the trial of subject B1. Vertical lines are placed every 5 gait cycles.

IV. DISCUSSION

In this study, a simple, low-cost solution for determining the stride length and the traversed distance using a single IMU attached to the waist was presented.

The proposed method is an extension of the method proposed in [19] and combines an optimal integration technique (OFDRI) and with a velocity update technique (VUT) for the identification of the initial velocity values.

The average percentage error over nine subjects (0.8 %) was comparable to the results obtained in those studies in which the IMU was placed on the foot. As opposed to other methods proposed in the literature [17], the estimate of the traversed distance is never consistently either an overestimate or an underestimate (average over subjects close to zero -0.02%)

It is worth to notice that if a simple optimal forward integration (OFI) [20] is performed, the traversed distance would be assessed with an error of about 150%, and with an error of 25% if the OFDRI technique is employed without the velocity update.

Another distinctive feature of the proposed method is that, as shown in [19], it is possible to gather temporal and spatial parameters for both left and right sides using a single IMU. Future work is required for validating the estimation of the gait symmetry parameters.

Moreover, the location chosen for the IMU (waist level) is practical for monitoring daily life activities.

It is important to stress that the method was tested on favorable experimental conditions: a) velocity transients were limited (three speeds), b) rapid and c) subjects walked straight. It is reasonable to expect that errors in distance estimation would be higher if the walking path is not straight and the walking speed changes were slower and/or more numerous.

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