2011 INTERNATIONAL CONFERENCE ON INDOOR POSITIONING AND INDOOR NAVIGATION (IPIN), 21-23 SEPTEMBER 2011, GUIMARÃES, PORTUGAL

Determination of heading information from gait cycle pattern using stride length estimation with reduced IMUs on right and left foot

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***Abstract*—For pedestrian indoor positioning the heading and distance information are needed to perform two dimensional dead reckoning. A new approach is described to determine the heading information from stride lengths, which are measured at both feet. The stride lengths are calculated from inertial measurements, which are conducted at both feet and evaluated with the support of zero-velocity updates. The stride lengths lead to the heading of the pedestrian and are used to calculate two dimensional coordinates. Using single gyroscope and dual accelerometer sensors on each foot, an experimental stride length estimation system was set up. First results show the proof of concept of the heading determination.**

***Keywords*—Pedestrian navigation; inertial sensors; zero-velocity updates; stride length estimation**

I. INTRODUCTION

Foot-mounted inertial measurement units (IMU) have been used to determine positions of pedestrians with zero-velocity updates (ZUPT) at the stance phases [1]. This was possible, because the movement of the foot follows a well known pattern in the sagittal plane, which is the plane in which walking is described, when it is observed from sidewards.

In this paper, we enhance the idea of using information from the human gait itself to correct inertial measurements and analysis for indoor positioning. So far, the characteristics of the human gait with its 60% swing time and 40% stance time in one gait cycle [2] was used to correct the determination of the velocities by applying ZUPTs at detected stances phases [1].

We further analyzed the human gait behavior and developed an algorithm to determine the change of heading α from the stride lengths (see Fig. 1) which were identified with inertial sensors attached on the right and left foot.

The heading determination algorithm was developed with simulated stride lengths of the right and the left foot, creating a virtual figure of 'eight'. An experimental measurement system was set up to determine the stride lengths on both feet using a hybrid MEMS sensor on each side, each with a single gyroscope and dual accelerometer (SG-DA). The heading information is therefore not depending directly on the gyroscope measurements and no magnet field measurements are needed, which are not reliable in indoor environments with strong disturbances by electronic installations.

The accuracy of the stride length was tested in a gait laboratory using a GAITRite system [3]. Real walking data of a figure of eight scenario combined with the true figure of eight demonstrates the validity of the approach. The trajectories of the real walking data show the potential of the heading determination, which delivers two-dimensional coordinates by dead-reckoning.

II. METHODS

A. Gait pattern geometry

We separate the gait cycle into a vertical component, which is located in the sagittal plane of the human body and horizontal part, which is located in the horizontal plane.

Important for applying ZUPTs to the inertial measurements is the characteristic of the vertical component and the stance phase. Following the Rancho Los Amigos National Rehabilitation Center (RLANRC) model, medical gait analysis is breaking the stance phase into four parts [4]. As part of the stance phase, the midstance is the relevant time period to detect for applying ZUPTs to the navigation computation. The midstance starts with the toe-off of the adverse foot and ends with lifting the heel. The characteristic of the midstance is the single leg support with full contact to the ground of the sole, though there is movement of the body over the resting foot [4]. Therefore the sensors used for pedestrian positioning with foot-mounted inertial sensors should be placed as close as possible to the ground. If they are attached at the ankle, there is still a movement, which as to be taken into account.

The horizontal geometry of human gait follows a pattern, which also could be used for pedestrian positioning. In Fig. 1, the gait is described by the stride length and the base of support of the left and right foot. We expect the variations in stride length and base of support to be small for walking

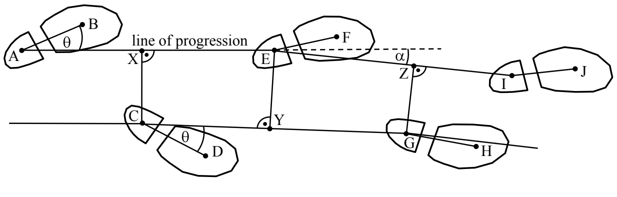

Fig. 1. Horizontal gait cycle parameters. Stride length SL (AE, EI, and CG) measured along the line of progression from two consecutive heel contacts. Support of base b (XC, YE, and ZG) is the perpendicular distance of one heel contact with respect to the line of progression of the other foot. The toe out angle θ is defined as BAE and DCG.

straightforward. For walking along a curved line the variations of the stride length indicate the direction and the radius of the curvature and a change of heading α. The base of support b will also vary with the curvature of the trajectory, but will stay within certain limits, which depend on the person.

The toe out angle θ is defined as the angle between the line of progression and the mid-foot line. It is by definition positive, if the foot is turned outwards with respect to the line of progression [3].

B. Experimental measuremt system

A full-IMU with three gyroscopes and three accelerometers can provide heading rate and linear acceleration for inertial analysis in three-dimensional space. To reduce hardware cost, the number of sensors can be minimized using other sensor combinations [5]. For the experimental system we use a micro-electromechanical system (MEMS) SG-DA sensor from Bosch. The SMI540 combines the two sensor elements for the measurement of the turn rate and the specific force into a single package [6]. Each foot was equipped with one SMI540 sensor, one accelerometer pointing in the forward direction, the other accelerometer pointing in the upward direction. The measurement axis of the gyroscope of the SMI540 is orthogonal with respect to the two accelerometers. The control system was placed in a backpack connected to the sensors by cables. The system was controlled by a second person with a laptop. The measurements are performed with a typical data rate of 230 Hz. Using a monitor channel we get typically values of up to ± 5 g for the accelerometers and up to ± 500 °/s for the turn rate.

C. Stride length estimation

The inertial raw data is used to detect the stance phases using a threshold based evaluation method, which uses only the accelerations. At the stance phases, pseudo measurements are applied to the angle derived from the turn rates. This angle is derived from the accelerations in the static conditions of the stance phase and is used to transform the raw accelerations from the sensor system into a horizontal coordinate system. In the horizontal coordinate system, the zero-velocity updates replace and correct the velocities, which are derived from the first integration of the accelerations. This eliminates the drift in the resulting positions, from which the stride lengths are derived.

D. Heading determination

For our evaluation (see Fig. 2) we use stride lengths for the left and right foot (SL_{left}, SL_{right}) and a given initial value for the base of support b. The direction of the curvature of a certain stride is determined by a comparison of filtered stride lengths from both sides, which directly allocates the stride lengths to the inner or outer lane. The switch in Fig. 2 implicates that the following calculations of the curvature radius R and change in heading α depend on the curvature c and are performed for the left and right foot separately, which leads to coordinates x and y of two trajectories for the left and the right foot.

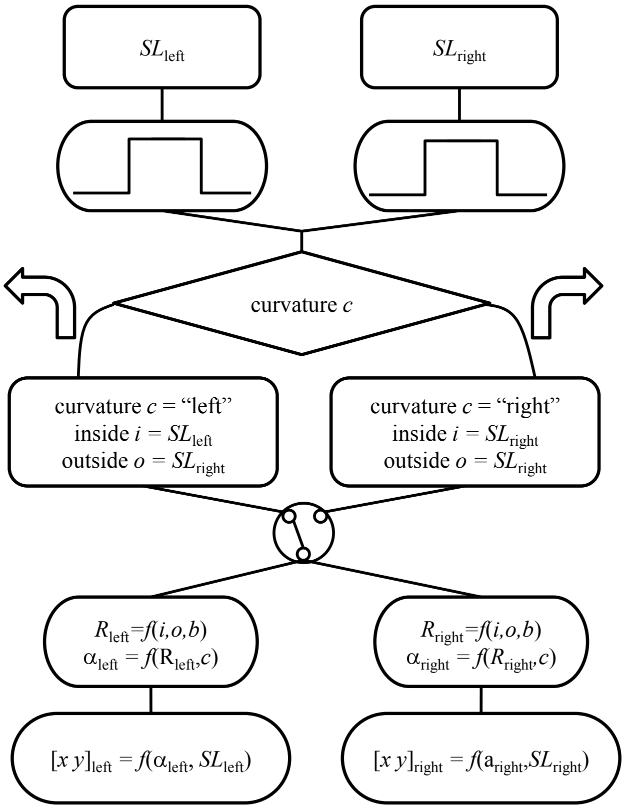

Fig. 2. Flow process chart for the calculation of changes in heading α derived from stride lengths of the left and right foot SL_{left} and SL_{right}.

E. Experiments

First accuracy checks were conducted with walking straightforward on the GAITRite system, which delivers coordinates for every contact of the sole on a matrix of pressure sensors every 1.37 cm apart. While midstance, the foot triggers the pressure sensors of the GAITRite in the area of the sole. The elements of the gait cycle geometry from Fig. 1 are all calculated by the GAITRite software [3].

For walking with a changing heading, we were inspired by [7], where a figure of eight test is described with two lines. For the layout we followed the modifications of [8], where the test is described with a single lined painted figure of eight. The figure of eight could not be performed with the GAITRite system, due to the limitations of its dimesions.

III. RESULTS

As expected, for walking straightforward, the stride lengths of the left and right foot vary in a small range of 0.1 m for the GAITRite system. Their minimum and maximum values of the left and right foot from the GAITRIte and from the experimental system are given in Tab. I. The length calculated from the inertial measurements are shorter than the lengths from the GAITRIte system, but the standard deviations σ of the stride length match, see below for the explanation. For this analysis the stride lengths of both feet were not separately evaluated.

TABLE I
CHARACTERISTICS OF STRIDE LENGTHS WALKING STRAIGHTFORWARD.

	Min [m]	Max[m]	σ [m]
GAITRIte solution	1.46	1.56	0.03
Inertial solution	1.34	1.46	0.04

TABLE II
CHARACTERISTICS OF STRIDE LENGTHS WALKING A FIGURE OF EIGHT.

	Foot	Min [m]	Max[m]
first part curvature c =”right”	left	1.18	1.41
	right	0.96	1.20
second part curvature c =”left”	left	0.96	1.19
	right	1.13	1.47

In Tab. II there are the characteristics of the stride lengths derived from the inertial measurements of the figure of eight walk. The range of their values is from 0.96 m to 1.47 m.

In the second and third line of Tab. II the stride lengths for the first half of the the figure of eight from beginning until the turning point of the curvature are analyzed separately for the left and right feet.

In the last two lines of Tab. II the characteristics of the stride lengths are shown, from the middle of the figure of eight until the end. This part has a different curvature from the part before, which can easily be derived from the ratio of stride lengths from both feet.

The reference trajectories $s(R_i, R_o, d)$ are defined by three parameters: the radii R_i and R_o of the inner and outer circles, and the distance d between the central points of the circles, which describe the figure of eight. The reference coordinates are described as a function of distance $[x\ y]_{ref} = f(s)$. The coordinates$[x\ y]_{map} = f(cumsum(SL))$ of the strides are calculated using the cumulated stride lengths SL, see Fig. 3.

The origin of the coordinate system is the starting point for the walking experiment. The test person followed the figure of eight from the origin first along the y-axis and then along the bended left line into the first part, then along a short straight and finally the last part with the right bended shape ending exactly at the origin.

From the heading detection algorithm implied by Fig. 2 we derived the trajectories plotted in Fig. 4. The reference trajectories are plotted with thin lines and the resulting trajectories with bold lines. Circles are used for the left foot contacts and squares for the right side respectively. The end positions are marked with triangles, which are about 1.5 m and 1 m away from their expected positions. The two trajectories cross each other after 14 strides.

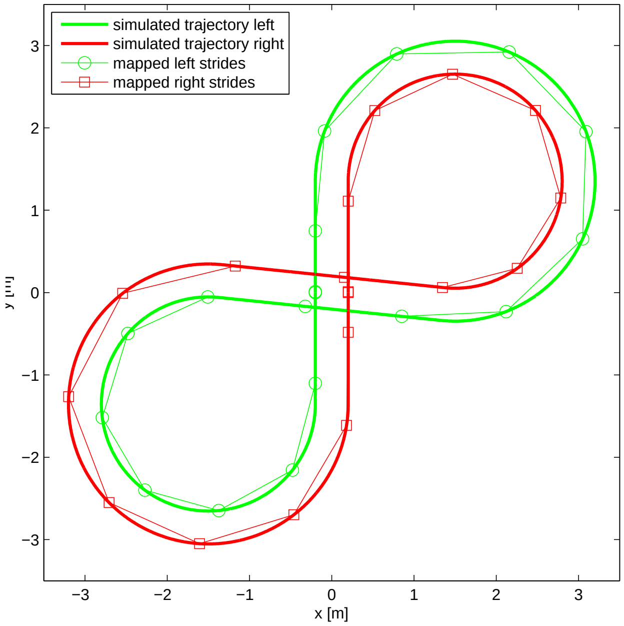

Fig. 3. Simulated Trajectories with the measured stride lengths mapped onto it.

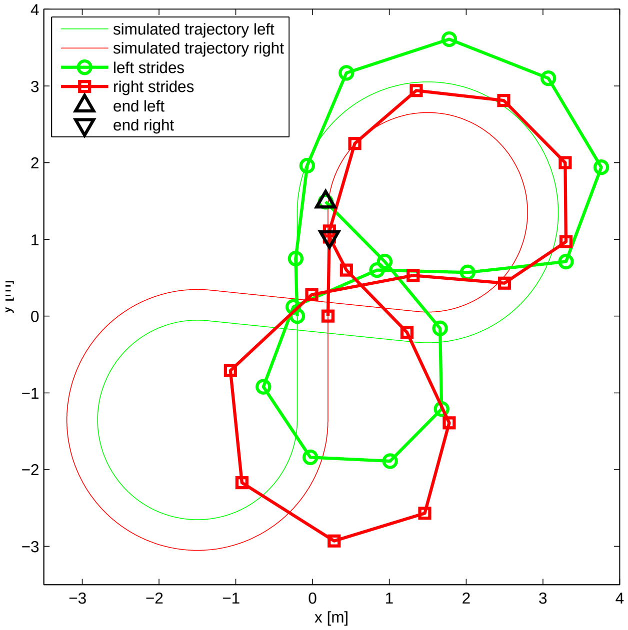

Fig. 4. Trajectories of the dead reckoning with measured stride lengths and derived heading for both feet.

IV. DISCUSSION

The ranges of the stride lengths from the two measurement systems do not match, this is because the misalignment of the measurement axis of the accelerometer is not taken into account. The toe out angle θ and the misalignment will add to an individual misalignment angle for every gait cycle. But from the matching standard deviations of the derived stride length we can conclude, that the experimental system with the Bosch SMI540 sensors deliver reliable and precise stride lengths. As we are looking for changes in the stride lengths for the heading determination, we can use these biased but precise results. The direction of the curvature can be derived from the differences of the stride lengths in Tab. II.

Even though the stride lengths are biased, the figure of eight can be identified in Fig. 4. The two trajectories cross each other after 14 strides, this should not be interpreted as a turning backwards while still walking. The two trajectories are calculated on the same data basis, but they are not connected to each other. They roughly follow their expected behavior of the horizontal gait pattern, where one heel contact is supposed to have a perpendicular distance of the base of support with respect of the middle of the line of progression. This can be seen until the fifth contact.

V. OUTLOOK

Additional information could improve the heading determination. So far the change of heading for the left and right feet are determined from the same data source, but the results are not combined, averaged or filtered. More information from the gait cycle geometry should be used. The two trajectories should support each other and crossings should not be allowed while walking.

Future research will concentrate on alternative ways of determine the change of heading using only the stride length. As the functional relation is based on presumptions for example about the base of support, another possible solution could be the use of artificial neural networks. With this method the functional model can be unknown, but reliable reference coordinates are needed to train these algorithms. The next experiments should be supported with motion tracking systems as for example a system from Vicon.

Reference data from motion capturing or GNSS positioning could be used to calibrate the stride length estimation. Also the SG-DA sensors could be replaced by full-IMUs to improve the stride lengths determination itself.

ACKNOWLEDGMENT

The author thanks his contacts in the industry and in other research institutions for their support and encouragements. A special thanks is due to the colleagues for their assistance.

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