Pedestrian Dead Reckoning for Person Localization in a Wireless Sensor Network

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***Abstract*—Localization in areas where no global navigation satellite systems (GNSS) are available is still a challenging task. For pedestrian navigation this is especially interesting because this problem is faced more often than in other scenarios like car navigation. Wireless sensor networks (WSN) are one approach to indoor localization and allow an easy setup in ad-hoc scenarios. However, for networks with a low density of nodes or uncovered areas an additional localization method is needed. Pedestrian dead reckoning (PDR) is an ideal complementary system to supplement the localization with short time accuracy.**

This paper concentrates on an approach to PDR with low processing power for the use in WSN with a hip-mounted inertial measurement unit (IMU). The purpose of the system is to provide a localization and tracking solution if temporarily none or only few anchor nodes are within range. Steps are detected, the step direction is determined in coordinates of the IMU and the length of each step is estimated. We present an experimental evaluation of the system under varying environmental conditions and show that the concept is promising for the intended applications.

I. Introduction

Localization in WSN has gained a lot of attention during the last years. One of the reasons is the fundamental question of the correlation between a measured value, its time and its location. One important application area is the localization and tracking of persons in scenarios where GNSS are not available. A system that can provide localization under such conditions could be of enormous help for firefighters or other action forces that want to logistically coordinate a mission. These scenarios require an easy installable and robust solution to localize the involved personnel. A dedicated WSN for the localization is a way to achieve this with the additional feature of providing communication within the network. This allows the integration of other sensor readings and leads to a modular system which can be extended with additional functionality easily.

The accuracies needed for the intended applications are in the range of a few meters, i.e. on room level. In WSN this can be achieved by evaluating the received signal strength (RSS) of radio packets from anchor nodes with known positions [1].

Location estimations from RSS range-based approaches are subject to fluctuations caused by the unpredictable behavior of RSS values especially in indoor scenarios. To cope with these fluctuations, a stochastic filter and a system model of the moving person can be used. Additionally, the use of inertial sensors can improve the localization accuracy to a certain degree [2]. However, in cases where the area of interest cannot be fully covered by the WSN or the anchor node density is too low, a short-time accurate localization system is needed to take over for some time.

In this paper the integration of a PDR unit into a WSN is presented. Because of the low processing capabilities of the sensor nodes microcontroller unit (MCU), the application demands a very simple approach in terms of computational complexity. Thus, a hip-mounted IMU-based system has been developed. We present the results of an experimental evaluation of this concept under different environmental conditions.

II. State of the Art

During the last years, the inclusion of micro electro mechanical systems (MEMS) based sensors in almost all smart phones resulted in technological improvements and in a price decline of such components. This development also led to an increase of research interest in pedestrian navigation systems based on MEMS inertial measurement units (IMU). Placing the IMU on the foot has gained a lot of attention recently because it allows using strapdown algorithms known from high precision applications like aerospace or marine scenarios [3], [4]. In these systems, the position is derived from a double integration of the measured accelerations. To compensate the inherent drift of today's MEMS IMU, additional system inputs have been proposed. The most famous are the zero-velocity update (ZUPT) which sets the velocity to zero during each stance-phase and analogously the zero-angular rate update (ZARU) [4]. A more recent approach is to use a heuristic drift reduction

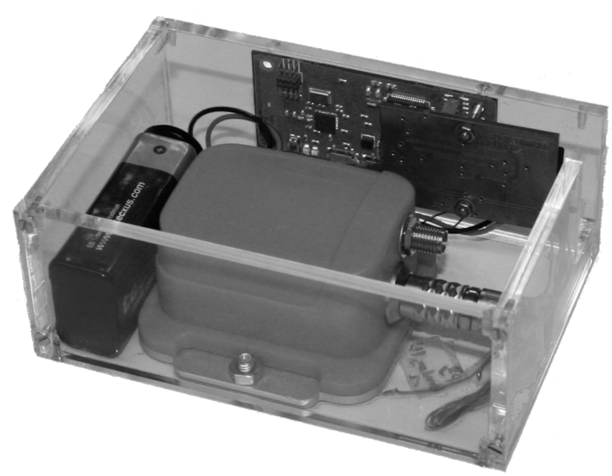

Fig. 1. IMU sensor node combination (Xsens MTi-G and ITIV LocNode).

(HDR) algorithm which assumes that the pedestrian is mostly walking along straight paths [5]. All these approaches with a foot-mounted IMU yield very competitive results with errors on the order of a few percent of the traveled distance [6]. The accuracies strongly depend on the performance of the inertial sensors and data processing. However, all these approaches have in common, that a complex system model and a large state vector is required. Because of the high dynamics occurring on the foot, it is also necessary to use high update rates for the data processing. Both characteristics require a fast processing system which is contradictory to WSN hardware with low power MCU.

Besides placing the IMU on the foot a lot of other positions have been evaluated. This includes the head [7], rucksack structures [8] or the hip [9]. All of these approaches have in common that strapdown algorithms with ZUPTs cannot be used because of the error evolvement with state of the art MEMS sensors. For these concepts step recognition and step length estimation approaches are considered. The performance in terms of accuracy for these systems cannot compete with foot-mounted systems. Resulting errors are on the order of 10 % of the traveled distance [10].

In the following, a hip-mounted IMU is considered because this is more practical and realistic for the intended applications. Other reasons for choosing this IMU position are the lower dynamics which allow for a lower update rate and make it possible to do the calculation on a typical WSN MCU. Furthermore this approach is easily portable to off-the-shelf smart phones [11]. This has a great potential for navigation in exhibition halls or airports, but also in shopping centers and underground parking lots.

III. System Concept

A. Pedestrian Dead Reckoning

The IMU model considered in this work is the MTi-G from Xsens Technologies B.V. It incorporates acceleration sensors, gyroscopes and magnetic sensors in three dimensions for attitude estimation. To further improve the heading estimation it can be extended with a GPS antenna. An internal digital signal processor (DSP) calculates the attitude based on a chosen preset. These presets allow influencing the attitude calculation, e.g. it can be selected if magnetic sensors should be used or not. The IMU outputs calibrated sensor readings from all sensors and also the internally calculated attitude. This is especially useful for the considered system because the sensor node does not have to handle this complex task. The drawback of this approach is that no further corrections (like HDR) on the attitude can be applied.

As stated in Section II, current MEMS-IMU do not provide a sufficient accuracy for strapdown algorithms if the IMU is placed somewhere on the human body.

Our approach to determine the user's position is based on step recognition which updates the position estimation at each detected step. Therefore it is also necessary to know the direction and length of that step. Beside the used coordinate systems, these three topics will be covered in the following.

1) Coordinate Frames: The solution of the position estimation process is with reference to the navigation frame (n-frame) which represents a local tangent plane (LTP) on the earth's surface. However, sensor measurements from the IMU are in body frame (b-frame)-coordinates of the IMU. To quantify the pedestrian's step direction an additional coordinate frame is introduced. This is referred to as the human frame (h-frame) in which the x-axis describes the forward-walking direction, the y-axis is perpendicular in the horizontal plane (sideward) and the z-axis is aligned with the human body (up-direction) and perpendicular to both other axes.

2) Step Recognition: The detection of successive steps is based on a peak and threshold analysis with the energy of the acceleration signal in all three dimensions

$$energy(\vec{a}) = \vec{a}^2 \tag{1}$$

Additionally, multiple peaks within a time-frame of 300 *ms* are rejected. This has the same effect as filtering the signal with a low pass filter beforehand and prevents a multiple detection of the same step.

3) Step length Estimation: For an online estimation of the users step length there exist a number of different approaches. However, they all perform very similar [12]. For the purpose of this paper the Weinberg Algorithm is chosen because of its simplicity [13]. The step length SL is calculated from the maximum and minimum measured acceleration in z-direction of the n- or h- frame

$$SL = \sqrt[4]{max(a_z) - min(a_z)} \cdot W \tag{2}$$

4) Step Direction: The step direction, i.e. the alignment of the IMU on the human body, needs to be known in coordinates of the b-frame so that it can be transformed to the n-frame. Assuming the user is walking forward, the step direction is given in the h-frame by the vector $[1, 0, 0]^T$. For normal and fast walking, the step direction is characterized by a larger acceleration than the sidewards acceleration. Thus, it can be obtained by a principal component analysis (PCA) [9]. From the raw-acceleration data in the b-frame the gravitational component and the acceleration a_z^n have to be removed. These can be obtained with the direction cosine matrix (DCM) C_n^b directly as shown for the gravitation (g)

$$g^b = {C_n^b}^T \cdot [0, 0, g]^T \tag{3}$$

With this information, also the z-acceleration in the n-frame can be removed. Applying the PCA to the remaining two components of the acceleration, the step direction will be given. It can, however, not be distinguished between forward and backward direction. Similar to [9] the alternation of maximums in x- and z-components of the h-frame acceleration is used to determine the step direction completely. With this kind of step direction estimation, also the relationship, i.e., the transformation matrix between the b- and h-frame is given by the three principal components of the PCA.

Because calculating the step direction puts a heavy workload on the MCU, the procedure is done for initialization only. Also

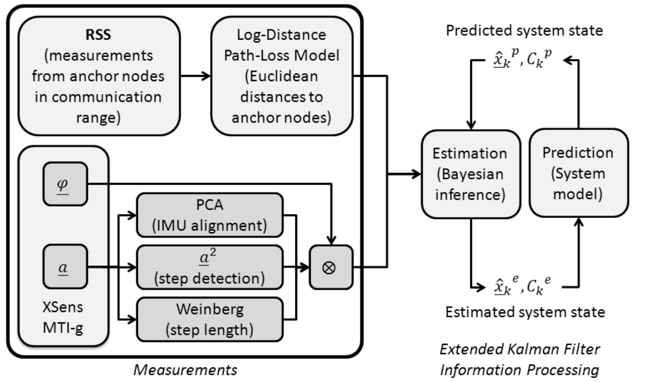

Fig. 2. Overview of the measurements and data processing.

the PCA delivers unreliable results if the person to localize is running or moving slowly.
For the intended use cases it is sufficient to call the procedure once after the device has beens attached to the user. For other applications (e.g. smart phones), the forward direction can change if the device is taken out of the pocket and being put back in. This implies a recalibration procedure whenever a reliable walking pattern is recognized.

B. System and Measurement Model

To model the system and the measurement inputs, a modified version of the model from [2] is used. Incoming measurements for the PDR are processed by means of a Kalman filter. Figure 2 shows an overview of the considered measurement inputs and information processing.

Additionally, to achieve long term stability, received signal strength (RSS) measurements to anchor nodes (with known positions) are used upon availability. As soon as the on-body node receives a broadcast message from an anchor node, an estimation of the distance is deduced from the RSS value of the received packet and the information is fused to the current position estimate. The scope of this paper is to evaluate the localization based on PDR alone, which has to be used whenever no or too few anchor nodes are available. As soon as the person to localize re-enters the WSN-covered area, the position can be updated and the incoming RSS measurements can be fused.

IV. System Implementation

A. Hardware

Figure 1 shows the Xsens MTi-G IMU with the ITIV LocNode [1]. The casing is designed to fit into a standard camera bag which the test person can easily carry on the hip. The IMU data as well as the radio packets received can be recorded on an SD-card to allow for an offline evaluation.

B. Software

A ZigBee framework is used to setup a WSN with self-organization and multi-hop capabilities. The localization functionality is implemented in this framework. For the purpose of an evaluation, the framework also allows to store received

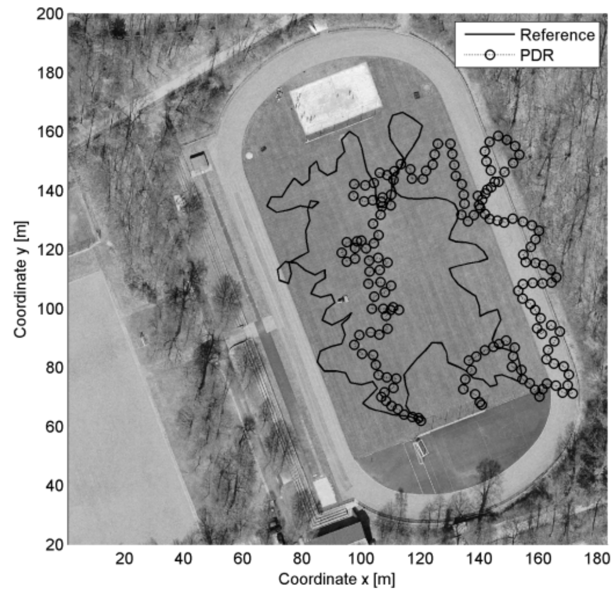

Fig. 3. Example of reconstructed trajectory for one run in the outdoors football field experiment.

radio packets on an SD card. Each anchor node is configured to broadcast its own position regularly at a rate of 4 *Hz*. The on-body node calculates its own position based on the described PDR concept at a rate of 10 *Hz*.
In the full version of this paper, we show how the position estimation is updated when the person to localize re-enters a WSN-covered area after localizing by means of PDR alone for some time.

V. Experimental Evaluation

A. Data Collection

For a comprehensive dataset four experiments in the institute office building, an underground car park, a football field and a parking lot were carried out. Therefore a WSN with 62 sensor nodes was brought out. One person carrying the IMU-equipped sensor node was walking in all experiments a total of more than 20 *km* through the network. The GPS antenna of the Xsens MTi-G was not used for heading correction but magnetic sensors were used for stabilization. Although magnetic sensors tend to be disturbed in indoor environments, they provide reliable long term stability.
The reference (ground truth) was recorded with a differential GPS (DGPS) in the outdoor experiments. Indoors, the user walked a predefined trajectory. A sequence of waypoints was set up and the time measured between reaching each of them. For every segment a constant speed was assumed.

B. Data Evaluation and Discussion

The gathered data was evaluated offline as described in Section III. In the case of the evaluated system, four error sources are dominant. The first can be observed in Figure 3. The heading estimation of the IMU becomes more reliable over time. This behavior seems to be typical for the chosen IMU

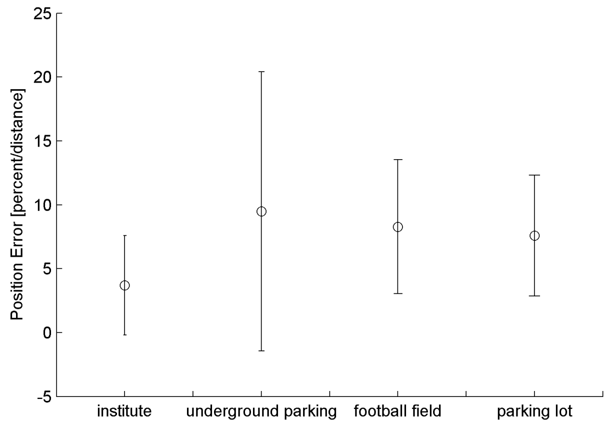

Fig. 4. Error evaluation for all runs in each experiment.

and cannot be corrected because the attitude is not modeled in the system state vector. The other errors are introduced by the calculations described in Section III. Each falsely detected step introduces an error of the step's length. The errors of the step length calculation add a small distance error during each step. A wrong estimation of the step direction results in a heading offset. Figure 4 shows the mean error and standard deviation over all runs for each experiment. The mean error lies between 3.5 % and 10 % of the traveled distance. The highest error is found in the underground parking experiment. The single runs in this experiment were rather short and the mentioned higher errors at the beginning of each run influence the results significantly.

In the full version of the paper, further evaluations on the collected data set are shown. Especially, it is shown how the system performs if a person to localize moves out of the WSN-covered area and has to rely on PDR-only navigation for some time. The behavior of the used stochastic filter upon re-entering the covered area is shown.

VI. Conclusion and Future Work

In this paper an approach to PDR in WSN is presented. A hip mounted IMU is used for step detection and step length estimation of the user. Additionally the orientation of the IMU in relation to the body of the person is estimated. The focus of this implementation lies on a very simple calculation which can be done by a typical WSN MCU. Because the attitude calculation is done by the IMU directly and cannot be corrected in the system model, it is necessary to use the magnetic sensors for heading stabilization over a longer time. Typical errors for the presented approach are on the order of 5 % to 10 % of the traveled distance. These values do not allow long term navigation without any stabilization by an absolute positioning system. But the method presented carries a large potential for localization applications where an absolute positioning system is generally available but not very reliable all the time. This includes applications for firefighters, security scenarios, localization on building sites and in hospitals. Especially the easy portability to state of the art smart phones opens a wide range of consumer applications like navigation in large buildings (e.g. airports, exhibition halls or shopping centers).

For the future it is planned to study how a classification of typical movement patterns can be used to improve the position estimation. Also the initialization process of the anchor node positions will be evaluated further. Therefore existing simultaneous localization and mapping (SLAM) approaches like loop-closures or map matching will be adopted. Currently we are working on a demo of the system that runs a central web-server for visualizing the estimated positions.

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