Omnidirectional Pedestrian Navigation for First Responders

Stéphane Beauregard

Abstract—**It might be assumed that dead reckoning approaches to pedestrian navigation could address the needs of first responders, including fire fighters. However, conventional PDR approaches with body-mounted motion sensors can fail when used with the irregular walking patterns typical of urban search and rescue missions. In this paper, a technique using shoe-mounted sensors and inertial mechanization equations to directly calculate the displacement of the feet between footfalls is described. Zero-velocity updates (ZUPTs) at foot standstills limit the drift that would otherwise occur with inexpensive IMUs. We show that the technique is fairly accurate in terms of distance travelled and can handle many arbitrary manoevers, such as tight turns, side/back stepping and stair climbing.**

Index Terms—**indoor positioning, pedestrian dead reckoning, inertial navigation, first responder**

I. Introduction

Positioning and navigation for firefighters and other first responders is a mission-critical function. For outdoor operations, several viable techniques currently exist, such as GPS and cellular-based methods. The performance of these generic systems can in principle be augmentated with rapidly-deployed outdoor local beacon positioning systems. However, outdoors is not where the critical needs lie: a large fraction of first responder injuries and deaths occur inside buildings, typically when these are on fire and/or structurally compromised. Consequently, the technical requirements for worst case scenarios are very demanding:

- Unknown building layout (i.e. no plan)
- Possibly damaged, irregular environment
- Possibly no communication infrastructure
- Possibly zero visibility (in visible spectrum) due to thick smoke
- Bad RF propagation due to fire, humidity and NLOS conditions
- Autonomy (no comms, no server)
- Accuracy req: <1-2 m or room scale
- Fast update: >1 Hz
- Max range from last known reference point: 100-500m

While many positioning techniques have been proposed for such scenarios, it is not clear whether they will be practical. For example, while UWB techniques show some promise, the deployment and calibration of UWB beacons may be too time-consuming for the typical search and rescue mission (over in roughly 20 minutes, on average). UWB signals will not likely penetrate deep into building interiors such as basements or parking garages, where first responders can quickly get disoriented and are particularly at risk. In principle, firefighters could deploy sensor nodes to form an ad-hoc network as they move through an unknown building. However, it is not clear how good positioning estimates can be obtained from a small number of arbitrarily-deployed nodes using readily-available, cheap technologies.

Consequently, we have been studying alternatives to RF-based positioning methods. Pedestrian Dead Reckoning (PDR) has been shown to yield positioning accuracy adequate for many end applications. The utilized MEMS-based sensors are relatively inexpensive and can easily be engineered into existing personnel clothing and procedures. In the remainder of this paper, we discuss our initial experiments with a PDR implementation that is better adapted to the expected locomotion patterns of first responders.

II. Conventional Pedestrian Dead Reckoning

There is an extensive body of research on Pedestrian Dead Reckoning (e.g. [1]) and its application, e.g. [2–4]. The conventional PDR approach involves the indirect estimation of step length (or walking speed) and course over ground (or direction of walking). By indirect, we mean that the distance between footfalls is estimated from accelerations sensed higher up on the body, i.e. on the waist, torso or head. Non-linear input-output algorithms such as neural networks relate the variance of the accelerations and/or their frequency to step length. The algorithms require ground truth step length training data, acquired via GPS or by walking a surveyed course. Step length estimates can be very good, on the order of 2-5% of the total distance travelled [5].

Unfortunately, this approach has some severe limitations. Not only must the model be trained for a specific user, inaccuracies can arise if the walking surface or shoes are modified. Step length estimation errors often occur during starts, stops, sharp turns and walking on inclines. Some researchers have attempted to overcome these limitation by using phase relationships between the up/down, left/right, forward/backward accelerations, but it is not clear that a large variety of locomotion patterns could be modeled property in this way. Fortunately, an alternative approach exists and it will be described in the following sections.

III. Foot-Inertial Pedestrian Dead Reckoning

In the foot-inertial approach to pedestrian navigation, the distance between footfalls is estimated from 3D acceleration and orientation measurements sensed directly at the foot.

Mr. Beauregard is with the Technologie-Zentrum Informatik, Universität Bremen, 28359 Bremen, Germany. E-mail: bogie@tzi.de

1-4244-0871-7/07/$25.00 ©2007 IEEE

Fig. 1. An XSens MT motion sensor is held on to the shoe by the laces. In principle, the IMU could be miniaturized and mounted in the heel or insole of a boot.

An inertial measurement unit (IMU), containing tri-axial accelerometers, rate gyros and magnetometers, is solidly attached to, or mounted in, footwear (Fig. 1). Foot displacements between footfalls are calculated directly by double integrating the accelerations in the world frame. Our approach is based to that taken in [6][7][8][9] and elsewhere.

A. Inertial Mechanization

Standard strap-down mechanization equations were applied to the IMU measurements. Very briefly, a rotation matrix that brings the sensor (or body) coordinate system to the world coordinate system is estimated. Then the accelerations in the body frame are rotated to the world frame with this matrix and the resuling accelerations are double integrated to yield a displacement in the world frame. See Fig. 2.

Initially, we used the rotation matrix calculated directly in our IMU's internal software. This proved to unsatisfactory as the orientation estimation algorithm (Kalman/complementary filter similar to [10]) must make assumptions about the spectrum of rotation rates. In the case of walking, there are two distinct sets of dynamics, one very fast for the swing phase, and an almost static one for the stance phase. We were unable to adjust the tuning parameters of the supplied filter so that the orientation results were stable in both phases. Rather than attempt to write our own very complex quaternion/Kalman sensor fusion filter (as is done [6]), we simply tuned the IMU software to give reliable orientations during the stance phase and integrated the gyro rotation rate estimates during the swing phase.

B. Stance Detection and ZUPTs

The key to the technique are the zero-velocity updates (ZUPTs) that are performed when the foot is at a standstill. These updates must be done correctly and at every step otherwise the position drifts very quickly due to the relatively low-performance sensors in the IMU. We have found that even a few running strides can wreck havoc on the position estimation.

In principle, a foot standstill is detected when acceleration and gyro sensor readings both drop below experimentally-determined thresholds. In [11], thresholds on various raw and derived signals were proposed. In our experience, we have found that that a product of acceleration magnitude and gyro magnitude works well, but other derived signals all work similarly well. However, they all suffer from the same shortcoming: the foot is must be almost completely stationary for a fraction of a second. In a future version of this system, a dynamic threshold detection algorithm and possibly additional sensors, such as a pressure or proximity switch, will probably be required to improve robustness.

IV. Tools

The main instrument for these experiments was the Xsens MTi IMU. The sensor was attached to the shoe using the laces and the data cable run up the pant leg. Data was logged on a carried laptop and post-processed using routines written in Matlab. A uBlox GPS receiver was used to collect ground truth data for experiments performed outdoors.

V. Results

Previous experiments such as those described in [9][7][12] were done with "normal" walking, mostly along smooth courses with shallow turns and relatively constant speeds. In [6], a non-stop, windy path through a two-storey house is followed but it is hard to tell from the figure how tight the corners are. No tests on non-standard walking patterns were reported. First responders are unlikely to use a normal style of locomotion for large portions of their missions. With the exception of the very beginning of their mission, they are continuously stopping, starting, and turning as they "sweep search" floors and rooms.

Very tight manoevers that may be more typical of a first responder's locomotion were tested. In Fig. 3(b), circles down to approximately 2m in diameter, or about 4 steps, were reliably tracked by the algorithm. In fact, the PDR trajectory is more stable than the GPS ground truth in Fig. 3(a). It seems the GPS receiver's positioning algorithm was unable to handle the rapidly turning and crossing track. In Fig. 3(c), side-stepping (from 97m to 77m), diagonal stepping (77m to 60m), and forward/backward criss-cross stepping (60m to 35m) are qualitatively correct, but the scale is off. This may be due to the ZUPT threshold settings but further investigation is required.

Stair climbing was also tested. Altitude changes for each step and for flights of stairs are easily resolved, see Fig. 4.

VI. Conclusion

Our preliminary results are encouraging but much further work is required to get a stable, repeatable system. Contrary to previous experiments with relatively normal walking, our tests have emphasized very tight turning manoevers including on-the-spot turns, side/back stepping and criss-cross walking that are more typical of a first responder's locomotion. Stair climbing was also tested. Not all sensor drifts can be eliminated due to the low quality of the sensors (especially the gyros) and due to magnetic perturbations indoors. Future challenging work in complex sensor fusion algorithms will be required to adress these issues.

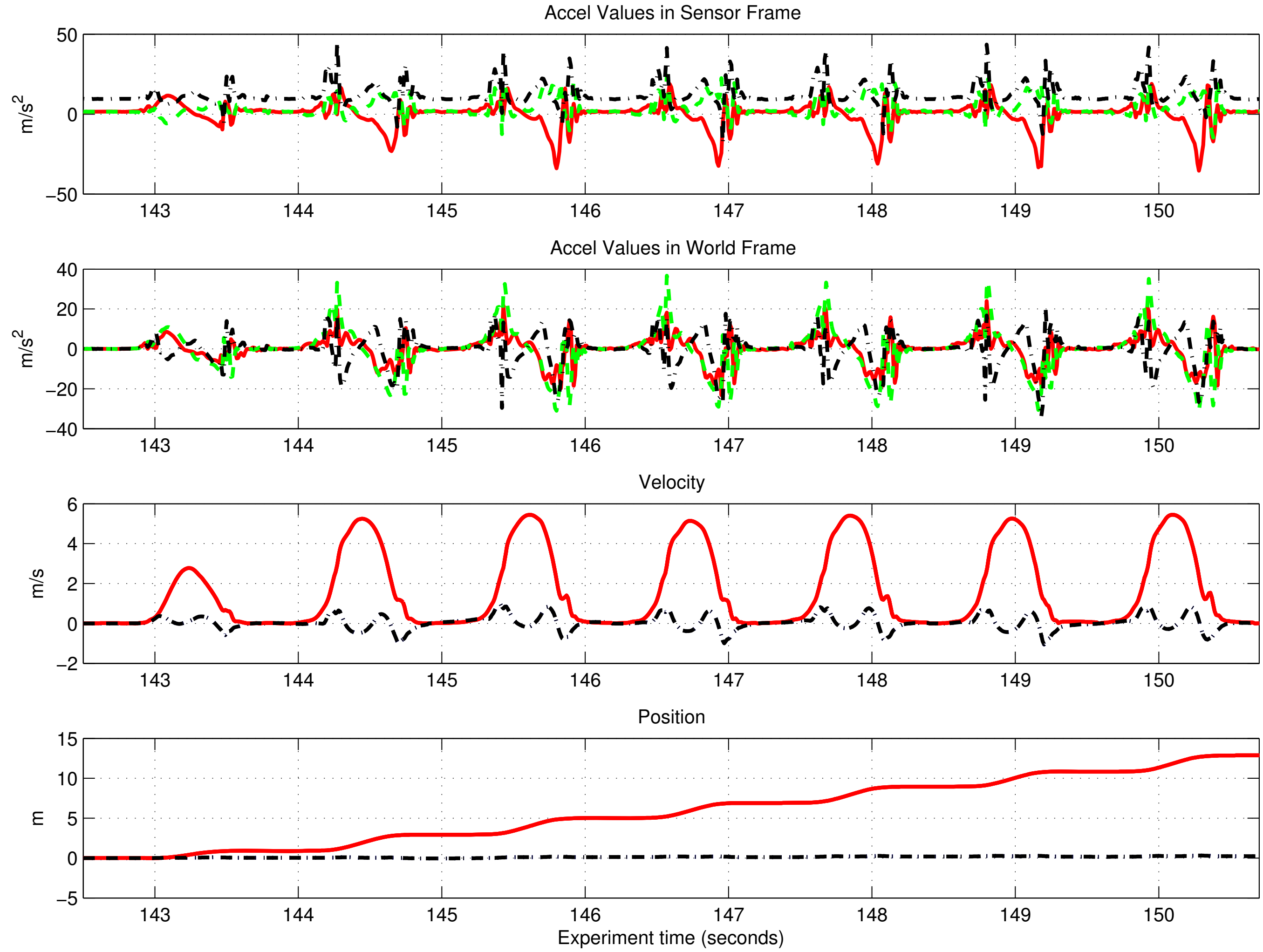


Fig. 2. Dynamics of right foot during start of straight ahead walk.

VII. Acknowledgements

This research was conducted in the context of the WearIT@Work project (EC IST IP2003 0004216) and under the direction of Prof. Dr. Otthein Herzog.

References

[1] Q. Ladetto and B. Merminod, "Digital magnetic compass and gyroscope integration for pedestrian navigation," in *9th Saint Petersburg International Conference on Integrated Navigation Systems*, Saint Petersburg, Russia, May 27-29 2002.

[2] G. Gartner, A. Frank, and G. Retscher, "Pedestrian navigation systems in mixed indoor/outdoor environment - the NAVIO project," in *9th International Symposium on Planning & IT (CORP 2004 & Geomultimedia04)*, February 2004, pp. 165–171.

[3] G. Abwerzger, B. Ott, and E. Wasle, "Demonstrating a GPS/EGNOS/Loran-C navigation system in difficult environments as part of the ESA project SHADE," in *EURAN 2004 Conference*, Munich, Germany, June 2004.

[4] J. Rouiller, D. Perrottet, Q. Ladetto, and B. Merminod, "Faciliter le déplacement des aveugles avec une carte numérique et une interface vocale," *MPG*, pp. 517–521, August 2002.

[5] H. Leppakoski, J. Kappi, J. Syrjarinne, and J. Takala, "Error analysis of step length estimation in pedestrian dead reckoning," in *ION GPS 2002*. Portland, OR: The Institute of Navigation, September 24 -27 2002, pp. 1136 – 1142.

[6] E. Foxlin, "Pedestrian tracking with shoe-mounted inertial sensors," *IEEE Computer Graphics and Applications*, vol. 25, no. 6, pp. 38–46, 2005.

[7] L. Ojeda and J. Borenstein, "Non-GPS navigation for emergency responders," in *International Joint Topical Meeting: Sharing Solutions for Emergencies and Hazardous Environments*, Salt Lake City, UT, February 12-15 2006.

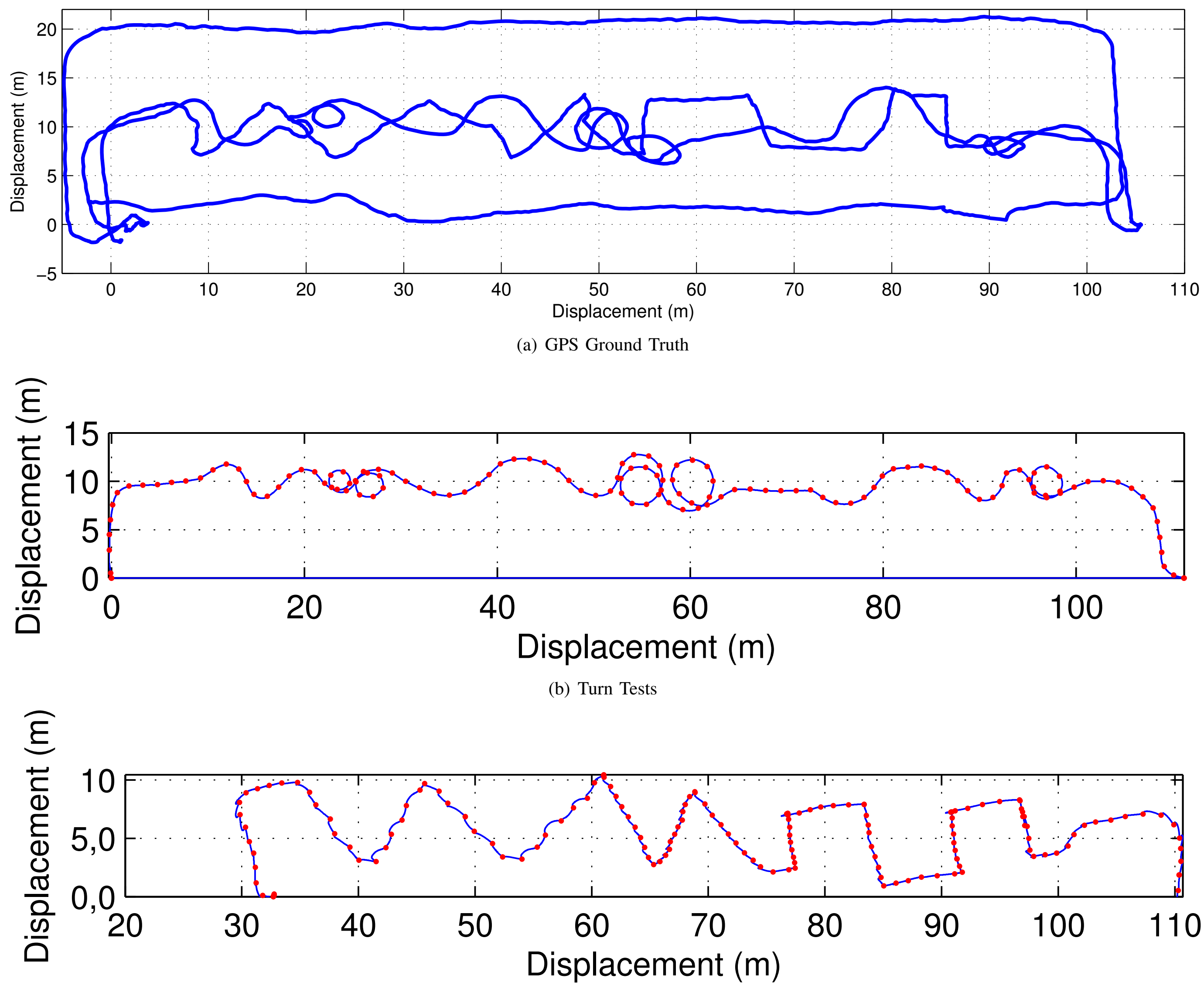
[8] K. F. Stirling, R. and G. Lachapelle, "Evaluation of a new method of heading estimation for pedestrian dead reckoning using shoe mounted sensors," *Journal of Navigation*, vol. 58, no. 1, pp. 31 – 45, 2005.

[9] F. Cavallo, A. Sabatini, and V. Genovese, "A step toward GPS/INS personal navigation systems: real-time assessment of gait by foot inertial sensing," in *Proc. IEEE Internat. Conf. Intell. Rob. Syst. (IROS 2005)*, Edmonton, Canada, August 2005, pp. 1187 – 1191.

[10] J. Marins, X. Yun, E. Bachmann, R. McGhee, and M. Zyda, "An extended kalman filter for quaternion-based orientation estimation using MARG sensors."

[11] R. G. Stirling, "Development of a pedestrian navigation system using shoe-mounted sensors," M.Sc. Thesis, Department of Mechanical Engineering, University of Alberta, Calgary, Alberta, Canada, October 2003.

[12] R. Stirling, J. Collin, K. Fyfe, and G. Lachapelle, "An innovative shoe-mounted pedestrian navigation system," in *Proceedings of European Navigation Conference GNSS 2003*, Graz, Austria, 22 – 25 April 2003.



(a) GPS Ground Truth

(b) Turn Tests

(c) Side/Backwards Tests

Fig. 3. Outdoor test results: The GPS ground truth plot (a) includes an outer perimeter segment of normal walking. This portion was correctly estimated by the algorithm and the results are not shown here. In (b) and (c), the points on the track represent individual footfalls as detected by the algorithm.

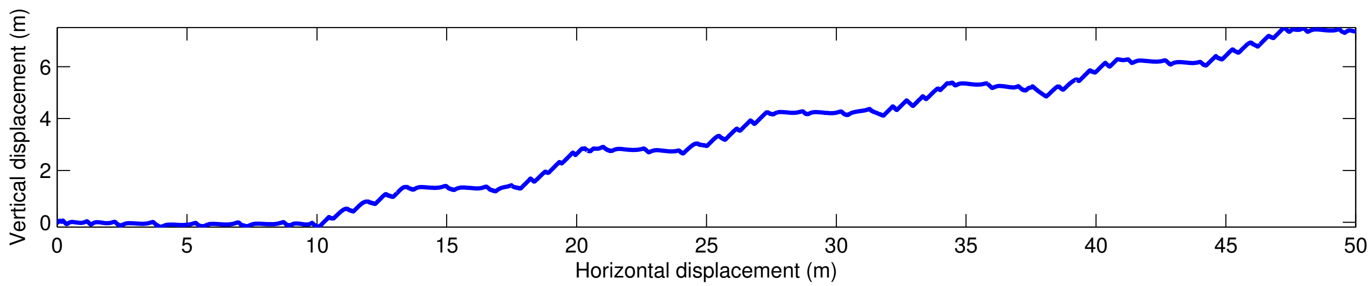


Fig. 4. Stair climbing: Six flights of stairs while climbing three floors are easily resolved. It is also possible to resolve the vertical motion of individual steps in some cases.