INDOOR POSITIONING SYSTEM USING ACCELEROMETRY AND HIGH ACCURACY HEADING SENSORS

Jussi Collin, *Institute of Digital and Computer Systems, Tampere University of Technology, Finland*
Oleg Mezentsev and Gérard Lachapelle, *Department of Geomatics Engineering, University of Calgary, Canada*

BIOGRAPHY

Jussi Collin received his M.Sc degree in June 2001 from Tampere University of Technology, Finland, in signal processing. Since 1999 he has been working at Tampere University of Technology in the Institute of Digital and Computer Systems doing research in the area of personal positioning.

Oleg Mezentsev is a PhD candidate in the Department of Geomatics Engineering, University of Calgary. He completed an Engineering degree in Bauman Moscow Technical State University in 1998 and MSc in Mechanical Engineering from the University of Illinois at Urbana-Champaign in 2001.

Professor **Gérard Lachapelle** holds a CRC/iCORE Chair in Wireless Location in the Department of Geomatics Engineering, University of Calgary, where he has also been a professor since 1988. He has been involved in satellite-based navigation since 1980 and has received numerous awards for his work. More information is available on http://plan.geomatics.ucalgary.ca

ABSTRACT

The current GPS signal structure and signal power levels are barely sufficient for indoor applications. Recent developments in high sensitivity receiver technology are promising for indoor positioning inside light structures such as wooden frame houses but generally not for concrete high rise buildings. Errors due to multipath and noise associated with weak indoor signals limit the accuracy and availability of GNSS in difficult indoor environments. An alternate approach makes use of inertial technologies. However, the use of a strapdown inertial navigation system (INS) system and its traditional mechanization as a personal indoor positioning system is rather unrealistic due to the rapidly growing positioning errors caused by gyro drifts. Even a high performance INS will cause hundreds of metres of positioning error in 30 minutes without GPS updates.

The majority of previously proposed personal positioning systems utilize the Pedestrian Dead Reckoning (PDR) approach. These systems use accelerometers for step detection and step length estimation and magnetic compasses or low cost gyros for heading determination. In such systems, the error sources are the step length estimation error and the heading error. Assuming no heading error, the positioning error is directly proportional to the number of steps and, thus, to the distance traveled. However, the critical component of these systems is heading. Indoor, apart from measuring the Earth’s magnetic field, magnetic sensors will be subject to other local electromagnetic fields. Over time, low cost gyros will drift in a significant and unpredictable manner which makes them unsuitable for obtaining adequate heading information.

In this paper, the heading problem is resolved by using one deg/hour ring laser gyros. A tactical-grade IMU is used to provide accurate heading information, and accelerometers are used only for step occurrence detection. A special study is carried out to examine errors in heading, if only one gyro is used instead of three. In this case, the three-gyro solution is used as a reference.

To test the concept, several long period tests were performed, carrying the IMU in a backpack. Both DGPS and stand-alone receivers were included to compare two different level initialization sources. 3D-gyro heading solutions initialized with DGPS are promising. However, if only one gyro is used or DGPS is not available, heading solution accuracy degrades significantly.

Size restrictions on current ring laser gyros limit the application of the proposed system. However, as gyro technology evolves, such a system may be beneficial for applications such as the positioning of rescue workers, police squads, and other indoor location and navigation applications.

INTRODUCTION

Satellite-based radio navigation systems provide accurate positions only when the signal path is unobstructed. Indoor positioning is not possible with traditional GPS receivers. Improvements in high-sensitivity receivers, with signal processing gain up to 20 dB, are making GPS navigation possible in light and medium structure buildings (e.g., MacGougan et al 2002, Lachapelle et al 2003). However, in a typical concrete office building even 20 dB gain is not sufficient and augmentation techniques are needed for positioning. Known techniques can be divided into two parts - methods that require special hardware in the building, and self-contained ones. With pseudolites, WLAN and UWB indoor-to-indoor positioning techniques, the radio signals are transmitted inside the building and thus the requirement for the signal power level remains reasonable. One of the drawbacks is that the signal propagation path is reflected and thus the accuracy is limited. If a positioning system needs to be completely building-independent, Dead-Reckoning (DR) methods with self-contained sensors need to be utilized. For DR-systems the dependence on the initialization source is a clear disadvantage, but an even worse problem for such systems is the position error drift over time. Inertial navigation systems require very accurate sensors and the errors in unaided mode are typically 1-100 km after one hour. For long-term navigation without any aiding, INS does not provide sufficient accuracy, considering that the required accuracy for indoor applications is usually 10 m or better to identify a specific room, as shown in Figure 1.

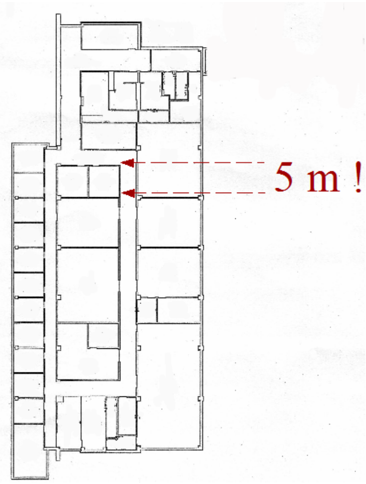

Figure 1: Required accuracy for indoor location and positioning systems

For the pedestrian case, more accurate results can be obtained by taking into account the motion state of the user. When walking, the velocity is very limited, and thus a system with error growth proportional to the traveled distance rather than to time would be advantageous. A Pedestrian Dead Reckoning (PDR) system with accurate heading input can be considered as such a system.

PEDESTRIAN DEAD RECKONING MECHANIZATION

In PDR, the physiological properties of walking are the core of the navigation procedure; accelerometers are used to detect steps (Figure 2), heading at step time is estimated (Figure 3), step length is estimated (Figure 4) and position is computed using a summation of vectors (Equation 1).

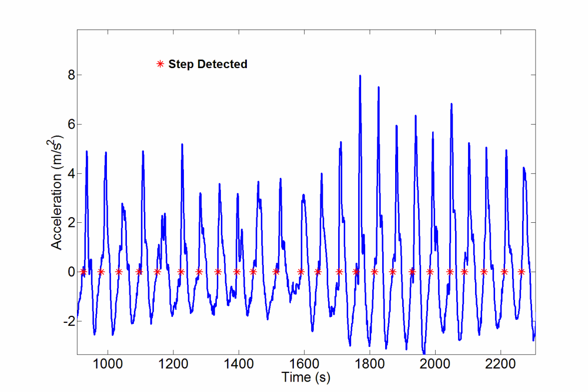

Figure 2: Step detection from accelerometer signals

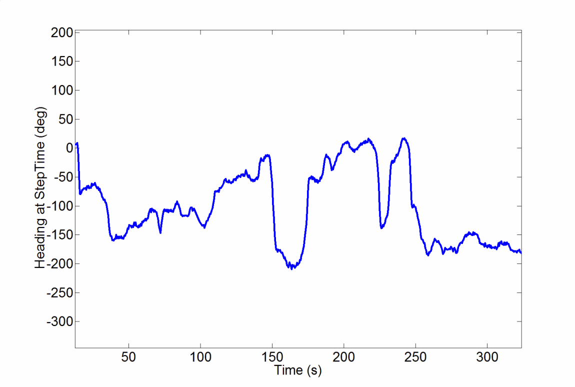

Figure 3: Heading estimation

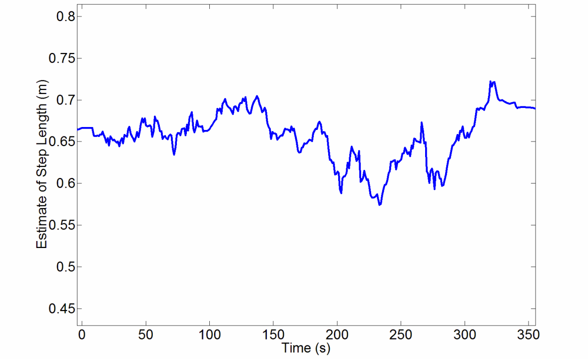

Figure 4: Step length estimation

$$\begin{aligned} &DR\_East_t = DR\_East_{t-1} + p_t \cdot \cos(\alpha_t) \\ &DR\_North_t = DR\_North_{t-1} + p_t \cdot \sin(\alpha_t) \\ &p = steplength \\ &\alpha = heading \end{aligned} \tag{1}$$

The clear advantages of such an approach are the error growth properties, and the possibility to combine the system fairly easily with an absolute positioning system such as GPS. The main disadvantage is the limited operational mode – the user needs to be walking, and more specifically, walking on a non-moving surface. However, if this condition is met, the system outperforms traditional INS over time.

As a simplified example, consider a person walking a straight line distance of 6 km for one hour. The user's heading is computed using a 1 deg/h grade gyro and the step length is estimated using methods described in (Ladetto 2000, Leppäkoski et al 2002), with an error of 3 % of distance traveled. The resulting error is about 200 m. By using a similar system to provide an unaided traditional INS solution, the expected error would be more than 100 km. Moreover, in this example the user walks all the time, and that is generally not the case in indoor environment.

The problem with the above example is that systems with 1 deg/h gyros are not yet designed for personal transportation, and are used typically on vehicles. The above example with very small, high drift MEMS gyros, would show very different results. On the other hand, if a compass is used as a heading source, the output would be very susceptible to disturbing magnetic fields.

PDR WITH TACTICAL-GRADE IMU

Even though 1-deg/h gyro systems are not yet very convenient for a person to carry, their feasibility using an inertial measurement unit (IMU) with the given accuracy can be tested. The gyros used in the tests reported herein were those of a HG1700 IMU used in the NovAtel BlackDiamond™ system. Accelerometer outputs from this full 6-degree of freedom IMU were used for step detection. In the tests performed, a person walked outside with a good GPS coverage allowing initialization of the system. Then, pre-surveyed trajectories inside a concrete wall building with no GPS coverage were traveled. The gyro-based heading accuracy is shown in Figure 5, where the magnitude of the rotation vector is shown for a 15 minute static period. The error in the output is well below 1 degree.

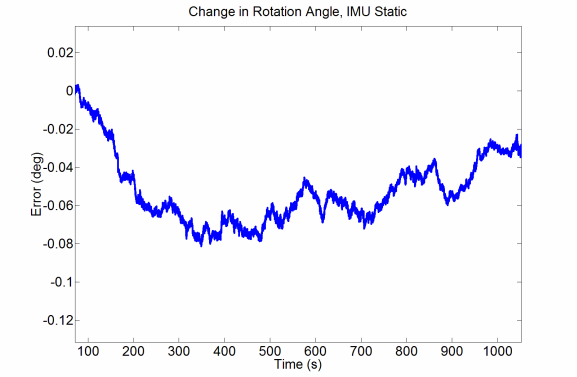

Figure 5: Change in rotation vector magnitude, IMU static

There is only one angular variable in Equation 1, namely α, which is defined as the angle of projection of the Body Frame y-axis with respect to the Local Level Frame North-axis. As there is only one angular measurement involved, the possibility of using only one gyro for the heading measurement was studied. In theory, two conditions must hold to use only one gyro:

1) No rotations along the Local Level Frame horizontal axes
2) The angle between the Local Level Frame vertical axis and the gyro sensitivity axis is known

In practice, these two conditions do not exactly hold, but generally (1) is limited due to pedestrian motion. For condition (2), the approximate value of the Local Level Frame vertical can be obtained by using the accelerometer measurements. The accelerometer triad output is a combination of inertial acceleration $\bar{a}^B$ and local gravitational acceleration $\bar{g}^B$, as shown in Equation 2. (The superscript B indicates that measurements are with respect to the Body Frame). Following Equation 2, it can be seen that if the system is not accelerating, the accelerometers output is $-\bar{g}^B$, and the angle needed can be obtained by using Equation 3 (assuming small angle ϕ, it can be shown that the use of horizontal accelerometers instead of vertical one provides more accurate estimates during walking). Then, the heading rate is obtained by dividing the gyro output by cos(ϕ).

$$\bar{a}_{SF}^{B} = \bar{a}^{B} - \bar{g}^{B} \tag{2}$$

$$\phi = \arcsin\left(\frac{\sqrt{(a_{SFx}^{B})^2 + (a_{SFy}^{B})^2}}{g}\right) \tag{3}$$

The assumption of zero acceleration is clearly wrong for a walking person as each step cause large acceleration outputs. However, if a moving average (MA) filter is used (Equation 4), reasonable estimates can be achieved, even when the user is moving. Choosing the window length for the MA-filter is a tradeoff between the slow response to changes in attitude and the susceptibility to linear accelerations. In the following section, 10-s and 1-s windows are compared using real data.

$$y[n] = \frac{1}{M} \sum_{k=0}^{M-1} x[n-k] \qquad (4)$$

As shown in Figures 6 and 7, the mean of the error is very close to zero with both windows. However, as the angular rates are integrated over time, the errors are remarkable in the heading domain, especially with the longer 10-s windows (Figures 8 and 9).

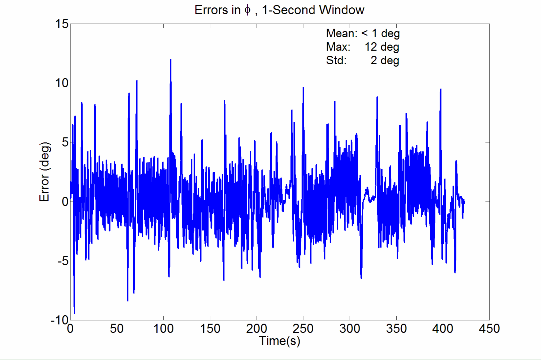

Figure 6: Errors in ϕ, 1-second window

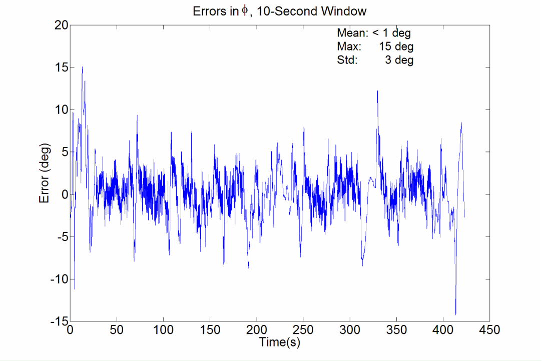

Figure 7: Errors in ϕ, 10-second window

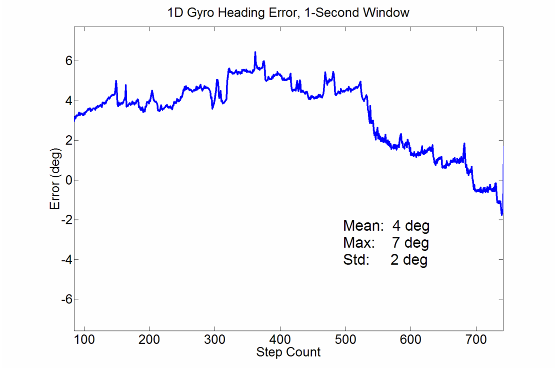

Figure 8: Errors in heading, 1-second windows

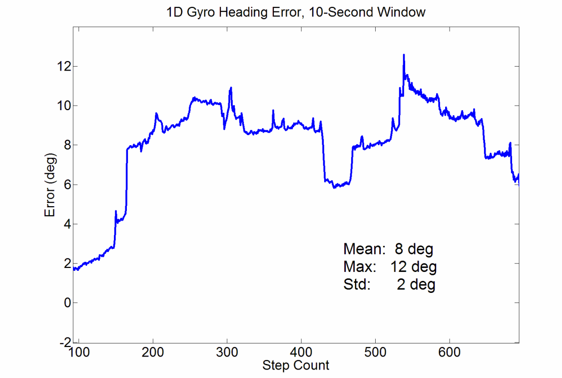

Figure 9: Errors in heading, 10-second windows

One possibility to improve the above results might be to adapt the window size to two step occurrences and increase the window size if the mean over the norm of the acceleration is not zero. In any case, it is obvious that with only one gyro the accuracy degrades significantly.

VERTICAL CHANNEL

With indoor positioning, the accuracy of the vertical channel is very important because the building floor level needs to be solved. In Equation 1, there is no vertical component, and changes in height need to be solved using a barometric altimeter. This is not straightforward due to the fact that height is not measured, but atmospheric pressure. To obtain the height, pressure measurement needs to be converted to height – and these do not always directly correlate. Specially, local changes in pressure inside buildings can corrupt the barometer-based solution.

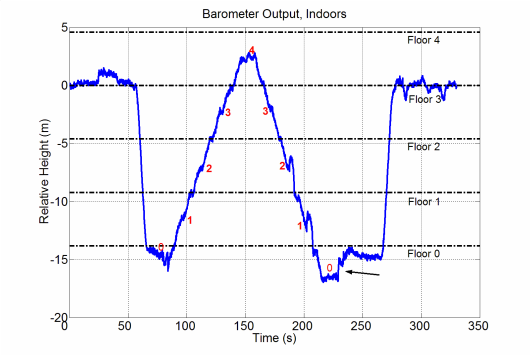

Figure 10: Barometer output from indoor test, converted to height

As an example, Figure 10 shows the barometric height output, from a test where a person walked between floors in a 4-floor building, using both elevator and stairs. In Figure 10, red numbers indicate the floor at the given time of the test. Black horizontal lines show the reference, and it can be seen that errors are about 2.5 m (half of the floor height) during the staircase part of the test. The main reason for this is the pressure change in the different parts of the building. The black arrow points to a place where the user walks from the staircase to a main corridor. There is a noticeable change in the pressure, and this is not due to height changes.

TESTING AND RESULTS

The system described above was tested in an indoor environment, and the indoor navigation time was intentionally made long to assess the properties of the PDR mechanization. The main goal of the test was to verify the accuracy of the heading for pedestrian motion. No corrections for the step lengths during the DR part were applied. The initial source for the step length was GPS and during the indoor part, the length was fixed. In the tests performed, such an approach resulted in approximately 3 % step length error. It should be noted that the fixed step length assumption for general human walking motion does not hold well, especially if the user changes walking pace suddenly.

Figure 11 shows the test track. It starts from an outdoor rectangle (up left in the figure), and continues inside the University of Calgary CCIT building where the rectangular corridor path was walked.

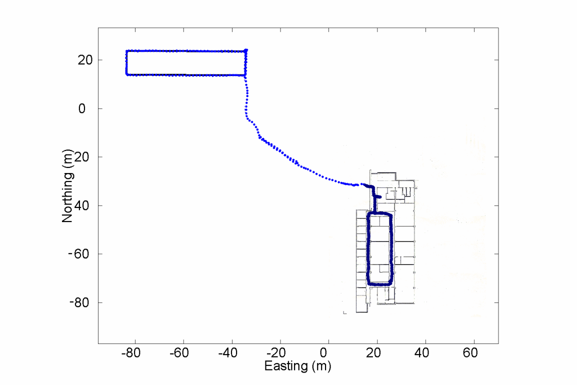

Figure 11: Test track

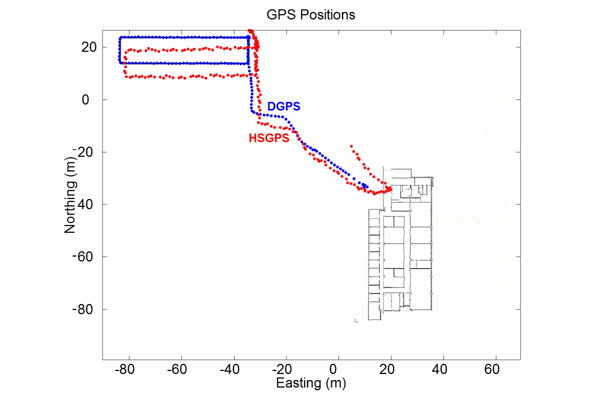

Figure 12: GPS receiver outputs

Two different GPS receivers were included in the test system, one to provide an accurate carrier-phase based DPGS solution, and another with a high-sensitivity signal capability. The GPS position solutions are shown in Figure 12. The blue line is the DGPS solution with cm-level accuracy. A well known property of GPS solutions without differential corrections is the low-frequency position error due to atmospheric delays, shown clearly in the HSGPS solutions (red line). As noted before, DR-systems are always dependent on accuracy of initialization source, and for accurate indoor navigation, standalone-GPS is not always sufficient.

Figure 13 shows results from a test where DGPS was used to initialize the PDR system. The test person walked 10 minutes in the corridor, took a 20 minute break and walked for 10 minutes again. During the static period no special algorithm was applied, there being no need for this in PDR mechanization. Since the gyro drift during the static period is well below 1 degree, the static part is not visible in the results. The main error source is the error due to the fixed step length assumption. The maximum error during this 40 minute test was 5 m.

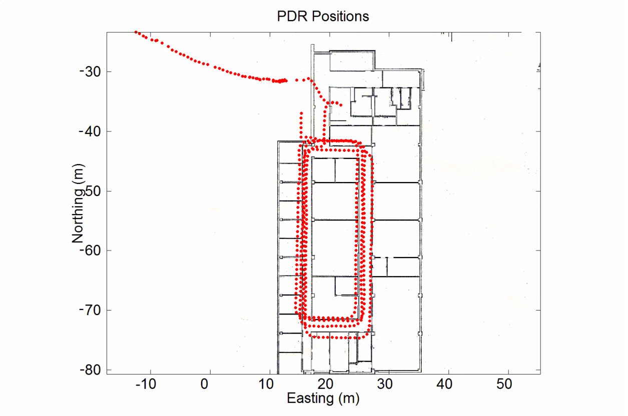

Figure 13: PDR solution with accurate initialization

The key point to a successful DR-navigation is a good initialization, as the previous example shows. If corrupted GPS solutions are used to provide the initial heading and position for the DR-filter, the results will be corrupted for the entire DR mission. To illustrate this, Figure 14 shows the results where HSGPS positions and velocities were used in the filter, even though they are clearly incorrect. The resulting trajectory is biased, and the heading is wrong as well. To avoid this kind of errors, the integrity monitoring of GPS solutions need to be efficient. Nevertheless, without differential corrections for GPS, the initial position error can be tens of metres depending on the satellite availability during the initialization phase.

The DR solution with only one gyro is shown in Figure 15. The heading errors, especially with longer MA window, are clearly affecting the solution accuracy. It should be noted that in this test the dynamics of walking were limited due to the use of a heavy backpack, and in normal walking more rapid turns are possible. One-gyro heading approach is very sensitive to such movements.

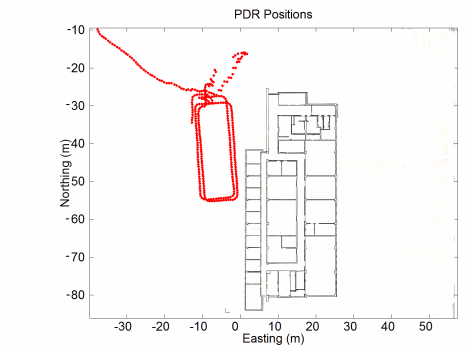

Figure 14: DR solution with incorrect initialization

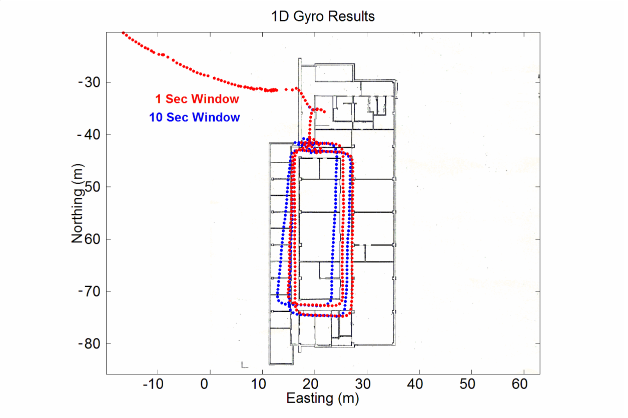

Figure 15: DR solutions with one gyro

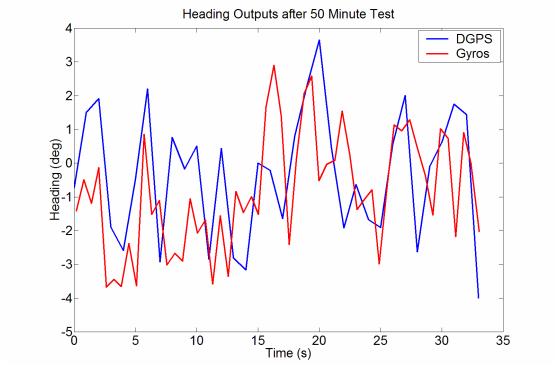

Figure 16: IMU-based heading compared to DGPS reference

Finally, to demonstrate that the used gyro assembly is capable of keeping the 1 degree heading accuracy during walking motion, headings from DGPS and gyro data are compared in Figure 16, using a 50-minute test. The test included both normal walking and walking in stairs. The mean error of gyro-based heading is less than 0.6 degrees. Other long term tests performed confirmed this result.

CONCLUSIONS

To meet the indoor accuracy requirement with a PDR system the following issues need to be considered:

- Initial position and heading sources need to be accurate to DGPS accuracy levels.
- To satisfy the 1-degree heading error budget, GPS velocity errors should not exceed 3 cm/s during the initialization process.
- A reliable heading source, such as a tactical-grade RLG, is needed during the indoor phase. If lower grade gyros are used, the scale factor errors and the bias stability need to be studied carefully.
- If only one gyro is used for heading, the accuracy degrades and the error estimation becomes more difficult.

- Due to step length estimation error, the accuracy of the solution degrades over the distance traveled – known techniques result in errors of 3-10 % of the distance.
- Special issues to consider: only walking is allowed with a PDR, the unit must be kept aligned towards the direction of travel, and step length estimation in staircases may be difficult

Even though the requirements for the proposed system to work reliably are strict, currently PDR mechanization appears to be the only choice for indoor positioning when RF-based methods are unavailable. Tests with the PDR system that provides accurate heading showed that a high level of accuracy can be achieved. Future improvements in gyro technology may permit effective PDR use indoor. Future research includes augmentation with 3D map-matching algorithms and development of a step length estimation system using external devices such as a foot-to-foot measuring system.

ACKNOWLEDGEMENTS

The assistance of SiRF Technologies, Inc. in providing the HSGPS receiver used in this research is acknowledged.

REFERENCES

MacGougan, G., G. Lachapelle, R. Klukas, K. Siu, L. Garin, J. Shewfelt, and G. Cox (2002) Performance Analysis of A Stand-Alone High Sensitivity Receiver. GPS Solutions, Springer Verlag, 6, 3, 179-195.

Lachapelle, G., H. Kuusniemi, D. Dao, G. MacGougan and M.E. Cannon (2003) HSGPS Signal Analysis and Performance Under Various Indoor Conditions. Proceedings of GPS 2003, The Institute of Navigation, in press.

Ladetto, Q. (2000) On foot navigation: continuous step calibration using both complementary recursive prediction and adaptive Kalman filtering. Proceedings of ION GPS 2000, The Institute of Navigation, Alexandria, VA, pp. 1735-1740.

Leppäkoski, H., J. Käppi, J. Syrjärinne and J. Takala (2002) Error Analysis of Step Lentgh Estimation in Pedestrian Dead Reckoning. Proceedings of ION GPS 2002, The Insititute of Navigation, Alexandria, VA, pp. 1136-1142.