

Evaluation of a New Method of Heading Estimation for Pedestrian Dead Reckoning Using Shoe Mounted Sensors

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In this paper, a novel method of sensor based pedestrian dead reckoning is presented using sensors mounted on a shoe. Sensor based systems are a practical alternative to global navigation satellite systems when positioning accuracy is degraded such as in thick forest, urban areas with tall buildings and indoors. Using miniature, inexpensive sensors it is possible to create self-contained systems using sensor-only navigation techniques optimised for pedestrian motion. The systems developed extend existing foot based stride measurement technology by adding the capability to sense direction, making it possible to determine the path and displacement of the user. The proposed dead-reckoning navigation system applies an array of accelerometers and magneto-resistive sensors worn on the subject's shoe. Measurement of the foot's acceleration allows the precise identification of separate stride segments, thus providing improved stride length estimation. The system relies on identifying the stance phase to resolve the sensor attitude and determine the step heading. Field trials were carried out in forested conditions. Performance metrics include position, stride length estimation and heading with respect to a high accuracy reference trajectory.

KEY WORDS

1. Pedestrian Navigation.
2. Dead Reckoning.

1. INTRODUCTION. Pedestrian navigation is the process of determining and maintaining positional information for a person travelling on foot. In situations of relative familiarity, it may consist simply of verbal instructions or directions on a map. Usually though, the term pedestrian navigation refers to the use of technological aids for positioning, such as global navigation satellite systems (GNSS) or sensors mounted on the body. Outdoors, where there is a clear line of sight to the satellites, GNSS provide location with accuracies ranging from tens of metres to sub-metre depending on the details of the receiver and methodology. Satellite positioning is a preferred method wherever it is practical because the

orientation of the receiver need not be known, and error in location does not increase in time. Recently developed high sensitivity receivers have made it possible to use GPS in dense forests and in various but not all types of buildings (MacGougan et al. 2002, Lachapelle et al. 2003b). Accuracy however, degrades substantially under such conditions.

Inertial sensors are used for navigation in environments that are challenging for GNSS. Standard inertial navigation systems (INS), such as those used in aerospace and marine navigation, calculate position by temporal integration of accelerometer and gyroscope data. Estimated positions are calculated at regular time intervals and the error growth is proportional to the time elapsed since the last known position. The dynamics generated by a walking person are small, making traditional INS impractical because temporal integration of sensor output will lead to rapidly propagating errors, even with high accuracy sensors (Collin et al. 2003). Instead, an alternate navigation method is sought that better suits the manner in which people walk.

2. PEDESTRIAN NAVIGATION. Analysis of the human gait shows that the basic pattern of human motion during a walk is cyclical, repeatable and remarkably consistent between individuals (Rose et al. 1993). The gait cycle consists of two main phases: The stance phase when the foot is on the ground, and the swing phase when the foot is lifted off the ground and carried forward to begin the next stride. By recognizing that people move one step at a time, various methods of sensor based dead reckoning have been developed that maintain the user position by measuring or estimating the length and direction of each step the user takes. Rather than calculating position at a fixed time interval, the user position is propagated in a stride-wise fashion by summing the vector components of each measured step. Accordingly, error in pedestrian dead reckoning is proportional to the number of steps taken and is independent of time.

Development of portable pedestrian navigation systems has been made possible by the relatively recent emergence of compact, inexpensive sensors. Miniature accelerometers and rate gyroscopes are most commonly applied, but two other types of miniature sensors – magnetometers and barometers – improve direction sensing and allow the measurement of vertical displacement.

2.1. Step Length Estimation and Measurement. Sensors for pedestrian dead reckoning are most commonly mounted on the user's torso because of the low dynamics and relatively constant orientation with respect to the user's direction of travel. Without a means to directly measure step length, torso based methods use accelerometers to detect the stride event and then apply a mathematical model to estimate the stride length. Step length is well correlated to step period, so an estimate for stride length can be made by determining the current gait frequency and adjusting the base stride length accordingly (Levi et al. 1996). A basic assumption is made that step lengths are not constant but exhibit a continuous variation around a more stable value (Ladetto 2000). The magnitude of the torso acceleration measured during a step may also be related to stride length (Käppi et al. 2001). Modelling step length as a function of step period, acceleration magnitude, and acceleration variance, and using GPS to calibrate the model parameters it is possible to measure user displacement within 2% of the distance travelled (Ladetto et al. 2000). The pattern of the measured

acceleration also indicates how the user is moving. Using triaxial accelerometers mounted on the torso, it is possible to detect when the user is walking sideways or backwards and the position estimate can be modified for the appropriate motion state (Ladetto 2003, Collin & Käppi 2002).

Stride length estimation by empirical modelling is effective when the user moves in anticipated conditions, but lacks the generality of application that accompanies a direct measurement method. Direct stride length measurement by integration of acceleration is possible with sensors mounted on the user's foot, provided that the sensor orientation is known (Morris, 1973). During walking, the motion of the foot generates high accelerations in a repeatable pattern, and the relatively stationary period during the support phase of the stride allows the determination or assumption of initial conditions for stride-wise temporal integration. However, because the angle of the foot continually changes through the gait cycle, it must also be measured so that the components of acceleration in the sagittal plane can be resolved.

A gyro oriented in the sagittal plane may be used to measure the angular velocity of the foot through the stride and the output integrated to yield the foot angle profile (Sagawa, 2000). Using this profile, the horizontal components of acceleration from a shoe mounted triaxial accelerometer can be resolved and then integrated to yield displacement. Over multiple 30 m trials, this method had a maximum error of 5%. An improved method of measuring foot angle uses parallel offset accelerometers to measure the angular acceleration of the foot, which is integrated twice to yield foot angle avoiding the inherent bias drift properties in gyros (Fyfe, 1999). Accurate over a wide population without requiring user calibration, this technique is valid for a complete range of gait velocities from a slow walk to full run.

The works by Sagawa and Fyfe rely on the assumption that the foot motion is primarily in the sagittal plane. However, these methods have a possible advantage over empirical models in that they measure step length directly and work without making further assumptions about the user's height, gait, or walking environment.

2.2. Heading Estimation. While the various methods of step length measurement have reached a practical level of accuracy, maintaining long term heading accuracy remains challenging. The Earth's magnetic field is relatively weak and nearby metal or electrical fields will distort the output from compassing sensors. Gyros on the other hand, have output that drifts in time. Käppi et al. (2001) used gyroscopes for the main heading sensor, and corrected the inherent drift with a digital magnetic compass compensated by accelerometers. Integrated with GPS, this technique was demonstrated to maintain sufficient accuracy to save power by reducing the required frequency of satellite position updates (Collin et al. 2002). Importantly, this system included an atmospheric barometer so that vertical travel could be resolved. Taking the opposite approach, Ladetto et al. (2002) developed a system that relied mainly on digital compassing, but used gyroscopes to compensate the heading calculation during rapid turns and when the magnetic field is detectably disturbed.

Recognizing that determining accurate heading with low cost sensors remains an obstacle for indoor positioning, Collin et al. (2003) tested the performance of pedestrian dead reckoning system applying high accuracy ring laser gyros for heading. Ring laser gyros have drift of less than 1 degree per hour, and are insensitive to the substantial magnetic field disturbances common indoors. Initializing the system outside and assuming a fixed step length determined by GPS, the error in position calculated by this system over a 40 minute test was just 5 metres. Though high

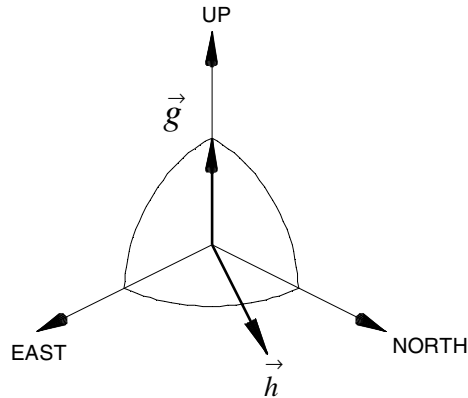


Figure 1. The global reference frame East, North Up.

accuracy heading systems are prohibitively expensive for consumer applications, this method demonstrates that effective indoor positioning is possible.

2.3. *Heading Estimation from the Foot.* Shoe mounted accelerometers provide an accurate means to directly measure stride length, but a viable self contained pedestrian navigation system also requires a means to measure heading from the foot. In this paper, it is proposed that anisotropic magneto-resistive (AMR) sensors may be applied to the shoe to measure the user's heading during the stationary stance phase of the gait cycle. Accelerometers are used to measure stride length using Fyfe's technique, and also to establish the horizontal plane for heading measurement. As this approach is novel, the research objective is to establish the basic feasibility of a shoe mounted sensor system for pedestrian navigation. The research previously described has shown that if this simple method shows merit, accuracy can be greatly improved with integration of further sensors and GPS. More detail on the method and results described herein can be found in (Stirling 2003).

3. **HEADING CALCULATION.** Shown in Figure 1, the global reference frame which relates the user to the surrounding environment is a right handed coordinate system with axes pointing North, East and vertically upward (N_G , E_G , U_G). Heading is defined as the user's direction of travel in the horizontal plane. To calculate the user heading, the direction of Earth's gravitational field \vec{g} and magnetic field \vec{h} are measured from the foot during the stance phase, when the foot is temporarily stationary. From these measurements in the sensor reference frame, and knowledge of the fields' relative orientation, the user's direction of travel in the global reference frame is calculated.

The Earth's gravitational field points directly down, perpendicular to the local tangent plane of the Earth's equipotential surface. A stationary accelerometer however, indicates an \vec{g} as an upward acceleration (as in Figure 1), which is convenient because it immediately yields the sensor frame representation of the vertical axis of the global frame. Magneto-resistive sensors are used to measure the Earth's magnetic field, which has a varying intensity and direction depending where the user is located on the earth. The magnitude of the magnetic field is not of interest, only the unit

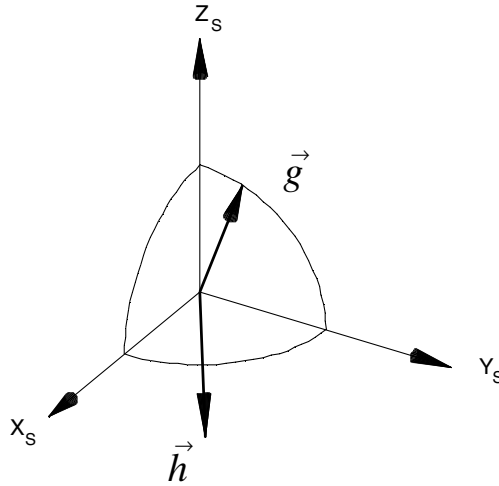


Figure 2. Sensor frame observations of the gravity and magnetic field vectors.

vector of field direction \vec{h} . Magnetic North is defined as the component of \vec{h} that lies in the global horizontal plane.

3.1. *Direction Cosine Matrix.* The sensor frame is a right-handed coordinate system with axes X_S, Y_S, Z_S indicating the direction of positive sensor output. Figure 2 shows an example of the gravity and magnetic field vectors as they may be observed in the sensor frame. Using these sensor measurements, a direction cosine matrix A^{S-G} is constructed that represents the global frame axes East, North and Up in the sensor frame. A^{S-G} is used to transform the sensor frame heading, d_S , into a heading in the global frame d_G .

$$d_G = A^{S-G} d_S$$

Figure 3 illustrates the construction of the direction cosine matrix A^{S-G} . The sensor frame gravity measurement g_s points vertically upward, so a representation of the global vertical axis is already found:

$$U_S = g_S$$

Magnetic East lies in the global horizontal plane orthogonal to the magnetic field vector. Since magnetic East is perpendicular to both \vec{g} and \vec{h} , it can be found by normalising the vector of their cross product. Regardless of the inclination and declination of the magnetic field, by the right hand rule, $\vec{h} \times \vec{g}$ will always point toward magnetic East. Expressed in the sensor frame this is

$$E_S = \frac{h_S \times g_S}{\|h_S \times g_S\|}$$

Last, magnetic North is the component of the magnetic field lying in the horizontal plane, perpendicular to gravity. The component of \vec{h} perpendicular to \vec{g} is found by scalar projection:

$$\vec{h}_{\text{perp}} = (\vec{h} - \vec{h} \cdot \vec{g} \vec{g})$$

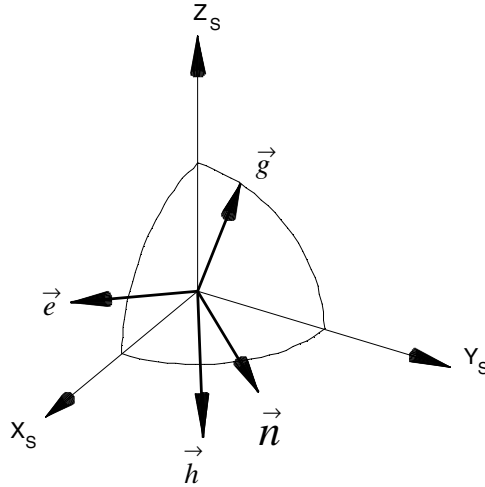


Figure 3. Magnetic East, magnetic North, and vertical are found from the gravity and magnetic field observations in the sensor frame.

So magnetic North expressed as a unit vector in the sensor frame is

$$N_s = \frac{(h_s - h_s \cdot g_s)g_s}{\|(h_s - h_s \cdot g_s)g_s\|}$$

The direction cosine matrix A^{S-G} is constructed from the three sensor frame coordinate matrices representing magnetic East, magnetic North, and vertical: E_s , N_s , and U_s . Note that the error caused by magnetic declination must be corrected, either by an explicit rotation about the vertical axis, or more preferably through calibration.

3.2. *Sensor Frame Heading.* With the direction cosine matrix known, the user heading \vec{d} must be defined in the sensor frame before it can be transformed into the global frame. If the direction the user is facing is not known in sensor frame coordinates, than any coordinate matrix d_s may be used as long as it lies in the horizontal plane, and has an invariant orientation with respect to gravity. In this investigation, the heading vector d_s is constructed using the vector product of gravity and an arbitrary but constant coordinate matrix a_s (e.g. $a_s = [1,0,0]$) as

$$d_s = \frac{g_s \times a_s}{\|g_s \times a_s\|}$$

The error in actual heading will be constant and is removed in calibration along with the magnetic declination. Finally, the user heading in the global frame can be calculated as

$$d_G = A^{S-G} d_s = [E_s, N_s, U_s]^T d_s$$

As the user makes a turn, the sensor frame rotates with respect to the global frame and d_G will rotate about gravity, indicating the user's direction of travel.

3.3. *Declination and Misalignment Correction.* As previously mentioned, because of magnetic declination and the unknown horizontal alignment between the user and the sensor frame, d_G will not point in the correct direction. The last step in the

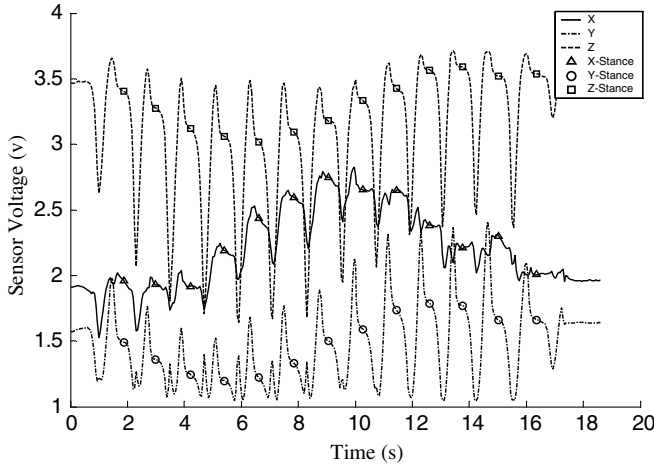


Figure 4. Magneto-Resistive Sensor signal measured while the user walks a circle of 4 m radius. Symbols indicate the time and average value during stance phase.

heading determination algorithm is to correct this heading error by rotating d_G in the horizontal plane by an angle ϕ to get the true heading:

$$d_{G-corrected} = \begin{vmatrix} \cos\phi & \sin\phi & 0 \\ -\sin\phi & \cos\phi & 0 \\ 0 & 0 & 1 \end{vmatrix} d_G$$

This of course assumes that the correction angle ϕ is known. The reason this heading correction is left to the last step is that it is simpler to determine ϕ directly from calibration than to explicitly sum the magnetic declination and sensor to user frame misalignment. The magnetic declination for a given latitude and longitude is available from reference tables but may vary locally at the user’s position. The sensor frame misalignment is often not known explicitly, and can be difficult to measure.

4. MAGNETO RESISTIVE SENSOR CALIBRATION. The difficulty in using Earth’s magnetic field for orientation is that it changes globally, locally, and in time albeit slowly. It is also a relatively weak field, easily disturbed by metal objects or electrical activity. Because of differences in local magnetic fields, it is not possible to calibrate the sensors in a laboratory apparatus and then use them elsewhere, so a method of field calibration must be devised.

To calibrate the magnetoresistive sensors in the pedestrian mode, the following simple field procedure can be followed: The user begins facing a known heading and then walks around a circle of 4 m radius, creating the signal shown in Figure 4. Due to the motion of the foot, the change in output due to heading cannot be easily distinguished from the change in output due to the motion of the foot.

Since the AMR output during the swing phase is of no interest, a gait event detection algorithm is applied to the acceleration signal (Aminian 2002, Hansen 2002). Symbols in Figure 4 show the average stance phase output of the sensors as the user walks around the circle. The change in output due to heading is now clear.

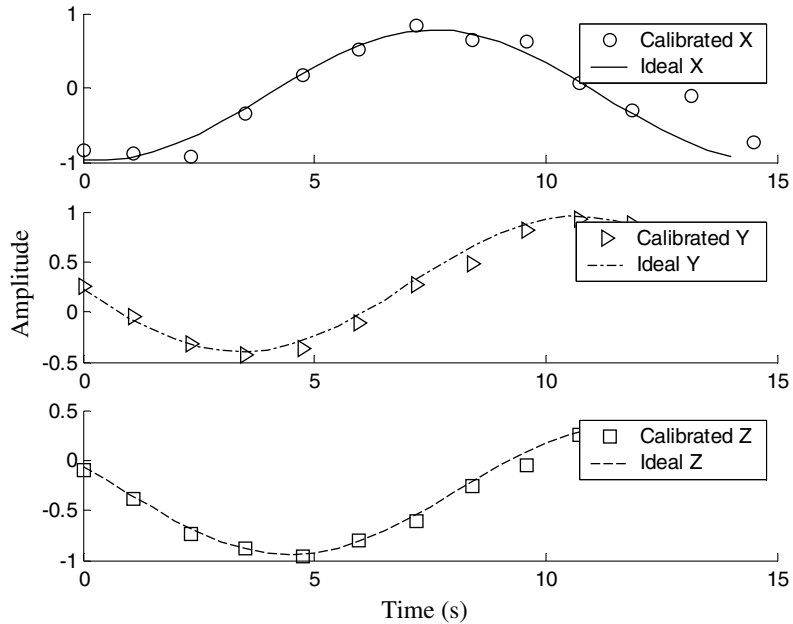


Figure 5. Calibrated magneto-resistive sensor signals for calibration circle walk.

User calibration by horizontal turns or walking a pattern of known headings is a common method of compass calibration (Ladetto, 2003). The difficulty with these methods is that while the sensors are exposed to the complete range of horizontal field components, they experience little of the vertical field range. Calibration of the vertical axis is important because of the range of orientations the foot may be in during stance phase, when the heading is calculated. Once fastened to the user's foot however, it is difficult to rotate the sensor in the vertical plane so the horizontal rotation techniques must be made to work. For heading determination, it is not important to accurately measure the magnitude of the field, only its direction, so for calibration purposes it is only necessary to ensure that the gain and sensitivity of the magneto resistive sensors are calibrated with respect to each other.

For a position of known latitude, longitude and time, a geomagnetic model can be used to estimate the global frame magnetic field vector (Campbell, 1997). Beginning from a known heading, and assuming that the surface is level, the relative output of each AMR axis can be predicted as the user walks around the circle at a constant rate. In this test condition, the output of the real sensors is approximately sinusoidal, and thus easy to fit to the ideal output. The gain and offset are adjusted to get the best fit between the raw and ideal output as shown in Figure 5. The correction angle ϕ , required for the last step of the heading calculation is simply the phase shift needed to align the sensor signals with the ideal signal. Importantly, this method allows an estimation of the nominally vertical compass axis to be made without requiring a rotation in the vertical plane.

5. FIELD TESTING. The shoe mounted pedestrian dead reckoning system was tested on a surveyed trajectory in a dense coniferous forested park located in



Figure 6. Field tests took place in a forested park in Victoria, Canada.

Victoria, Canada as shown in Figure 6. Looking ahead to practical applications, this was an appropriate test environment for evaluation because thick forest cover attenuates standard GPS signals, and the magnetic field is free of disturbances.

The sensors used for the pedestrian navigation system consisted of three Analog Devices ADXL210 accelerometers, two mounted orthogonally and the third offset in the sagittal plane. A tri-axial magneto resistive sensor was constructed from two biaxial Honeywell HMC1022 sensors. The sensors were mounted in a light, compact foot pod worn on the user's left shoe as shown in Figure 7. For comparison, the user also carried a backpack with multiple SiRF STAR IIe HSGPS receivers, and a triad of Honeywell GG1308 ring laser gyros used in a HG1700-based Novatel BlackDiamond™ GPS/INS system. A hand trigger was used to synchronize the sensors. The University of Calgary designed system was used in a multi-purpose experiment to test location and navigation under the forest canopy. The SiRF HSGPS receiver used herein has proven to be capable of tracking signals up to 25 dB below line-of-sight signals (e.g. Lachapelle et al 2003a).

The test track was a gravel and boardwalk loop approximately 900 metres in length and divided into 13 main sections by accurately surveyed checkpoints as shown with triangles in Figure 8. At the beginning and end of each test, the user completed the compass calibration circle walk. The user walked at a comfortable pace counter clockwise around the course.

5.1. *Long Course Trajectories.* Figure 8 shows the user trajectory estimated over the entire course successively by the foot pod, high sensitivity GPS (HSGPS) and the



Figure 7. Footpod mounted on a shoe.

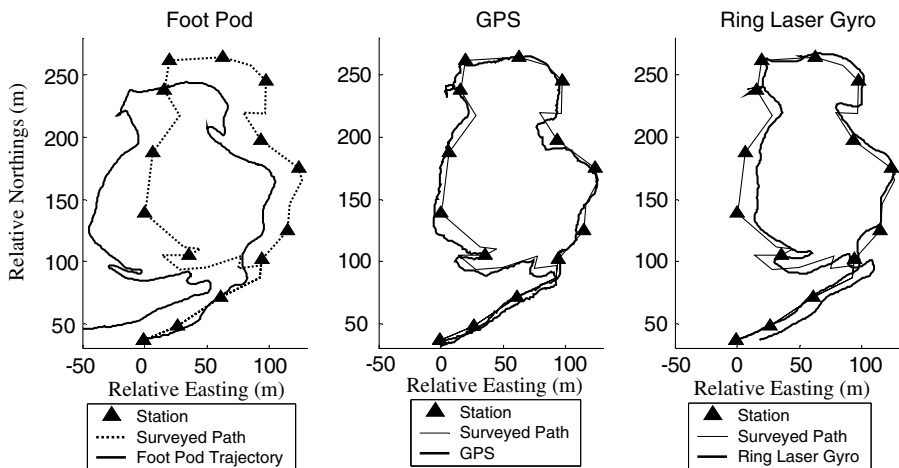


Figure 8. Comparison of trajectories measured by: Foot Pod (Left), GPS (Middle), Ring Laser Gyro (Right).

ring laser gyro system. (A fixed stride length was assumed for the ring laser gyro.) The trajectory calculated by the foot pod (left plot) clearly shows the features of the test course but is clearly less accurate than the GPS trajectory (middle plot) or the ring laser gyro (right plot). It is interesting to note that GPS signal attenuation reached 20 dB, resulting in noise and multipath that translated in horizontal position errors up to 30 m.

5.2. Position Error Analysis. The position error at each control station is compared for all three navigation methods in Figure 9. Vertical lines indicate the time that the user arrived at each control station. As expected, the error for HSGPS is consistently less than 10 m, and shows no dependence on time or stride count. The position error for the ring laser gyro slowly increases with the number of steps taken by the user, which is consistent with the pedestrian dead reckoning model. After 641 detected strides, the error in position is 25 m for an average error growth of 4 cm per

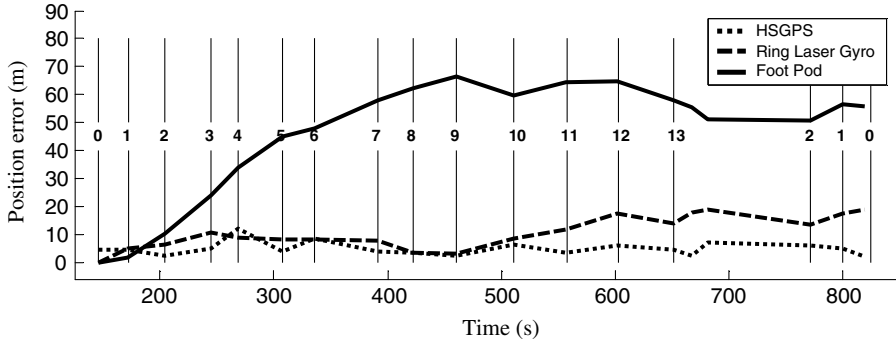


Figure 9. Comparison of error in calculated position.

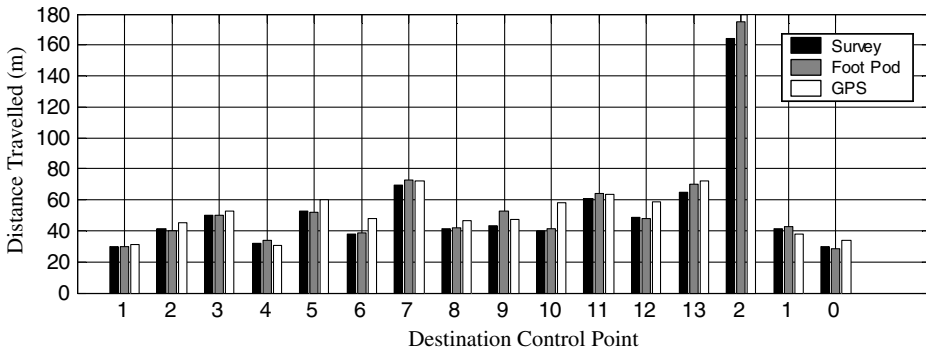


Figure 10. Comparison of distance measurements.

stride which, as mentioned, will be largely due to the error in the constant stride length assumption. The error in the foot pod solution also appears to behave consistently with the linear error predicted by the pedestrian dead reckoning model but with a substantially greater average error per stride of almost 30 cm.

5.3. *Stride Length Error.* Figure 10 compares the distance travelled between control points for the entire test. The surveyed distance of 847 m is obtained by summation of the straight distances between control points and will be slightly less than the actual distance travelled because the path sections are not quite straight between the surveyed points. The total distance measured by HSGPS is 940 m, which is more than the distance travelled, because of the occasional solution divergences when the user is moving slowly or through thick cover.

The distance measured by the foot pod stride length measurement is expected to be between the limits set by the survey and GPS solutions. The total length measured with the foot pod is 880 m which is within 4% of the surveyed distance and 6% of the distance measured by GPS. For the section ending at Station 9, the foot pod measured a greater distance than either the survey or the GPS, because the extra distance the user walks around a tree located along the path to verify how well such a circular motion with such a small radius would be detected.

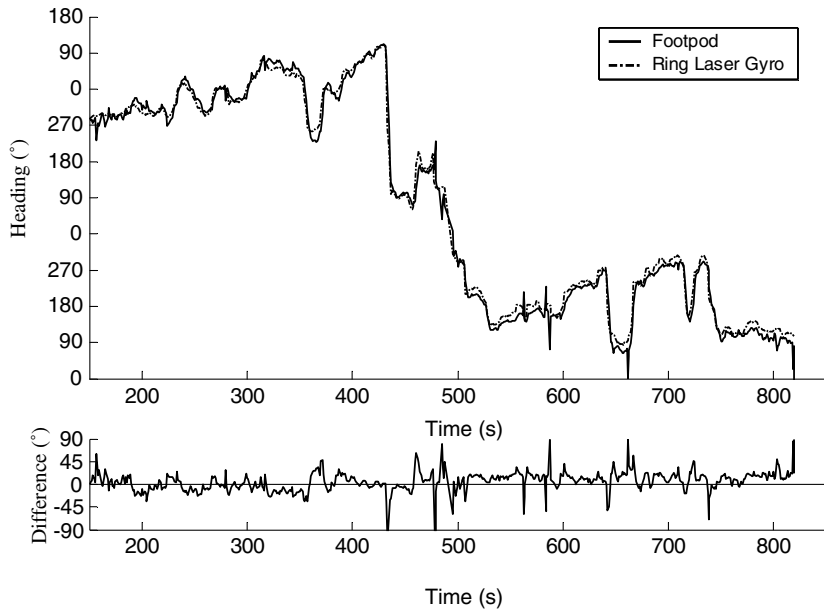


Figure 11. Comparison of ring laser gyro and foot pod heading.

5.4. *Heading Error.* The top plot in Figure 11 shows the heading calculated through the test by the foot pod and ring laser gyro. The difference between them is shown in the lower plot, and has a mean value of 4 degrees. Over the course of the entire test, the heading measured from the foot sensors tracks the ring laser gyro heading closely, though there are occasional errors of up to 90 degrees. Inspection of the course showed that these larger heading errors occurred on inclines, indicating that the vertical compass calibration may not be sufficiently accurate, as expected.

5.5. *Short Term Performance.* The relatively large rate of error growth in the foot pod trajectory makes it difficult to see how the system performs over individual sections of the course, especially later in the test. Figure 12 shows the trajectory calculated by the foot pod, corrected at each control station.

Examining the short-term performance shows that it is possible to discern details of the user motion with the foot pod that the high sensitivity GPS does resolve. An example is shown in Figure 13. Here, the user walks from control point 9, enters a light wooden structure and stays stationary before continuing on to control point 10. The pedestrian navigation system on the foot clearly shows the user retrace his steps. In contrast, the GPS solution wanders while the user is motionless.

6. CONCLUSIONS. A novel method of pedestrian dead reckoning using shoe-mounted sensors was proposed and investigated. In this preliminary study, an algorithm was developed to propagate a position by detecting stride events, measuring their length and estimating their heading with low cost accelerometers and magneto-resistive sensors mounted on a shoe. Existing research established the validity of measuring stride length with shoe-mounted accelerometers, but measuring heading with shoe-mounted sensors is novel. Because the goal of this research was to

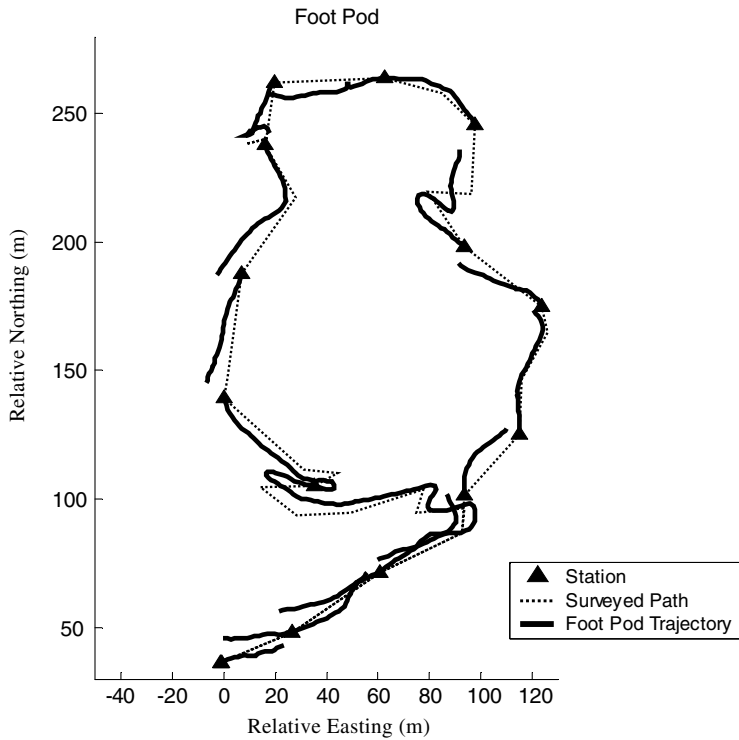


Figure 12. Short-term performance of the foot pod.

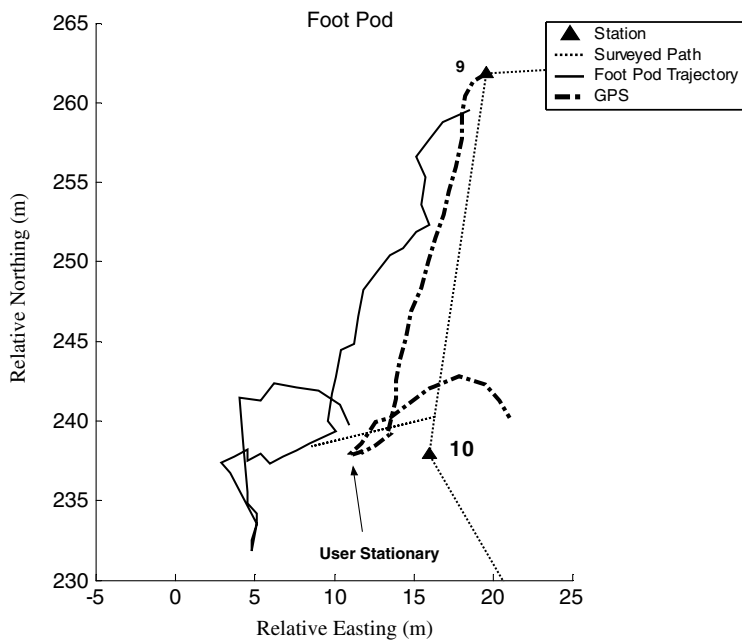


Figure 13. Example of pedestrian navigation systems resolving details of user motion.

establish the basic feasibility of shoe based pedestrian navigation, low cost sensors were applied and the system was operated strictly in dead reckoning mode. Though the accuracy observed in the field trials was substantially inferior to the references, the references used are relatively sophisticated and relatively expensive positioning systems. In addition, the method described herein will operate with a uniform level of performance, regardless of GNSS signal availability. Having shown that it is possible to measure position with shoe mounted sensors, the system may be improved by a combination of improving measurement accuracy and increasing system sophistication.

Examination of the short-term performance of the system, and special components of the test course showed that the foot pod system is capable of measuring detailed motion with finer resolution than HSGPS. The majority of pedestrian navigation systems are integrated to some degree with GPS, as the combination of microscopic detail from the sensors and macroscopic accuracy of GPS make a good match. Torso mounted systems are appropriate for GPS integration as the entire system can be contained in one enclosure. Signal masking by the leg, and the increased weight make it seem unlikely that GPS would be added directly to the foot pod but this system could otherwise be integrated. Efforts are currently taking place to evaluate integration of GPS with low cost inertial sensors (e.g. Mezentsev et al. 2004).

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