Personal Position Measurement Using Dead Reckoning*

Cliff Randell   Chris Djiallis   Henk Muller
Department of Computer Science, University of Bristol
cliff@cs.bris.ac.uk

Abstract

This paper compares position measurement techniques using dead reckoning. We are seeking to find a technique which is suitable for use by pedestrians, and have compared a number of sensors that can be used to achieve a robust and accurate dead reckoning system. All our techniques are step based. To measure steps we have compared the use of pedometers and accelerometers. To determine heading we have compared two and three dimensional compasses and a rate gyroscope. Finally we have performed four case studies based on real applications with standard deviation measured at 2.2m for a short test and 19.9m for an extended test. These errors can be reduced by using more computationally expensive filtering operations.

1 Introduction

The use of the Global Positioning System (GPS) has become established as the preferred method for outdoor position sensing for wearable computers and mobile computing in general. The disadvantages of GPS for wearable computing, particularly in city environments, are loss of signal due to obstruction e.g. by buildings and/or by the human body; attenuation of signal e.g. by foliage; erroneous signals due to multipath effects commonly caused by 'urban canyons'; and poor accuracy in relation to the scale of the locations in which we have an interest e.g. seeking entrances to buildings. While a dual frequency GPS receiver using RTK techniques, a local base station, and with a clear view of the sky, can achieve centimetre accuracy, most off-the-shelf units typically achieve an accuracy within 10m 95% of the time. At worst there may be no position fix at all. For most vehicle applications, GPS is augmented with inertial sensing to provide a higher degree of accuracy and for short term position sensing when there is no GPS signal available. Inertial systems usually combine magnetometers, gyroscopes and accelerometers with high level processing. We are interested in the use of simple inertial techniques for the economic improvement of the performance of position measurement for wearable computer users. We do this by detecting heading and by estimating step size [1].

Navigation using inertial sensing has been important throughout history. One of the earliest techniques, used in particular by sailors, was dead (or 'deduced') reckoning (DR). This involved combining compass heading with a knowledge of sea currents and the speed of the vessel measured by the time taken by an object thrown overboard to travel a fixed length along the side of the ship. This was the technique used by Columbus in his voyages to discover the New World. While full inertial sensing provides heading, velocity and acceleration in three dimensions, dead reckoning uses measures of heading and velocity to provide a two dimensional positioning solution based on a known starting point. It is well suited for already instrumented vehicles such as aircraft, ships and automobiles [2]. On a smaller scale, dead reckoning has also been used for robot navigation and, of special interest to wearable computer users, it has been used to aid navigation for walking robots [3].

The use of motion sensors for virtual and augmented reality head trackers has become commonplace [4, 5] demonstrating that these sensors can be used satsfactorily for position prediction in small areas with a high degree of accuracy. Also of relevance is research undertaken using treadmills to navigate in virtual worlds [6, 7]. A commercial dead reckoning system for wearables has already been developed by Point Research Corporation utilising tri-axial accelerometers and tri-axial magnetometers [8] for use as part of the U.S. Army's Land Warrior program. Lee and Mase have explored a location classifying system based on dead reckoning data [9]. In their paper they describe a system based on a bi-axial accelerometer, a simple digital compass and an angular velocity sensor. Using data from these sensors they are able to achieve a recognition ratio for ten indoor location transitions of 91.8 percent.

In this paper we compare the use of three heading sensors - a rate gyroscope, a two-axis and a three-axis electronic compass; and of two different motion sensors - a sports pe-

---

* Funding for this work is received from the U.K. Engineering and Physical Sciences Research Council, Grant No. 15986, as part of the Equator IRC.

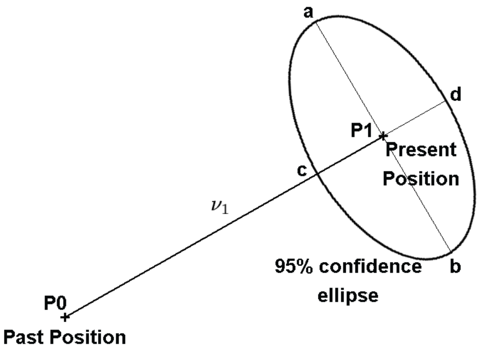


Figure 1. Determining of the Confidence Ellipse.

dometer and various accelerometer configurations. We are seeking economic and wearable solutions primarily for outdoor position sensing in locations where GPS positioning is not viable. We also give consideration to available battery and computational power.

This research is presented as a comparison of the three heading sensors; a description of step sensing techniques using pedometers and accelerometers; and four case studies - City Streets, Ambient Wood, Garden Path and Tourist Trail - which compare the performance of different practical wearable implementations of dead reckoning with results and discussion.

2 Background Theory

Dead reckoning is the process of estimating present position by projecting heading and speed from a known past position. The heading and speed are combined into a movement vector ν_1 representing the change of position from a known position, P0, to an estimated position, P1. The accuracy of this estimation can be quoted as a confidence ellipse whose population mean is in the ellipse 95% of the time. The axes of the ellipse are determined by the accuracies of the heading detection and speed measurement. This is illustrated in Figure 1. A user moving from point P0 to point P1 can be described as being within the 95% confidence ellipse centered on P1 with axes **ab**, determined by the heading sensor accuracy, and **cd**, determined by the speed sensor accuracy.

While the uncertainty of a single reading can be described this way, the uncertainty of multiple readings is calculated as the cumulative sum of the uncertainty on all readings since the last precisely known position. This is simply expressed in the equation:-

$$P_n = P_0 + \sum_{i=1}^{n} (\nu_i + \nu_e)$$

where n is the number of dead reckoning calculations since P0; P_n is the current position; and ν_e is the error vector for each calculation. Assuming a straight path, the resultant confidence ellipse after n iterations has axes of dimension $n \times ab$ and $n \times cd$, or more simply, in the worst case these ellipses grow linearly with travel distance. Clearly the accuracy of our sensors is critical to the confidence we can place in position estimation using dead reckoning.

Figure 2. Vector 2x in use a) Handheld, b) Shoulder mounted, and c) in Backpack.

3 Heading Detection

Traditionally a magnetic compass is employed for this function, however low cost vibrating rate gyroscopes offer a possible economic alternative. Both two axis and three axis electronic compasses using magnetic sensors and a single rate gyroscope are suitable for incorporating into everyday wearable computer designs and are considered. Multiple gyroscopes are not evaluated due to cost and form factor considerations however these have also been successfully used in specialist wearable computer applications for augmented reality [4, 5, 10] and also for motion capture [11]. For evaluation and comparison the three heading sensors were mounted on a single board for a series of tests.

3.1 Two-axis Compass

For our initial dead reckoning experiments a Precision Navigation Vector 2X was used [12]. This is a low cost - \$50 - device with two orthogonally mounted magnetometers in a 4cm x 4cm package with 2 degree accuracy when level. The amount of error varies depending on where you are on the Earth. For example, in Mountain View, CA, for each 1° of tilt, there would be about 3° of heading error. In Greenland, for 1° of tilt, there can be about 10° of heading error. The Vector 2x was used in several different configurations illustrated in Figure 2:

- **Handheld** The compass was attached to the back of a handheld PDA. The mounting was fixed to ensure that the compass board was level when the PDA was held at a comfortable viewing angle.
- **Shoulder Mounted** In this configuration the compass was mounted on the user's shoulder. Two variations were experimented with - illustrated is a compass taped to the user's shoulder ensuring that the best possible results would be obtained without the effects of clothing movement. As an alternative, the compass was mounted using velcro on the shoulder of a jacket worn by the user.
- **Backpack** The compass was placed in a fixed position within a close fitting backpack intended to minimise any extraneous movement. This arrangement was especially suited for user testing with untrained subjects.

In the shoulder mounted configuration, using a jacket or velcro mounting, a small error angle results as the jacket moves over the shoulder. With 2 coils in the compass at a 90 degree angle, one coil can be mounted close to the horizontal whereas the other coil will not be horizontal and may move according to how we wear the jacket. Very little sideways movement occurs. Given that the earth's magnetic field with strength H is under an angle θ (around 70 degrees in the UK), the field will have a vertical component $H\cos\theta$ and a horizontal component $H\sin\theta$.

Given a heading α, the field that will be measured by the perfect horizontal coil will be $H\sin\theta\sin\alpha$. If we assume that the non horizontal coil is under an angle ϕ, then the field measured with that coil will be $H\sin\theta\cos\alpha\cos\phi + H\sin\phi\cos\theta$. Hence, the heading $\overline{\alpha}$ that the compass under an inclination of ϕ and a heading of α will produce is

$$\begin{aligned}\overline{\alpha} &= \tan^{-1}\frac{H\sin\theta\sin\alpha}{H\sin\theta\cos\alpha\cos\phi + H\sin\phi\cos\theta}\\ &= \tan^{-1}\frac{\sin\theta\sin\alpha}{\sin\theta\cos\alpha\cos\phi + \sin\phi\cos\theta}\end{aligned}$$

We are thus able to use a look-up table for $\overline{\alpha}$ in order to correct the compass readings. This was implemented for the case study described in Section 5.4.

3.2 Three-axis Compass

A three-axis compass is able to fully compensate for tilt and thus should be able to give better accuracy when compared to a two-axis compass worn on the body. For our tests we have selected the Honeywell HMR3300 using magnetoresistive sensors to give 3° accuracy over a tilt angle of ±30° and 4° accuracy over ±60° [13]. While it is possible to mount two Vector 2Xs orthogonally with a tilt sensor to obtain similar results at a lower cost than the $450 HMR3300, the Honeywell device provides a complete package with smaller dimensions and improved wearability characteristics.

3.3 Rate Gyroscope

A vibrating element (vibrating resonator), when rotated, is subjected to the Coriolis effect causing secondary vibration orthogonal to the original vibrating direction. By sensing the secondary vibration, the rate of turn can be detected. This principle is employed by the CRS-03 Rate Gyroscope produced by Silicon Sensing Systems Japan Ltd for $250 [14]. By integrating the rate of turn the change in heading from an initial reference direction can be obtained. While a gyroscope cannot provide an absolute heading, it is not affected by extraneous magnetic fields. Though considered a low drift device, we measured drift at around one degree per minute. This compares with one degree per hour which can be obtained using a more expensive fibre optic gyroscope [15]. For our tests we filtered the signal at 1kHz and sampled the gyroscope output at 50Hz.

3.4 Heading Sensor Comparison

The two compasses and the gyroscope were mounted in fixed positions on a 1m board with the compasses at either end and the gyroscope in the middle to minimise any interactive magnetic or electrical effects. Tests were carried out by carrying the board at different angles of tilt and roll along a prescribed 10m by 4m figure of eight path. A typical result is shown in Figure 3 where the tester followed the path 5 times in a period of three minutes. For the first circuit the board was held level, for the following four loops the board was held at approximately +/- 30° of tilt and roll as indicated by the tilt sensor incorporated into the HMR3300.

Trace a) in Figure 3 shows the headings from two-axis compass being badly affected by both tilt and roll. The three-axis compass in trace b) appears unaffected by tilt and roll and the gyroscope headings in trace c) only display a significant error in the final loop. Though care was taken to avoid extraneous magnetic fields and a 180°/sec filter was introduced, both the compasses produced noisy traces while the gyroscope produced a smooth result. If we use the 3D compass readings as the reference source, then we can see that the gyroscope exhibits two error characteristics. Firstly the amplitude of the heading signals appears to be attentuated. This can be corrected easily by adjusting the scaling coefficient (in mV/(deg/sec)) which was set to the default value for these tests. Secondly there appears to be some drift which manifests itself in this test as a time lag. This drift is usually caused by electrical noise and temperature variations and once measured can be corrected dynamically.

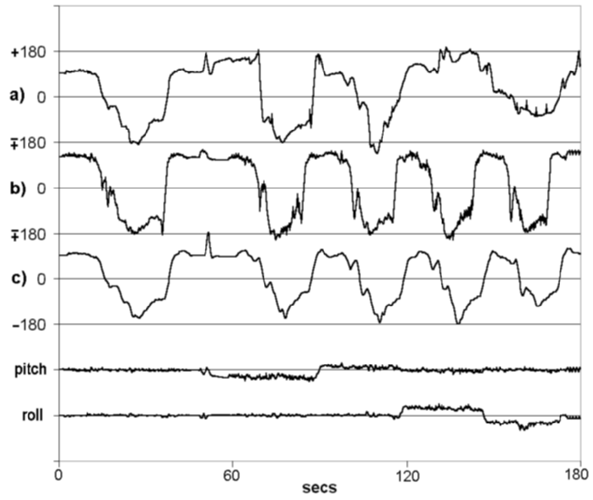


Figure 3. Heading Sensors a) 2-axis compass, b) 3-axis compass, and c) rate gyroscope.

4 Speed Detection

Most conventional mobile positioning solutions fitted to aircraft, boats and automobiles take advantage of speed sensing devices already fitted to the vehicle. The user of a wearable computer does not normally have such instrumentation. However there are movements associated with walking and running which can readily be detected by simple mechanical or electrical sensors. In our tests we have successfully used sports pedometers as well as accelerometers as our speed detection devices.

4.1 Sports Pedometer

Conventional sports pedometers use a spring mounted weight with a damped resonance which operates a switch synchronously with the user's walking or running pace. By using multiple springs the resonant effect is maintained over a band of frequencies corresponding to the range between gently strolling and running. The pedometer has the significant advantages of minimal power consumption and no requirement for step detection processing. After filtering bounce in the switch, it is a simple procedure to measure the time between switch operations and then, either by pre-calibration or by dynamic measurement using an external reference such as GPS, estimate the speed of the user.

4.2 Accelerometers

4.2.1 Initial Study

The use of accelerometers as context sensing devices to recognise various movement signatures of users has previously been described by Schmidt [16]. In particular recognition of walking and running has been detected using dedicated neural networks [17]. Both the pedometer and neural network analyses assume a cyclic pattern of movement, however the act of walking is event driven with measurable impacts which can also be detected using accelerometers.

For a dead reckoning application we wish to determine both the state and the speed of walking. This does not suggest a neural network solution. Initial tests were carried out using the detection of peaks in movement from a backpack mounted accelerometer (see Figure 2c), along with the Vector 2X compass (see Section 5.2). The device demonstrated that both movement could be reliably detected and that dead reckoning using accelerometers was feasible. However this approach was at best crude and gave no measure of speed.

4.2.2 Detailed Analysis

A greater understanding of the movements and forces was required and a more detailed analysis of the motion of the feet was carried out. Also, since every step is independent of any other then we believed that it would be possible to realise an improvement over the systems that employ step frequency analysis as a means of deducing current speed across the ground. This event driven approach could also prove valuable in analysing disjointed steps that occur when altering course and changing speed [18]. An important point is that when humans stride further, apart from just stretching out the legs further, the feet move faster for stability reasons [19]. Hence, it is postulated that the acceleration of the foot (in the vertical plane rather than in the direction of motion) is greater when the foot makes a larger stride. It is this hypothesis that allows us to deduce that the greater the vertical acceleration of the foot during a step, the greater the distance that was travelled across the ground. This is a relationship that we can exploit to enable us to adjust the pedestrians pre-calculated stride and hence reduce the error associated with a fixed stride.

Another observation is that humans rarely under-step their minimum average stride again for stability reasons [19] except for when they are turning on the spot (which does not affect distance across the ground). In using this stride length scaling technique based on step energy we can analyse the variations in the raw acceleration data rather than rely on noise intolerant integration techniques.

To test this theory we taped an accelerometer on each foot of our tester and recorded the data output as he walked (see Section 5.3). A typical result is shown in Figure 4. It

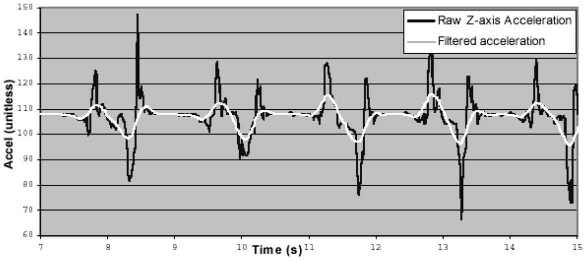


Figure 4. Acceleration experienced by a pedestrian's foot in the vertical plane whilst gently strolling. Raw and filtered data.

can be seen that the foot initially accelerates rapidly forwards into the air and then slows to the point where it moves backwards slightly before coming into contact with the ground at the end of the step. The flattened regions of the graph represent the periods when the pedestrians foot is in contact with the ground (stationary).

A filter was constructed from a double moving average of the raw data and this enabled the detection of individual footsteps. At first glance, the filtered data set seems to be quite straightforward to feature detect but further analysis shows other characteristics where the period and amplitude of the motion changes considerably as the pace of the user varies.

4.2.3 Further Analysis

For the sample datasets we were able to design filters to accommodate these difficulties however we wished to devise a generic signal conditioning filter that would accommodate motions from single steps to walking at considerable pace. The smoothed signal transitions in the sample data-sets are a result of two moving average filters of equal size. The first application of the filter removes outliers or major noise spikes whilst the second round of filtering provides a large degree of smoothing. Moving average filters can be applied here generically since we have to find the moving window size that satisfies the common case. For the extreme cases, the output will only be affected by the recorded maximum amplitude of the step, which we can tolerate since this will have only a minor effect on accuracy.

The ideal filter window size was found using experimental methods applied to sample datasets to achieve the required degree of smoothing whilst retaining the identifying characterisitics of the step motion pattern. We found that a window size of 11 samples can be applied twice to any type of foot motion signal to enable the recognition of the full range of step patterns in these datasets. The difficulty in developing a step characteristic extraction algorithm is that it has to be dynamic and must do feature detection based on the general form of the pattern to be recognised. Based on our hypothesis, we need to:

- detect when a step has occurred ; and
- extract the peak acceleration during that step to give us an indication of the step magnitude.

A naive method of step detection would be to just perform peak and trough detection by differentiation however localised maxima and minima would interrupt progress since these cannot be completely filtered out. Therefore we need to take advantage of the fact that in a true step transition, a peak is immediately followed by a trough where the peak and trough are outside of the low-level noise margin.

These techniques, developed using the foot mounted accelerometers, could then be applied to a more user friendly solution of simply carrying the accelerometer on the body and relying on the movements being transmitted through the musculo-skeletal system. While some damping efects were to be expected, the waveforms remained consistent and step detection could be performed (see Section 5.4). The use of more sophisticated statistical filters was thus unnecessary however we may return to this as part of our future research (see Section 7).

5 Case Studies

In this section four case studies are described applying the devices and techniques previously presented. These case studies are not intended to be exhaustive, but do give useful results which can be taken as typical indicators of the performance which can be expected from these, and similar, dead reckoning configurations. The case studies inform the discussion which follows in Section 6. The first study provides an example of the sports pedometer usage, and the other three employ accelerometers with differing approaches to the data analysis. All the studies used the Vector 2X compass to aid comparison, though different mounting techniques and degrees of data analysis were used. The two axis compass was selected for these tests as we wished to evaluate both the cost effectiveness of this solution and techniques for correcting the errors resulting from tilt. From the results given in Section 3 we know that improved results would be achieved with a three axis compass, but this would be at a financial cost especially if a significant number of these units were to be built. The gyroscope option, apart from the cost factor, would be acceptable only if there was a reference heading occasionally available to counteract the effects of drift. This would be the case with an integrated GPS configuration however in this work we wished to address a dead reckoning only solution.

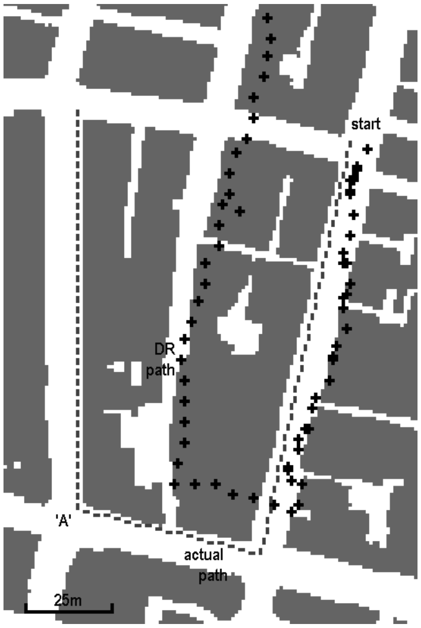


Figure 5. Using DR in City Streets. Dotted grey line is actual path,'+'s are DR positions.

5.1 City Streets

As part of the Equator City project [20], we are exploring ways that people can interact and maintain awareness of each other in City environments even though they may be spatially separated. A sensing system which can continuously track a user's position anywhere in the city is an important element of this research, and the accuracy necessary for effective interaction one of its anticipated outcomes. Dead reckoning offers the potential of providing position data between areas of either GPS or indoor positioning system coverage. The preferred form factor for this project is a handheld PDA to which we have added the compass and a 418 MHz wireless receiver (see Figure 2a). A belt mounted pedometer is used to detect whenever the user takes five steps, and an eight byte RF packet is consequently transmitted to the wireless receiver. The packet contains a header byte and a sequenced reference number. The PDA's magnetic properties had no observable effect on the performance of the compass, however it's RF radiation did marginally reduce the sensitivity of the wireless receiver. The heading and pedometer data is analysed to provide position data with a fixed distance travelled based on a predetermined average step length. A typical result is shown in Figure 5.

The primary error using this configuration resulted from poor speed estimation. This was largely due to pedestrian congestion along some parts of the path leading to varying speeds of walking. The handheld compass in this example worked reasonably well with the heading error appearing to be within 12°. A measurement taken at point 'A' shows that after 39 readings, or 4 minutes, over a 279m path, the error is 27m. By analysing the error at sample points along the path we are able to estimate standard deviation, σ, for this test at 14.8m.

In addition by post processing the collected data, it was possible to use the time between steps to adjust the step length, and hence speed. This technique reduced the error at point 'A' to around 15m. It should also be noted that the heading data obtained with an untrained user and handheld compass were significantly worse to the point of being almost unusable. Mounting the compass on the torso is clearly preferable as is shown in the remaining case studies.

While this paper is not intended to address sensor fusion techniques, it is worth noting that this configuration when used to supplement GPS, and combined with a correction technique utilising knowledge of building locations, was able to effectively track a user through the city streets. This was despite frequent loss of the GPS signal for periods of several minutes. The fundamental accuracy was dependant on the performance of the GPS receiver.

5.2 Ambient Wood

The Equator Ambient Wood project [21] was designed as a playful learning experience where pairs of children explore and reflect upon a woodland environment that has been augmented with a range of digital abstractions. The latter are represented in a number of ambient ways, designed to provoke children to stop, wonder and learn when moving through, and interacting with, aspects of the physical environment. For this research it was necessary to track the progress of the children as they moved around the woodland. GPS reception was affected by the tree canopy, and hence dead reckoning was trialled as an alternative approach. The children were equipped with a backpack - see Figure 2c) - which as well as a GPS receiver, contained a module combining the Vector compass and an accelerometer. Again a wireless connection to a handheld PDA was used, but this time the RF packet was triggered every time the accelerometer data exceeded a threshold value, signifying movement. In this instance the packet contained the heading and identifier data. The GPS data was also transmitted to the PDA using a similar wireless technique.

The main error again, and not surprisingly, resulted from poor speed estimation as can be seen in Figure 6. This was largely due to the unsophisticated analysis of the accelerometer data, though the uneven and obstructive nature of the woodland may also have contributed. The compass in the

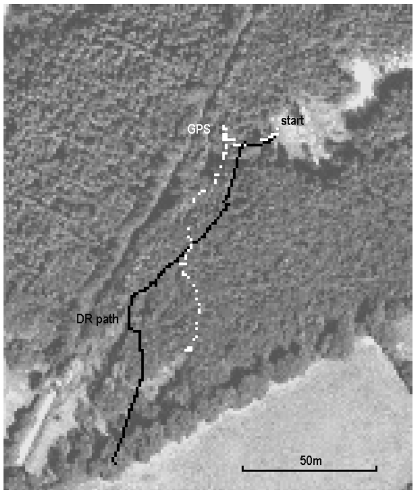


Figure 6. Using DR in Woodland. The white line is the actual path as measured by a GPS receiver, the black line shows the DR path.

Figure 7. Clockwise from top left: compass sensor taped to shoulder; accelerometer sensors attached to pedestrian's shoes; Bitsy motherboard carried in pocket; and accelerometer sensor, extracted from sole holster to show size.

backpack worked reasonably well with both testers and the children. The overall direction error was around 5°, though the woodland path was not suitable for precise confirmation of this. The accumulating error was 39m after 170 readings, or 6.5 minutes, over a 131m path. The standard deviation measured over a set of sample points was 22.7m.

The integration with GPS data is not illustrated in this paper as after the initial tests a high gain active patch antenna was used to compensate for the attenuation of the GPS signals by the foliage. Nevertheless this arrangement demonstrated the potential usage of an accelerometer and helped to inform the design of the following studies.

5.3 Garden Path

The previous case studies show the importance of accurate speed measurement and demonstrate that a simplistic approach can give misleading results. To further investigate the fundamental theory a test configuration was assembled using two accelerometers, one attached to each foot; a compass taped to the tester's shoulder; and a pocket mounted StrongARM based processor, the ADS Bitsy. This rig facilitated in-depth analysis of the movements of the tester's feet as briefly described in Section 4.2.2 and is shown in Figure 7.

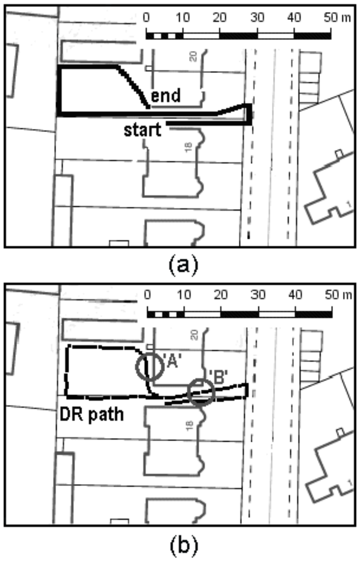
A test path was devised and surveyed for this configuration. Due to the need for close coupling to the body, tests were carried out only with a single user. The test area, the actual surveyed path, and the DR result are shown in figure 8. The overall results were excellent with some minor anomalies. The physically measured route was 126 metres whilst the dead reckoning application calculated it at 122 metres, thus being 4 metres out on total distance covered equating to a 3% error. With regard to positional accuracy, the dead reckoning application plotted its final position 1.55 metres out in the east-west axis and 2.1 metres off course in the north-south axis. The sampled standard deviation was 2.2m.

The circles 'A' and 'B' in Figure 8c highlight the periods in the dead reckoning route where there was significant deviation from the actual route taken. The anomaly indicated by circle 'A' can be explained by the increased gradient in the ground at that point, since the test area was not completely flat. Moreover, the wearable computer was not equipped with an inclinometer, although such a device could be used to investigate a method of compensating for gradient effects. The anomaly denoted by circle 'B' may have been induced by the close proximity of solid iron railings, which could have biased the compass sensor.

This test provided a performance benchmark though we would not expect a typical user to adopt such a configuration. The real-time analysis required high level computation, and with it a relatively high power consumption.

5.4 Tourist Trail

The final case study presents a walk through the streets of Bristol's tourist area where immersive applications are being designed to enhance the experience of a visitor to the city by using 3D soundscapes. Continuous position estimation is essential for the smooth delivery of audio and it was apparent that GPS could not provide an uninterrupted service, especially in covered areas and narrow lanes. To



(a)

(b)

Figure 8. a) Path taken by tester; b) Path measured using DR.

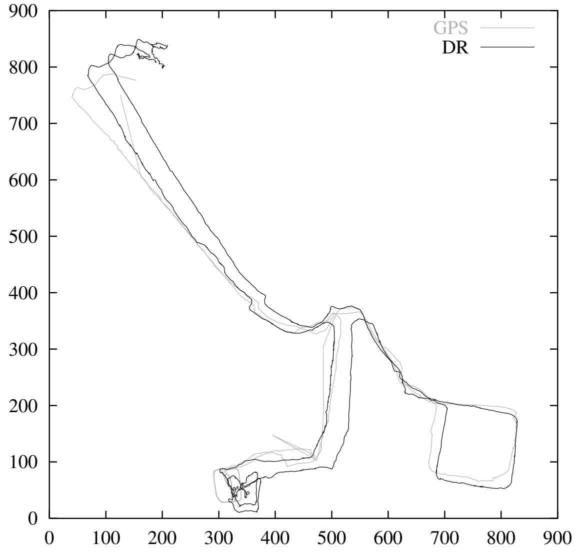


Figure 9. Using DR along an 4km urban Tourist Trail. The grey line is the path as measured by a GPS receiver, the solid black line shows the DR path. The scales are in metres.

address this a refinement of the system presented in the previous case study was used. In this test a trained tester maintains a steady pace and endeavours to keep the compass level. A ground truth is obtained by recording the output from a GPS receiver.

The speed sensing is carried out using a single body mounted accelerometer with step analysis software programmed into a PIC microcontroller instead of using a relatively power hungry StrongARM processor. The filter constructed from a double moving average is used once again to detect the steps. A constant step length is assumed for this test.

Heading is determined by mounting the Vector two-axis compass on the shoulder of our CyberJacket. Though every effort is made to mount the compass horizontally, a small error angle results as the jacket moves over the shoulder. Using the look-up table described in Section 3.1 we are able to correct for this. Our intention was to correct in real time, using for example a Kalman Filter and GPS data as a rough reference heading. The accuracy of the data suggests that the dead reckoning data is greater than that of the GPS in the short term, so we can tune the Kalman filter to assume that GPS data is correct on a 100 reading average, and use dead reckoning data to do short term adjustments.

The reason we haven't implemented this filter is because of serious inaccuracies in the compass readings which cannot be traced back to errors in levelling, but which are most likely due to anomalies in the magnetic field. When walking over one particular part of the test area, Millennium Square, we consistently receive anomalous compass readings for no apparent reason. The reason may be in the presence of an underground electric substation, electric cabling for lights etc. In this area, the dead reckoning error is very high. This illustrates the susceptibility of magnetic compasses to localised magnetic fields, particularly in an urban environment. In these circumstances a gyroscope solution is clearly advisable.

Figure 9 shows a best fit of the DR path to the GPS path. The results are comparable with those in Section 5.3 with a final offset of 52m after a 45minute/4,029m walk. Analysing sample positions along the main section of the path results in a standard deviation of 19.9m.

6 Discussion

The four case studies present different approaches to dead reckoning for wearable computing and illustrate the levels of accuracy which can be achieved with various devices and alternative levels of computation. The results are summarised in Table 1 showing the sensor types, overall distance, cumulative error and standard deviation calculated using sample points .

Case Study 3 with the compass taped to the shoulder, and a full analysis of the foot mounted accelerometer data provided the most accurate results. Apart from the phys-

	Compass mount	Speed sensor	Dist.	Error m	σ m
1	Handheld trained user	Pedometer	279m	27	14.8
2	Backpack	Accel'mtr peak sensing	131m	39	22.7
3	Shoulder taped	Accel'mtr full analysis	126m	4	2.2
4	Shoulder fixed angle	Accel'mtr step sensing	4km	52	19.9

Table 1. Case study results showing cumulative error and standard deviation over the distance of the test.

ical discomfort of such a system, it also required processing power which would not normally be found in a simple sensing device. The simplification of our algorithms to enable the step analysis to be carried out with a PIC microcontroller (Case 4) gave step detection results which were comparable without the requirement for careful positioning on the body, and our heading correction algorithms compensated for not taping the compass to the body. In Cases 1, 2 and 4 a satisfactory method is required to convert steps into speed. A simple single measurement of step length was shown to be insufficient, especially in Case 1. Three alternative approaches are proposed to address this shortcoming. Firstly we can measure the time between steps and use this to determine speed by including preset maximum and minimum step lengths. Secondly, as described for the Garden Path scenario, the amplitude of the acceleration forces can be used to scale the step length, and thirdly if we have another position sensing system in use, e.g. GPS, the data from this system can dynamically recalibrate the DR speed sensing.

The estimation of heading with the two-axis sensor was found to be satisfactory where either the tester took particular care to control the compass tilt, as in Case 1, or where the compass was strapped or taped firmly to the body in a level position, as in Cases 3 and 4. Simply mounting the compass on a piece of everyday clothing or placed in backpack gave poor results. Unless special measures are taken, such as compensating for compass tilt, or giving particular attention to tilt while in use, a three axis compass or gyroscope will give improved performance. The use of GPS to dynamically recalibrate the heading sensor is also a practical proposition and, where this is available, is particularly suited to use with the rate gyroscope. In theory this combination should give the most accurate results and the inaccuracies experienced with local electromagnetic fields would be eliminated.

7 Future Work

The tests described here took place to evaluate dead reckoning as a self-contained positioning system. Our longer term intention is to integrate DR with other positioning systems, including GPS and indoor ultrasonic positioning, making use of prior knowledge of the area in which the user is located e.g. maps, 3D models. The techniques described here show that there is potential for DR to usefully and economically augment wearable positioning systems which can provide reference positions. We are in the process of examining both logical and linear approaches to this sensor fusion problem, and expect that a wearable design incorporating Bayesian analysis and Kalman filtering will result in an integrated positioning system which will provide comprehensive coverage for most locations.

8 Conclusions

We have presented theory behind the use of dead reckoning for wearable computers and investigated the use of a number of different sensors. The use of dead reckoning in practice has been presented with four case studies using a selection of practical configurations providing insights into the use of DR and achieving accuracies of the same order as a basic GPS receiver.

Speed sensing has be carried out using pedometers or accelerometers with accuracy improving with increased complexity and computational analysis. While results can be obtained by simple step sensing, substantially improved performance is obtained using step length estimation. This has been demonstrated using acceleration analysis and also tests using time between steps to vary step length measurement also show improved performance.

Sensing heading using the two-axis compass gave satisfactory results when particular care was taken to ensure that it was maintained in a level position with close coupling to the body, or alternatively by computing a correction angle. The single gyroscope showed promising results and where an external reference is occasionally available, e.g. from GPS, satisfactory results should be obtained. For use in loose fitting clothes, or by untrained users with no external reference, a three-axis compass is recommended.

If the intention is to supplement GPS, or ultrasonic position sensing, then any of these configurations would be suitable for providing useful position data during lapses in position sensing. Indeed given occasional reference corrections, a system which fully analysed accelerometer data, combined with a three-axis compass, or a gyroscope where extraneous magnetic fields are a consideration, could provide the basis for a standalone positioning system.

9 Acknowledgements

Many thanks go to Yvonne Rogers, Sara Price, Eric Harris and Ted Phelps of the University of Sussex and the other collaborators in the Equator Ambient Wood Project; and to Matthew Chalmers and Ian MacColl of the University of Glasgow, Anthony Steed of University College, London, and all the other participants in the Equator City Project.

We are also very grateful to the anonymous paper reviewers for their helpful comments, suggestions and references.

References

[1] P. Terrier, Q. Ladetto, B. Merminod, and Y. Schutz. Measurement of the mechanical power of walking by satellite positioning system (gps). In *Medicine and Science in Sports and Exercise*, volume 33(11), pages 1912–1918, 2001.

[2] E.M. Nebot. Sensors used for autonomous navigation. In SG Tzafestas, editor, *Advances in Intelligent Autonomous Systems*, pages 135–156. Kluwer Academic Publisher, 1999.

[3] G. P. Roston and Eric Krotkov. Dead reckoning navigation for walking robots. Technical Report CMU-RI-TR-91-27, Robotics Institute, Carnegie Mellon University, Pittsburgh, PA, November 1991.

[4] E. Foxlin and N. Durlach. An inertial head-orientation tracker with automatic drift compensation for use with hmd's. In G. Singh, S. K. Feiner, and D. Thalmann, editors, *Virtual Reality Software and Technology: Proc. of the VRST'94 Conference*, pages 159–173. World Scientific, London, 1994.

[5] G. Welch and E. Foxlin. Motion tracking: No silver bullet, but a respectable arsenal. In *IEEE Computer Graphics and Applications*, volume 22(6), pages 24–38, 2002.

[6] F.P. Brooks. Walkthrough - a dynamic graphics system for simulating virtual buildings. In *Proceedings of 1986 ACM Workshop in Interactive 3D Graphics*, pages 9–21. Chapel Hill, October 1986.

[7] M. Slater, A. Steed, and M. Usoh. The virtual treadmill: A naturalistic metaphor for navigation in immersive virtual environments. In M. Goebel, editor, *First Eurographics Workshop on Virtual Reality*, pages 71–86, 1993.

[8] T. Judd. A personal dead reckoning module. In *the Institute of Navigation's GPS Conference*, September 1997.

[9] S-W. Lee and K. Mase. Activity and location recognition using wearable sensors. *Pervasive Computing*, 1(3):24–32, July-Sept 2002.

[10] Tobias Hollerer, John V. Pavlik, and Steven Feiner. Situated documentaries: Embedding multimedia presentations in the real world. In *Proceedings of The Third International Symposium on Wearable Computers*, pages 79–86, 1999.

[11] P.H. Veltink, P. Slycke, E. Morsink, J. Hemssems, G. Bultstra, and H. Hermens. Towards automatic optimization of gait supported by a two channel implantable drop foot stimulator. In *7th Vienna International Workshop on Functional Electrical Stimulation*, September 2001.

[12] PNI Corporation. The vector-2x magnetometer. http://www.precisionnav.com/legacy/technical-information/pdf/vector-2x.pdf.

[13] Honeywell International Inc. Hmr3300 digital three-axis tilt compensated compass. http://www.ssec.honeywell.com/magnetic/datasheets/HMR32003300_manual.pdf.

[14] Silicon Sensing Systems. Crs-03 rate gyroscope. http://www.spp.co.jp/sssj/sirikon-e.html.

[15] K. Sawada, M. Okihara, and S. Nakamura. A wearable attitude measurement system using a fiber optic gyroscope. In *In Second International Symposium on Mixed Reality*, pages 35–39, March 2001.

[16] A. Schmidt, H.W. Gellersen, and M. Beigl. A wearable context-awareness component. In *Proceedings of The Third International Symposium on Wearable Computers*, pages 176–177, October 1999.

[17] C. Randell and H. Muller. The well mannered wearable computer. *Personal and Ubiquitous Computing*, pages 31–36, February 2002.

[18] Arthur D. Kuo. A simple model predicts the step length-speed relationship in human walking. In *Journal of Biomechanical Engineering*, pages 264–269, 2001.

[19] Catherine E. Bauby and Arthur D. Kuo. Active control of lateral balance in human walking. In *Journal of Biomechanics*, pages 1433–1440, 2000.

[20] B. Brown, I. MacColl, M. Chalmers, A. Galani, C. Randell, and A. Steed. Lessons from the lighthouse: Collaboration in a shared mixed reality system. In *Proceedings of CHI '2003*. ACM Press, April 2003.

[21] The equator interdisciplinary research challenge. http://www.equator.ac.uk/.