Combining Gyroscopes, Magnetic Compass and GPS for Pedestrian Navigation

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BIOGRAPHY

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ABSTRACT

The key components in 2D dead reckoning navigation are the azimuth and the distance travelled. The devices used to obtain such information vary significantly with the application. In pedestrian navigation, the limitations on weight, size and ergonomics of the devices play important roles that make the classical inertial or GPS-aided inertial approach unsuitable. To overcome these constraints, other concepts have been investigated that integrate a digital magnetic compass and/or gyroscopes, bi-axial or tri-axial accelerometers, and altimeter with a single-frequency GPS receiver. The distance travelled is computed by merging the accelerometer signal with a physiological model whose parameters are calibrated on-line by GPS data.

This paper presents the algorithms developed for pedestrian navigation as well as real-time considerations about the azimuth processing. Experience shows that the main source of error in position is associated with the azimuth determination. Two different approaches to determine the azimuth are compared: one using a magnetic compass, and the other using gyroscopes.

Magnetic sensors determine the azimuth by sensing the components of the Earth's magnetic field. However, local disturbances in the field caused by nearby permanent magnets, electric currents, or large iron bodies can dramatically affect the derived azimuth. As a consequence of this phenomenon, the determined azimuth bias changes more in relation to location than with the time elapsed since the last update. For the gyroscopes, the bias is independent from the location, but changes continuously with time. The raw signal of the compass needs to be filtered as its noise is generally high. Moreover, its character strongly depends on the sensor placement. Band limiting the signal to lower frequencies has to be done carefully in order not to filter out the actual motion. To recover the narrow-band motion frequencies between 0.5-3 Hz from the raw signal of 60 Hz, a succession of cascade filters are applied. The computed azimuth is then merged with GPS data through a Kalman filter to correct the errors. As the direction of the walk can vary in particular circumstances even if the position of the body remains unchanged, the detection of forward/backward displacements as well as side-stepping is performed.

Tests conducted in parallel show that an absolute positional accuracy better than 5 meters can be achieved and maintained with magnetic sensors even in pure dead reckoning mode. They show the advantages and drawbacks of both systems. The magnetic compass allows for long-term accuracy and repeatability as well as absolute azimuth information, but suffers from unpredictable external disturbances. Gyroscopes, on the other hand, are not sensitive to disturbances, but require external input to correct the drift and compute the absolute azimuth.

In conclusion, all the results agree that an optimal and more reliable system will be obtained by coupling both sensors. The gyroscope derived azimuth can be used to identify magnetic disturbances, while the magnetic compass can determine the bias of the gyro and the initial orientation, even when no GPS signal is available.

INTRODUCTION

At first sight, because of similar needs and objectives, pedestrian navigation might appear as a particular case of vehicle navigation. However, the walking style is very personal and may change very quickly in both speed and orientation. The classical GPS/INS approach, whereby measured accelerations are integrated twice to obtain the change in position, is not suitable for low-cost, wearable devices. Limitations apply to the weight, size and ergonomics of the device. The system must be able to determine the trajectory of a person in both presence and absence of GPS measurements. The main challenge is to maintain a good accuracy of the position even when no satellite data are available.

The increasing demand in positioning people for medical applications, GIS, fire rescue or military requires adapted technologies. New miniaturised low power Inertial Measurement Units (IMUs) coupled with satellite receivers can provide accurate position in indoor and outdoor situations. IMU are generally built to provide 3D acceleration and rotation information. The azimuth information could be provided with either a compass or a gyroscope or with a combination of both. The advantages and drawbacks of both systems are presented in Table 1 (Gabaglio et al 2001, Ladetto et al 2001).

	Advantages	Disadvantages
Magnetic compass	- absolute azimuth - long term accuracy - repeatability	- unpredictable external disturbance
Gyroscopes	- no external disturbance - short term accuracy	- drift - relative azimuth

Table 1 : comparison between compass and gyro

In order to avoid misunderstandings, the equipment carried by the person will be called Pedestrian Navigation Device (PND)

As satellite signals are not always available, the development of Dead Reckoning (DR) strategies is necessary to provide continuous positions. The nature of human walking varies greatly and is difficult to predict. These characteristics suggest the implementation of navigation models that take the physiological aspects of the walk into account. Previous studies can be found in Ladetto 2000, Perrin et al 1999.

DETERMINING THE AZIMUTH OF DISPLACEMENT OF A PERSON

Computing the correct azimuth of the displacement of a person by the mean of a carried navigation system is far from trivial. The challenge comes mainly from the complexity and freedom of movement of a human. For this purpose, one should consider the following aspects.

a. Detection of the direction of displacement

b. Filtering and de-noising the raw azimuth & angular rate data

c. Determination of the misalignment of the PND compared to the walking line of sight of the person

d. Repeatability of the trajectories

e. Application of different scenarii according to the comportment of the person (quick turn, come back…)

f. Detection of the different perturbations that affect the navigation system (bias, drift for the gyroscope, magnetic disturbances for the magnetic compass)

Depending on the placement of the measuring device on the body, the output signals to analyse can vary greatly. In this study the tri-axial accelerometers as well as the digital magnetic compass were carried on a belt at the waist level while the gyroscope was held on the thorax of the pedestrian.

a. Direction of displacement

Consequence of the complexity of the human walking behaviour, the prediction of an a priori trajectory from one point to another in free-living conditions is difficult, not to say impossible. The displacement can be influenced by various parameters such as meeting someone, stopping by a shop window, being in a hurry etc. In order to overcome these restrictions in modelling, the detection of each displacement simultaneously with its direction is necessary. A reliable solution is given by studying the physiological movements that characterize a person's walk. For example, a walking cycle can be determined as the time interval between two successive heel impacts of the same foot (Murray 1967, Cavagna et al 1966). For normal people, heel-strike marks the initial foot-floor contact. One total right walking cycle comprises one period or right stance and one period or right swing. The stance phase is that period when the foot is in contact with the floor, and the swing phase is when the foot is off the floor and moving forward to create the next step. During a walking step, the centre of mass of the body is lowered during the forward acceleration and raised during the forward deceleration. The deceleration is caused by the link between the centre of mass of the body and the point of foot contact on the ground in front of the centre of mass. It is of interest to mention that while running the centre of mass is, in contrast, lowered during the forward deceleration and raised during the forward acceleration (Cavagna et al 2000).

By detecting typical features by means of accelerometers, one can tell whether a person is walking forward, backward, left or right. To measure these motions, or to estimate gait dynamics, positional fidelity must be maintained up to 15 Hz (Antonsson et al. 1985). Figure 1 presents the patterns detected in both the antero-posterior and vertical accelerometeric signals, which allow distinguishing between a forward and backward movement. Left and right moves are characterized by similar pattern in the corresponding signals. The compass and/or the gyroscope is usually fixed to provide the azimuth of the front part of the body, that is not necessarily the direction of the walk. It is therefore necessary to correct the signal to correspond to the type of movement detected. While adding 180° to the azimuth signal in case of backward displacement appears evident, a rotation of the body can be observed during lateral moves. This additional angle, which may exceed 20°

according to the tests made, must be removed to compute the real azimuth of the displacement.

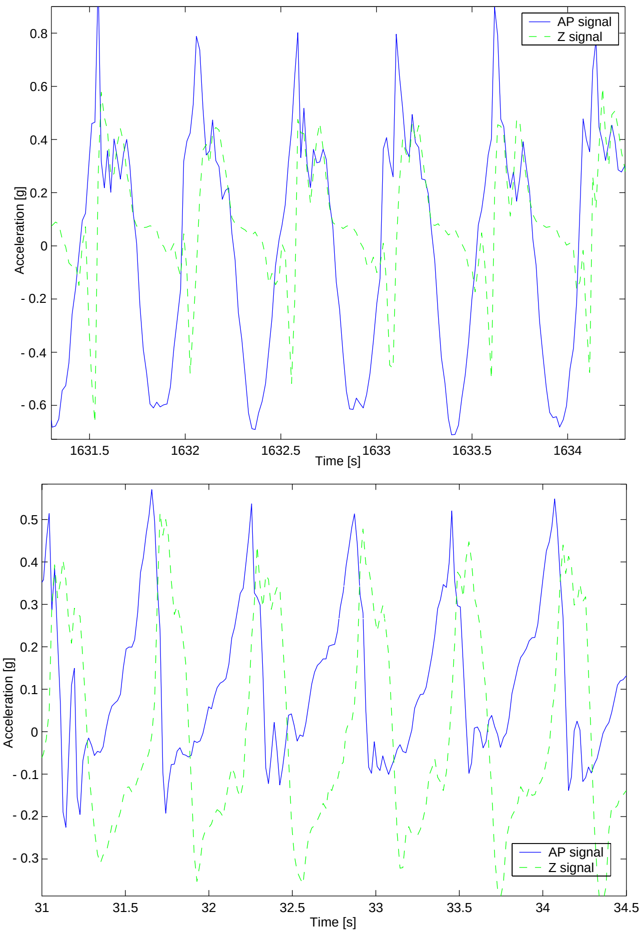

Figure 1: typical accelerometer signals expressing the accelerations obtained from a pedestrian walking respectively in a forward and backward direction.

b. 1. De-noising and filtering the azimuth signal

The main difference between a magnetic compass and a gyroscope is that a compass directly provides the azimuth signal instead of an angular rate. A direct consequence when sampling at 60 Hz is a very noisy signal. However, significant changes in azimuth can be considered as band-limited to 3 Hz. A single filter would not be appropriate to optimally smooth the azimuth signal, and a cascade of successive low-pass filters was considered to de-noise it. The different stages are illustrated in Figure 2.

1. For each step, one azimuth is computed as the average of the sampled azimuth between two successive heel impacts. At this stage, the signal is still relatively noisy.

2. Because of the dynamics of the walk, the signal may contain some fairly narrow peaks (high frequencies) corresponding to quick changes in direction. If the filter length is longer than the duration of the peaks, these will be overly smoothed, thus not reflecting the real trajectory of the person. The Savitzky-Golay filter (Orfanidis 1996) is a finite impulse response averager filter that can preserve the high frequency content of the signal at the expense of not removing as much noise as an optimal low-pass filter. This aspect can be considered as very suitable for pedestrian navigation where noise and quick direction changes can be easily mistaken. The filter used for the real time approach fits a set of 7 azimuths to a polynomial of second order. This causes a delay of 3 steps (i.e. more or less 1.5 seconds at normal speed) that is acceptable for the considered applications. If not enough data are present in the buffer to filter the azimuth in the steady state mode, then a transient Savitzky-Golay filter is applied.

3. The final smoothing step is realized with the use of a Kalman filter where the azimuth is modelled as a second order Gauss Markov process.

$$\dot{\mathbf{x}} = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & -\beta \end{bmatrix} \cdot \mathbf{x} + \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} \cdot w$$

$$z = \begin{bmatrix} 1 & 0 & 0 \end{bmatrix} \mathbf{x}$$

The process noise has been determined empirically to the value of 0.01^2 [degree^2/step]. As the azimuth degradation is not directly time dependent, the update rate is connected to the step occurrences rather than to a time period. Therefore all values will have to be coherent with this specific step unit.

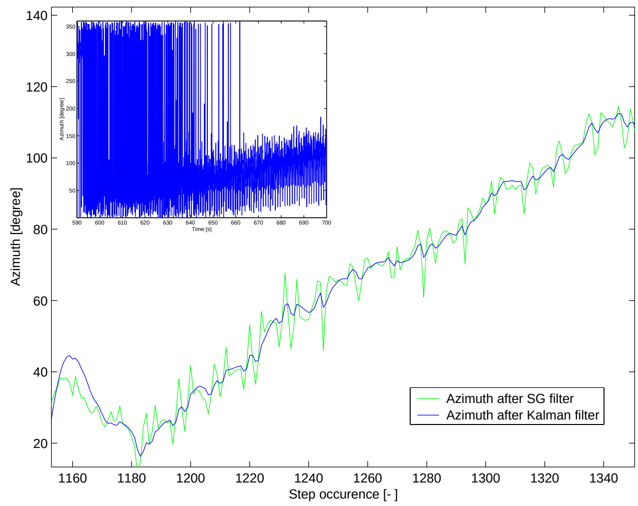

Figure 2: Different stages in the processing of the azimuth data. Compared to the original 60 Hz signal, the final filtered azimuth is much smoother but still accounts for rapid variations in the direction of the walk.

When facing a direction close to the north, the signal is frequently jumping across the 0 (or 360) degree limit. This causes an apparent additional noise that is filtered using the additional following steps. Such procedure was shown to yield better results than working with the raw azimuth itself.

1. The sine and cosine of the sampled azimuth between two successive displacements are computed.

2. Independent Savitzky-Golay filtering is performed on both signals.
3. Once the sine and cosine have been filtered, the azimuth is deduced, taking the trigonometric quadrant into account (atan2 function).
4. The final smoothing step is realized using the Kalman filter described previously.

In case of a jump across the North line, the smoothing process will result in a particular pattern of a small loop, as if a turn progressive transition from 0 to 360° had taken place.

b. 2. De-noising and filtering the angular-rate data

The gyroscope used for pedestrian navigation is fastened to the human body, in this case on the back or on the thorax. The consequence is that it oscillates vertically and horizontally during a walk (see raw signal in Figure 3). The raw data provided by the gyroscope is then a mix between:

- changes in the walking direction
- movements of the body
- noise

The de-noising and filtering process aims at separating those effects while keeping the one of main interest: the change in direction.

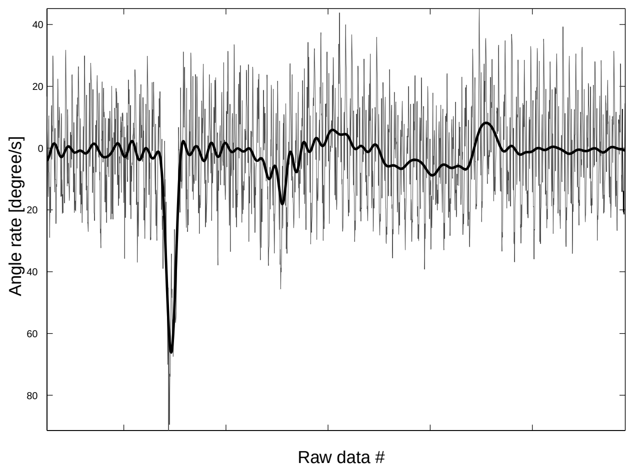

Figure 3: Gyro output signal (grey) and approximation (bold) at level 5 (symlets, 8). The raw signal shows clearly the effect of the oscillation of the trunk during the walk.

First investigations attempted at detecting turns with a gyroscope placed on a person. Two situations are critical. Very fast turns may be rejected as noise while very slow turns may be absorbed by the bias parameter. The analysis of the signal and the separation between turns and oscillations has been done by applying the wavelet transformation (Matlab, 1998). The raw signal is decomposed with a symlets wavelet (sym8) that is suitable for this type of signals. The decomposition is done up to level 5. Figure 3 illustrates the raw signal at its approximation level. The detail levels are not shown. The wavelet analysis shows that such a gyroscope, despite the oscillations, can provide the necessary information on turns.

The high frequency noise is eliminated with a low pass filter (delay less than 1 second). For the body oscillation, a band-stop filter can be applied. However the filter must be adapted when the oscillation frequency changes. It means that the frequency of the oscillation must be determined continuously. This is done thanks to the step detection: the step frequency is twice the oscillation frequency. The band-stop must stay relatively sharp to avoid eliminating or attenuating turns that occurs during just two or three steps. This adaptive stop band filter is difficult to implement and must be calibrated frequently.

When working in DR mode, the final result is not deteriorated if the oscillations are not eliminated. Indeed the orientation is computed at each step as an average of the values of the signal obtained for the left and right steps. However the oscillation is considered when combining the azimuth obtained from the gyro with an azimuth coming from another source (GPS or magnetic compass). The GPS azimuth gives the orientation of the walk while the gyro azimuth provides the body orientation. The amplitude of the oscillation can exceed 5 degrees and depends where the gyro is fastened. Its phase must be clearly known when a comparison is performed.

In practice, no band stop filter is used in DR mode. However the oscillation is eliminated when comparing the azimuth from the gyro with another one, that is, when updating the parameter of the gyro (Gabaglio, 2001b).

c. Misalignment of the PND

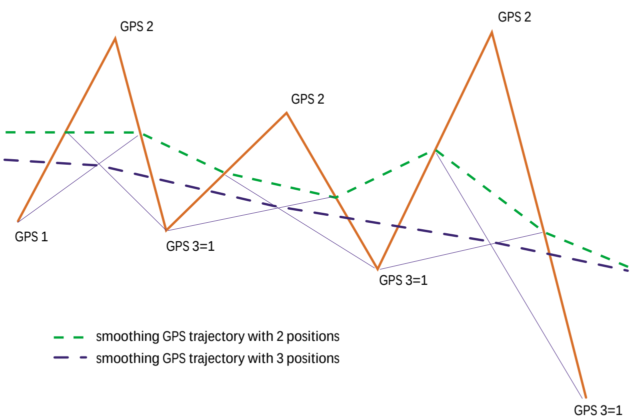

Figure 4: two different ways to smooth the GPS trajectory in order to compute a precise GPS azimuth and correct the misalignment of the PND.

As the PND is carried on the person, the azimuth measured is not generally aligned with the walking line of sight. Such bias can be determined only when GPS positions are available. In this case a comparison with the azimuth derived from the satellites data takes place continuously. No Kalman filter is used to merge the two directions, but another approach has been developed. No differential corrections are applied, hence the algorithms work only with the pseudorange navigation solutions. Errors in position may be large, and they strongly influence the azimuth. In consequence, the computed GPS heading will depend mainly on the distance between the considered positions. This error depends on the type of receiver used. Without any doubt, smoothed carrier phase solutions provide much better results than standard navigation solutions.

In order to reduce the effect of the noise in the raw GPS positions, virtual GPS positions are computed. This approach is based on the assumption whereby the navigation solutions can be considered as alternatively distributed on both side along an ideal trajectory (which may be obtained with differential carrier phase GPS). The centre of gravity of the selected points will constitute the new virtual GPS position taken into account in the computation of the azimuth as shown in Figure 4. This process can be seen as a low-pass filter. Selecting more points improves the smoothing of the trajectory but also increases the computation time as well as the delay in adaptation. Several tests indicate that averaging two successive positions already improves the azimuth determination significantly, and that working with 3 points presents a good compromise, see Figure 5.

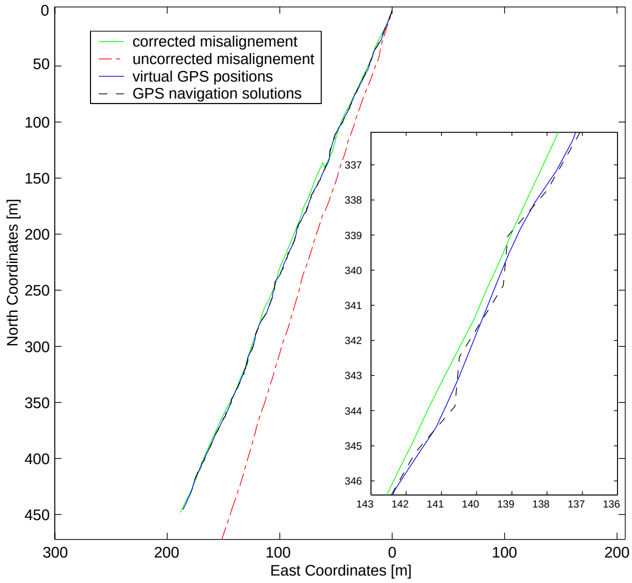

Figure 5: Comparison of the trajectories computed with and without the correction of the misalignment. The uncorrected trajectory (dashed/red) shows a constant deviation from the GPS solution. This is the typical signature of a misalignment of the device with respect to the walking line of sight.

d. Repeatability of the trajectories

One advantage of using a magnetic compass is that it senses directly the earth magnetic field vector from which the azimuth is derived. In the absence of disturbances, such vector can be considered as constant within a reasonable time span. A priori there is no need to update the bias and no drift to account for.

Unfortunately, local disturbances affect the magnetic field. Hard-magnetic perturbations are caused by permanent magnets and electrical currents, which add changes to the earth field irrespective of its strength and orientation. Soft-magnetic disturbances are caused by magnetic material distorting the earth field and are therefore dependent on the strength and position of this field. As these perturbations tend to be reasonably constant for a given environment, magnetic correction maps can be created to compensate them. If the repeatability of the trajectories is the main interest, rather than absolute positions, no particular compensation is required.

Several three kilometre walks have been realized along the same pathway but on different days. All of them, presented in Figure 6, show a similar comportment and deviation. At present, investigations are directed at mapping these disturbances, modelling them and interpolating the corrections between the calibration points. Similar research is done in geophysics for the determination of the geoid and the objective is to adapt the developed processes to fit the particularities of this application.

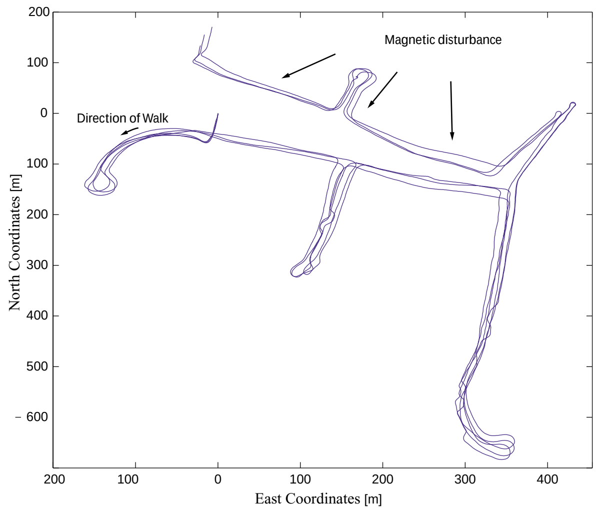

Figure 6: Walks done on three different days, always following the right edge of residential roads. Apart from small differences caused by cars parked along the way, the trajectories can be superposed easily. Between both edges of the East-West section, there is a systematic difference in the magnetic azimuth (underground power line).

e. Appropriate strategies

Like fingerprints, the way humans walk can be used to identify a person. The action of moving on foot can be schematically divided into simple components such as walking periods, turns and stops

During quick turns, the length of the stride is reduced by up to 80%. Considering the normal step length in such cases would produce a shift in the trajectory. Such a shift may be really important when doing 180° turns as can be seen in Figure 7. Therefore it is worthwhile to detect quick turns and to apply an appropriate algorithm as suggested in (Soehren et al. 2000). If the azimuth rate of change exceeds a given threshold, then a quick turn is detected. Most of the time during such turns, even if the person is walking, the centre of gravity of the body experiences no significant change in position during the turn and can be considered as immobile.

If this particular event is detected, it means that the person is retracing the own footsteps. Taking advantage of this information, the algorithm checks whether the azimuths in the forth and back trajectories are, with a difference of 180°, statistically equal. As long as no significant difference is detected and that the distance travelled on the back journey is shorter or equal to the outward one, then the azimuth and positions can be combined together. As soon as the two azimuths show discrepancies or that the distance for the return journey is exceeded, then the computed position is part of a new trajectory. Of course, if GPS positions are available, they will be integrated in the main Kalman filter to check the validity of the strategy.

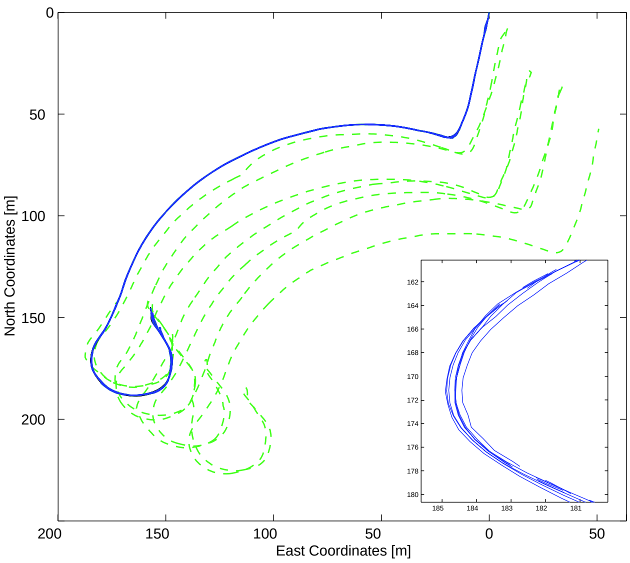

Figure 7: Trajectory with (solid line) and without (dashed line) the quick turn strategy algorithm. Over-estimated distance while turning propagates during the walk back, leading to a shift in the repeated path. Without the 180° approach, the final error in position is 60 m for a total distance of 2'430 m, i.e. 2.5% of the travelled distance, while with the 180° approach, the difference is 2.8 m, i.e. 0.1% of the total distance.

f. Detecting disturbances

As mentioned previously, the main drawback of the magnetic compass is the unpredictable perturbation of the magnetic field. On the other hand the drawback of the gyroscope (especially for the low cost ones) is that it needs frequent update of the bias with external azimuth information. However in the short term, the gyroscope can provide a measure of the change in azimuth. Then combining a gyro and a magnetic compass becomes obvious. The magnetic compass is able to provide the external azimuth to update the parameters of the gyro and the gyro can be used to detect the disturbances.

This principle is presented in the following example issued from a test conducted on a path in a perturbed area. The effect of the magnetic disturbance can be seen in Figures 8 and 9 by computing the trajectories with the two different sensors.

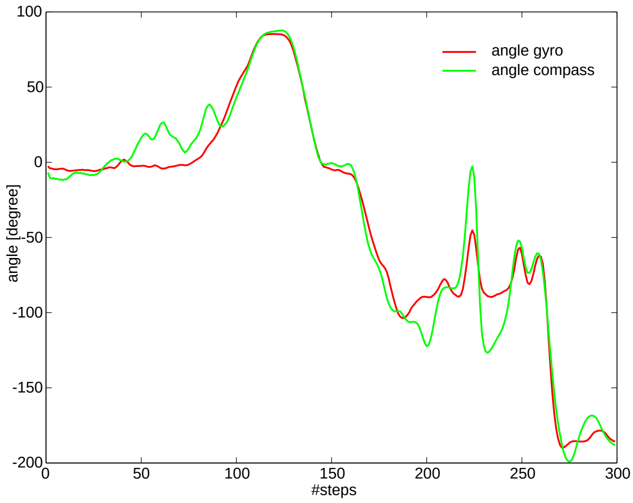

Figure 8: Comparison of the azimuths of a same trajectory computed independently using a digital magnetic compass and a gyroscope.

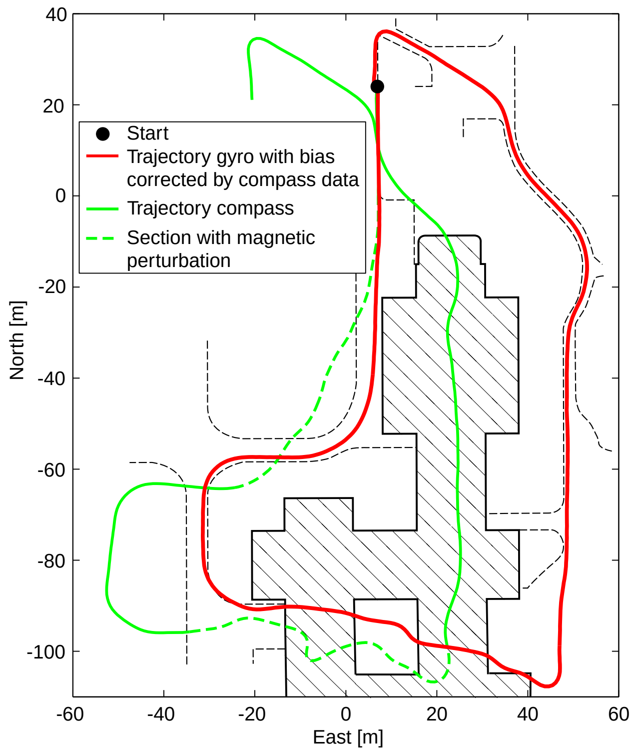

Figure 9: Superposition of two trajectories, one obtained using the compass output only (light grey/green) and the other one using both the gyroscope and the compass data. Even if the compass trajectory is out, the use of the azimuth still improves the gyroscope trajectory.

The detection of the magnetic disturbances is performed by comparing the two angular rates. For the gyro, the filtered data are considered. For the magnetic compass, the difference between two successive de-noised and filtered azimuths is divided by the time span. The difference between both signals (azimuth rate and filtered data of the gyro) is computed. Figure 10 illustrates this difference.

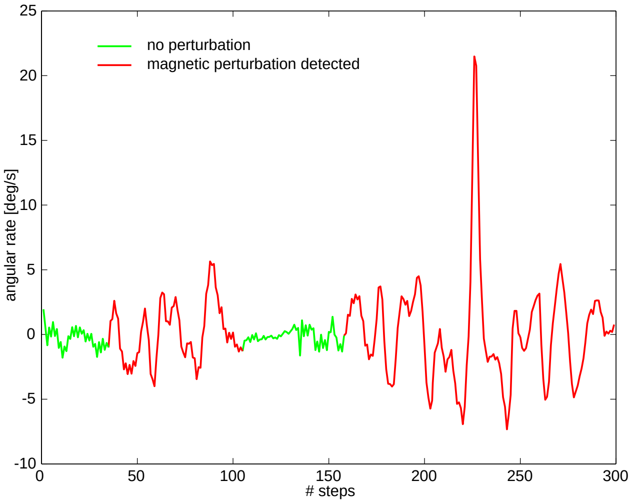

Figure 10: Differences in the angular rate of change between compass and gyroscope allow detecting magnetic perturbations.

In Figure 10 one can observe a first period of 30 steps without important disturbances. The small differences are due to small errors in the synchronisation between compass and gyro as well as different locations of the sensors on the body. A first perturbation occurs from step 30 to step 110. It is caused by the iron structure of the building and by an electrical source located close to the wall. After 40 steps without perturbation, a new perturbation occurs. The peak at step 230 is clearly identifiable in Figure 9: at coordinates (–10 East, –100 North) the two trajectories are almost orthogonal! The compass indicates a turn of 20 degree/second while the gyro does not detect such movement. This comportment is not a surprise in a passage under a building with many metallic components.

This example shows that the compass and the gyro can be efficiently combined for the detection of disturbances. If the gyro is considered only for this purpose, it is not even necessary to calibrate the bias and even a low cost gyro can be used. If the gyro is also used in the DR algorithm, then the bias and the scale factor must be included in the state vector.

For the DR algorithm two different strategies can be adopted. The first one is to consider the magnetic compass as the main tool for azimuth determination and to use the gyro to detect the disturbances and fill up these “magnetic” gaps. The second approach is to consider the gyroscope signal as the main azimuth input and to use the magnetic compass, as long as no disturbances are detected, to update the gyro parameters (bias, scale factor) as often as required.

The second approach is illustrated in Figure 11. This test takes place on an athletic track. A gyroscope and two accelerometers have been placed on the thorax of a person. The magnetic azimuths illustrated with an arrow are fictitious and are built using the stadium geometry and the travelled distance. These azimuths are considered as free of disturbances. At the beginning of the walk, neither the bias nor the scale factor are calibrated. The first magnetic azimuth provides the initial orientation.

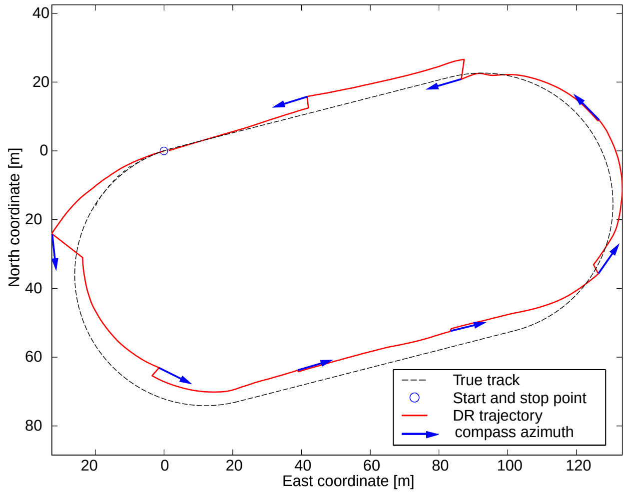

Figure 11: An azimuth provided by the magnetic compass allows to compute the initial bias of the gyro and to update its error parameters.

The combination of gyro and compass azimuth is done through a Kalman filter. The parameters of the filter are the bias the scale factor, the position and the initial orientation. At this stage, the distance is considered as errorless. The raw data of the gyro are mechanized and variance propagation is done. When the accuracy of the gyroscope azimuth reaches a chosen value (e.g. 5^{o}), the azimuth of the magnetic compass is taken as external observation for the KF and new gyro parameters are computed.

This approach permits to update the gyro parameters as well as the position even when no GPS positions are available. The Kalman filter is schematised in Figure 12.

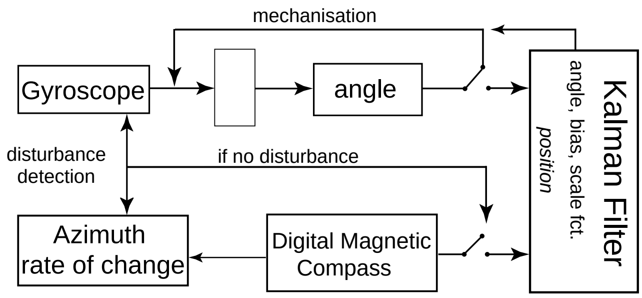

Figure 12: Schema of the Kalman filter used to update the gyroscope bias as well as the position when no GPS data are available.

A complete description can be found in Gabaglio et al 2001 and Gabaglio 2001a.

CONCLUSION

Even if the sensors used for pedestrian navigation present the same characteristics as the ones for vehicles, the way to deduce similar information is quite different. Because of the high degree of freedom when walking, the direction of the movement of a person does not always coincide with the line of sight. To correct the azimuths of the displacement, the detection of physiological patterns is used.

The high dynamics encountered does not allow strong low-pass filters. Therefore, to optimally smooth the azimuth signal without loosing crucial information, a cascade of successive low-pass filter is applied. The Savitzky-Golay filter and the symlets wavelet are applied to the magnetic compass and gyroscope outputs respectively, and they provided good solutions.

As no drift affects the compass, even if the magnetic environment is disturbed, the repeatability of the same trajectory is of interest. The magnetic compass can determine the bias of the gyro and its initial orientation. On the other hand, the gyroscope is insensible to magnetic perturbations and the derived change in azimuth can be used to identify them. Such integration allows to update the azimuth via the main Kalman filter even when no GPS signal is available.

Present and future research will focus on how to analyse both signals and get a reliable long-term DR solution, even where the magnetic field is disturbed.

ACKNOWLEDGMENTS

Part of these studies were done at the KINGNAV laboratory, Department of Geomatics, University of Calgary, Canada, thanks to a grant from the Swiss National Science Foundation held by the first author.

The second author is supported by CSEM, Centre Suisse d'Electronique et de Microtechnique SA, Neuchâtel, Switzerland.

Special thanks to Mr Jack Runyon from Locametric LLC, Virginia, for the testing and data collection as well as to Mr. Josephus van Seeters and Dr. Silvio Gnepf of Leica Geosystems for their advice.

This research is performed under a collaboration scheme financed jointly by the Swiss Government and Leica Geosystems AG.

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