DIGITAL MAGNETIC COMPASS AND GYROSCOPE FOR DISMOUNTED SOLDIER POSITION & NAVIGATION

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Abstract

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When satellite signals are available, the localisation of a pedestrian is fairly straightforward. However, in cities or indoors, dead reckoning systems are necessary. Our current research focuses on the development of algorithms for pedestrian navigation in both post-processing and real-time modes. Experience shows that the main source of error in position comes from the errors in the determination of the azimuth of walk. By coupling a magnetic compass with a low-cost gyroscope in a decentralized Kalman filter configuration, the advantage of one device can compensate the drawback of the other.
If we compare the rate of change of both signals while measuring the strength of the magnetic field, it is possible to detect and compensate magnetic disturbances. In the absence of such disturbances, the continuous measurement of the azimuth allows to estimate and compensate the bias and the scale factor of the gyroscope. The reliability of indoor and outdoor navigation improves significantly thanks to the redundancy in the information. Numerous tests conducted with different subjects and in various environments validate this approach as well as the necessity of specific hardware components dedicated to pedestrian navigation.

Introduction

The US Army has long been evolving through application of technology into a responsive, deployable, agile, versatile, lethal, survivable and sustainable force it is today. It has been recognized that epoch advances in technology applied to Army challenges take on distinct characteristics such as the less frequent paradigm shift that introduce new dimensions in capability such as the Tank or Helicopter to the more typical evolutionary development of more capable platforms such as the Abrams Main Battle Tank replacing the M-60 or the Apache Attack Helicopter replacing the Cobra. Today new concepts that integrate individual platform capability and distribute information is shaping the Army's future with the promise of ever more efficiency in prosecuting war and keeping the peace. Although the introduction of information is not new to the Army, as information dominance has long been precious to war fighters, the application of technology to integrate the forces in such a way as to enable distribution and presentation of information in a timely and easily assimilated form has been a challenge for the Army.

The Army has begun a massive transformation from a Legacy Force to an Objective Force, which incorporates and relies critically on information integration. This effort can be viewed as a paradigm shift, which captures a new dimension of warfare that integrates disparate platforms that enable the platform and commander's clearer situation awareness information. In the Army's Objective Force the dismounted soldier is envisioned as a fully integrated platform with its commensurate situation awareness and command and control capability. Implicit in the dismounted soldier's capability is his ability to self locate, send, receive and display situation and command and control information.

Dismounted soldiers have been operating in progressively more complex and hostile environments and facing increasing lethal weapons form enemy forces. Military Operations in Urban Terrain (MOUT) is one environment that small units will be required to operate. The dismounted soldier will need to incorporate several new technologies to self locate, collect, collate and convey information effectively in these applications.

The dismounted soldier's needs exceed the state of the art due to the environment they operate in and the extreme limitations on size, weight and power. Reliable and accurate situation awareness is vitally important for dismounted operations. The ability for each dismounted soldier to maintain and distribute knowledge of his position is essential to supporting reliable and accurate situation awareness. Today's dead reckoning solutions require accurate indications of occurrences (steps), precise measurement of step size, and azimuth of the step taken. Implementation of digital magnetic compass to measure azimuth of step occurrences in environments where the local magnetic field is corrupted directly impacts the accuracy of the dead reckoning solution. This

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paper addresses the benefit of adding gyro technology to the digital magnetic compass to address the magnetic anomalies expected to corrupt dead reckoning navigation systems carried by dismounted soldier's operating in urban terrain.

The application of gyro technology must consider carefully the total freedom of motion together with the type of equipment carried by the dismounted soldier, which will play a major role in the filtering of the azimuth. Sudden rotations measured by a magnetic compass can be caused either by the movement itself or by a magnetic disturbance. Intuitively, if there is a disturbance, the total value of the earth magnetic field changes too. Some examples show that this condition might be sufficient but not necessary to reliably determine a disturbance. In order to improve the reliability of the azimuth determination, a gyroscope will be used. The aim is not to navigate with a gyroscope heading only, as presented in Gabaglio (2002), but to bridge the gaps when the compass gets disturbed. Vice versa, the magnetic azimuth will contribute to determine the absolute direction of the gyroscope as well as a continuous calibration of its errors (bias and scale factor), even when no satellite signals are available. The suggested methodology takes into account the possibility of a non-aligned system. It is therefore possible to use a gyroscope having multiple tasks. Using the occurential approach (Figure 1) with the combination of such sensors has the advantage of keeping the cost relatively low compared with the classical mechanization that requires a full high grade IMU.

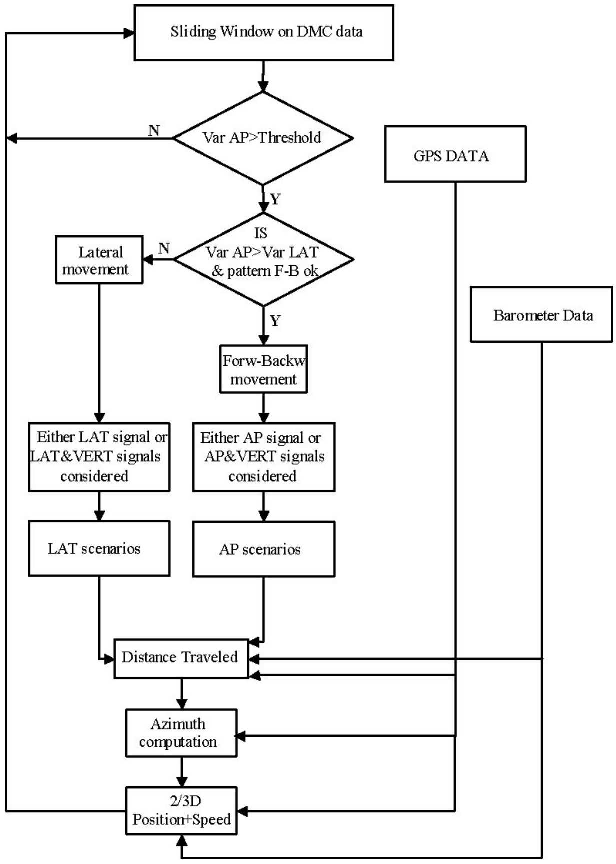

Figure 2: Flow chart of the occurrential approach considering each step occurrence instead of a double integration of the acceleration

This paper will present the different hypothesis and empirical results building the occurential approach together with a calibration procedure necessary to compensate magnetic apparent disturbances induced by human motions. The comparisons of trajectories in a non-disturbed area between the occurential and total mechanization approach are described. The identification of magnetic disturbances as well as the continuous calibration of the gyroscope errors for indoor and outdoor navigation are detailed. A reliability concept complementing the indicator of precision is introduced. Finally, we describe several test results obtained with components optimised for pedestrian navigation that together built the Pedestrian Navigation Module (PNM).

1. The occurrential approach

Like fingerprints, the profile of walk uniquely characterizes a person. If the frequency content varies so much between individuals, a general model will require a normalization procedure followed then by an adaptation to each person. The concept of normalization comes from the observation that the step frequency of unconstrained displacement is more or less equal for everybody. The speed differences are therefore a direct consequence of the stride length. The hypothesis that the step length is proportional to the height, or even better, to the leg length of the person, seems to be reasonable.

Normalizing the displacement speed of people by these parameters, it is theoretically possible to go from individual to more universal models. Each stride is however, and fortunately, not equal to a fix value. This internal step variability, by the same person and at a given frequency, is simply impossible to predict. The scope will therefore not be the precise modelling of a step *occurrence* but to reliably reproduce a travelled distance composed by a sample of steps. This approach can be expressed as followed: *For a given frequency, the step length of an individual can be considered as constant. The natural variation of the stride follows a normal distribution centred at zero and where the variance is inversely proportional to the step frequency*. This means that to a longer step will correspond a shorter one, assuming so a constant distance for a given number of step at a defined frequency. Table 1 presents the variation of the step length in function of the kind of walk.

Person	Slow [cm]	Fast [cm]	Normal [cm]
1	12	4	5
2	8	4	3
3	11	3	6
4	9	7	4
5	10	3	2
6	12	3	6
7	6	6	8
8	9	2	2
9	8	3	6
10	7	5	6
11	11	4	5
12	10	5	8
13	7	4	3
14	11	1	5
15	13	3	4

Table 1:Variation of the step size relative to different type of walk. On a 1 km track, people were asked to walk at different rhythms. The free walk took place on a 4.6 km trajectory. If the internal step length variability is similar for the normal and rapid walk, slow walking implies an important variation of the stride length. This makes it more difficult to predict

In opposition to all these intents of modeling, one should stress the almost total freedom of movement of the people as well as the direct influence of the kind of ground. Fatigue, bad training, snow in hiking conditions can make obsolete well calibrated parameters for a different environment. The adaptation of the models to fit the situation will be realized with the use of external information mainly coming from the GPS-NAVSTAR satellites constellation. Figure 2 shows the influence of the slope on the step length, simultaneously to the individuality of the approach towards changes in the terrain.

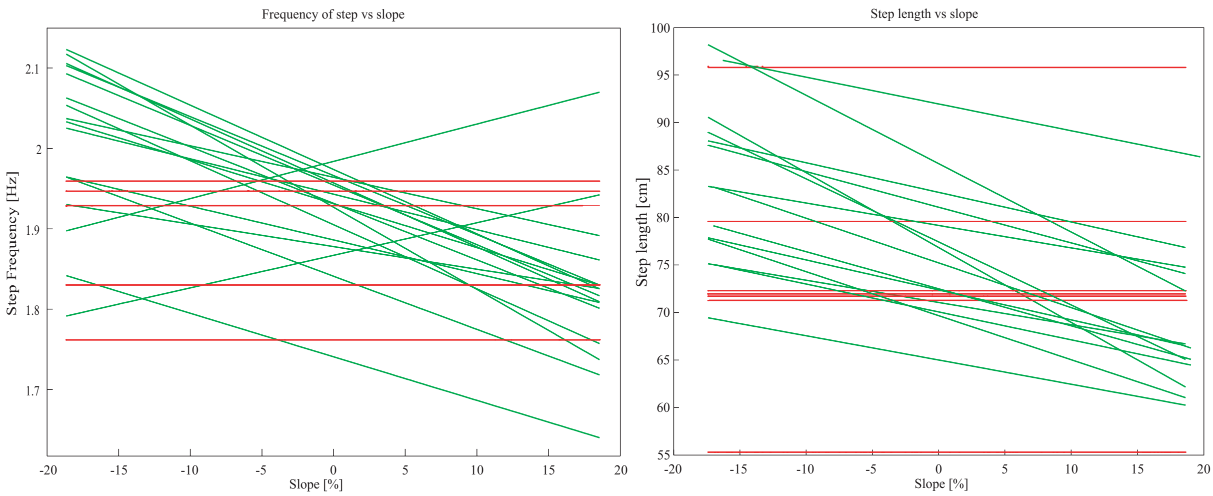

Figure 2: The influence of the slope on the step frequency (up) and the step length (down). More than every other parameter, the fitness of a person influences these parameters in the short time. The augmentation of the step frequency/length by people expresses the tentative to maintain a constant speed independently of the slope. This is generally observed to fit people who walk or run regularly. Others tend to maintain a constant frequency and/or step length (red) independently of the environment.

1.1 Morphology of the steps to improve the detection of the movements.

Also most of the time people are walking in the forward direction, given applications need to detect backwards displacement as well as sidestepping (Figure 3). This is done by directly analysing the pattern of the tri-dimensional acceleration signals. Several movements of interest were discretized in order to get a dictionary of patterns to match (Steiner 2002, Ladetto 2002). As the measuring unit is held fix to the body, corrections to the measured azimuth of walk will then be applied according to the displacement, as shown in Figure 4. The step model used to compute the distance is also specific to the kind of movement detected.

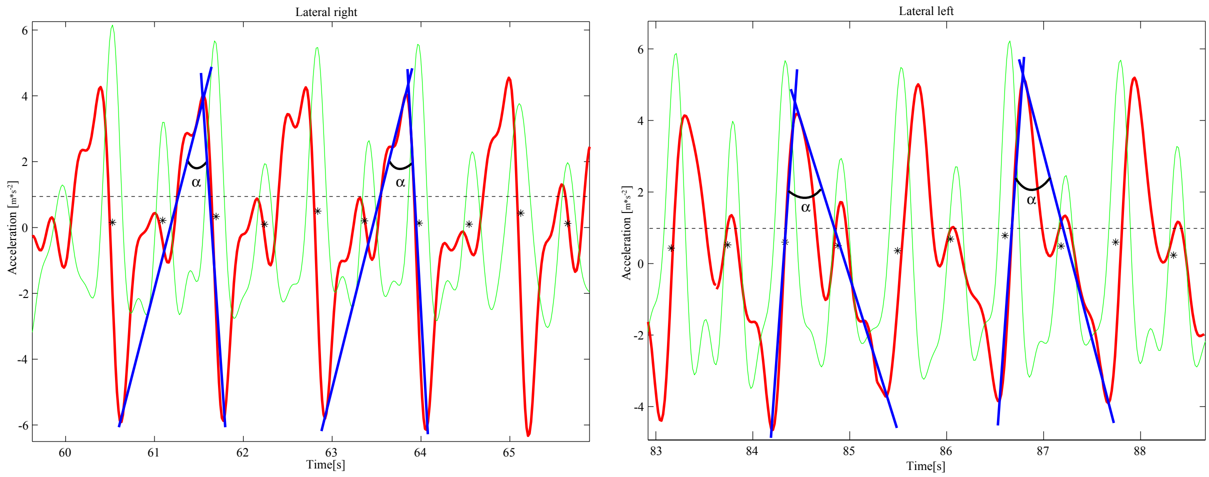

Figure 3: Detection of the sidestepping displacement analysing the pre-filtered lateral acceleration. According to the value of the angle α, it is possible to identify if the person is going left or right. The stars represent the values for each step of the Antero-Posterior acceleration divided by the Lateral acceleration.

2. Compass Navigation: errors, disturbances and solutions

The magnetic azimuth is the horizontal component of the Earth magnetic field. Its determination requires implicitly the knowledge of the horizontal or vertical plane. This is commonly done by sensing the gravity vector at rest. To compute then the azimuth of walk, one has to constantly compute the attitude of the sensor in order to correct the measured magnetic values. Using the 3D rotation matrix with the Yaw(ψ)-Pitch(φ)-Roll(θ) sequence, the horizontal components H_y and H_x are

$$H_x = b_x \cos\varphi + b_y \sin\varphi \sin\Theta + b_z \sin\varphi \cos\Theta \quad (2.1)$$
$$H_y = b_y \cos\Theta - b_z \sin\Theta \quad (2.2)$$

where b_i are the components measured by the sensor.

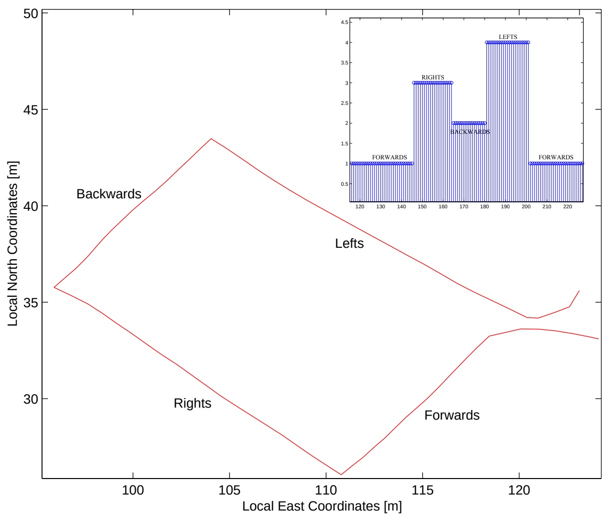

Figure 4: Trajectory realized walking in the 4 directions. All the steps were correctly detected and given an appropriate indicator in order to correct the azimuth accordingly. The error in closing is 1.2 m for a trajectory of 62 m (1.9 % of the distance travelled).

The azimuth derived from these values will contain and propagate the errors present in the attitude angles themselves. According to the first order Taylor development of the azimuth computation, this uncertainty becomes

$$\alpha + \Delta\alpha = \arctan(\frac{-H_y}{H_x}) + \frac{\partial(\arctan(\frac{-H_y}{H_x}))}{\partial H_y}\Delta H_y + \frac{\partial(\arctan(\frac{-H_y}{H_x}))}{\partial H_x}\Delta H_x \quad (2.3)$$

Simplifying (1.3) and taking into account that

$$H_e = H_h \begin{bmatrix} \cos\alpha \\ -\sin\alpha \\ \tan\delta \end{bmatrix}$$ where δ is the inclination of the magnetic vector and H_h the horizontal magnetic field (2.4)

The error produced can be written as

$$\Delta\alpha = -\Delta\theta \cdot \tan\delta \cdot \cos\alpha - \Delta\varphi \cdot \tan\delta \cdot \sin\alpha \quad (2.5)$$

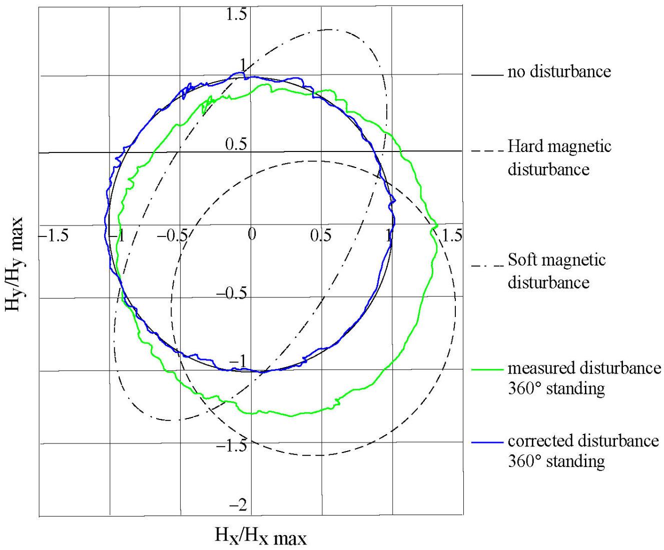

Figure 5: Description of the different effect of magnetic disturbances. The result of the simplified procedure adapted for pedestrian navigation corrects the disturbances caused by clothes and accessories.

This relation shows that the error in determining the attitude angles affects directly the azimuth and its effect strongly depends on the azimuth itself. The same errors will have different effects according to the latitude of displacement. This can be understood considering that the higher the latitude, the weaker the measured horizontal field. Therefore, the secondary component induced by the attitude errors will have a more important influence. For mid-latitude, the average value of 2 for $\tan\delta$ can be considered. A complete theoretical description can be found in Denne (1979).

Independently to these errors, disturbances, divided into *soft* and *hard* categories will affect the Earth magnetic field in the three dimensions of the space. A rigorous approach would require the determination of 12 parameters at known elevations, which, considering the previous remark, would also be affected by some errors. A simplified approach (Caruso 1997) consisting of determining only the corrections in the horizontal plane is more convenient considering also that the pedestrian navigation system is worn by a person at the belt level. The four parameters are two scale factors (X_{sf} Y_{sf}) and two translations (X_0, Y_0). Applying the corrections to the projected magnetic values, the components of equation (1.3) become

$$H_x = X_{sf} \cdot H_{xmes} + X_0 \text{ and } H_y = Y_{sf} \cdot H_{ymes} + Y_0 \quad (2.6)$$

The result of the calibration procedure to determine the disturbances caused by the clothes and accessories of a person is illustrate in Figure 5.
While this static procedure already takes into account an important part of the azimuth error, a second dynamic calibration will be necessary to compensate the individual errors occasioned by walking. Low-pass filtering the additional accelerations eliminates the typical oscillations in walking. If the computed pitch and roll values reflect the movements done by the hips, virtual values have to be defined to compensate the displacement effects on the horizontal plane. These additional constant corrections have no physical meaning but reflect the individual characteristics of a walk and the symmetry between left and right strides. Figure 6 shows the effects of the different calibration phases and their additional effects for a 400 m track on an Olympic stadium. The lower parts show the pitch and roll computed step by step from the filtered accelerations. The optimal constant values are 1.48° for the pitch and 4.92 for the roll angles. Without any calibration process, these values are impossible to retrieve from the data, as shown in the bottom part of Figure 6.

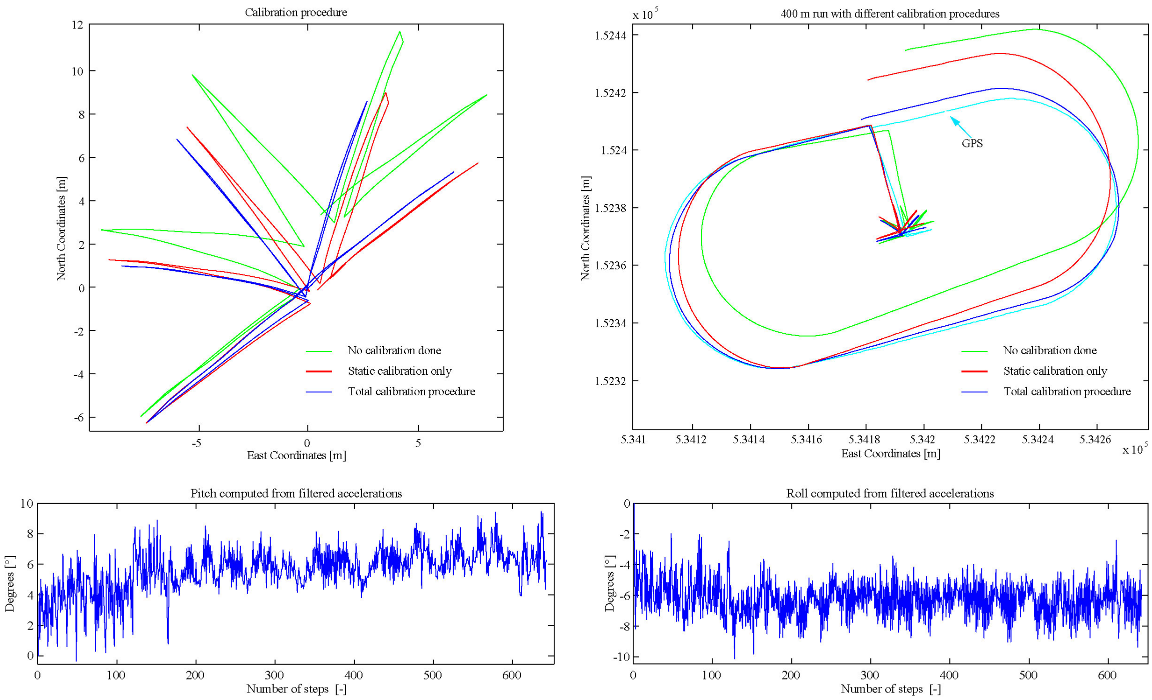

Figure 6: Effects of the different and complementary calibration phases (up). The pitch and roll angle values computed directly from the filtered acceleration don't provide the optimal attitude values to find the horizontal projection plane (down).

3. Occurential vs. total mechanization approach

In order to test this approach versus a golden standard, trajectories were covered using two different devices (Figure 7). The measurement procedure as well as the data integration are completely different (Gillet et al. 2000). The reference path is computed with the POS/LS^{TM} system of Applanix by double integration of the 3D acceleration vector coupled with a triad of gyroscopes. The measurement frequency was set to 200 Hz. In order to keep an optimal precision and avoid any divergence, Zero Velocity Updates (ZUPT) were performed every 1 or two minutes for less than 10 seconds. After an alignment procedure between 5 and 10 minutes, the strict respect of such procedure allows maintaining accuracy at a decimetre, even centimetre, level over several kilometres. As this system only measures effective displacements, the results are independent of the type of ground and environment.

Figure 7: Right, the POS/LS^{TM} (Position and Orientation System for Land Survey) system of Applanix for high precision surveying.) Left, Pedestrian Navigation System (PNM) developed together with Leica Vectronix. With a size of 74.7 mm x 48.3 mm x 18 mm and a weight inferior to 50 grams, it fulfills all ergonomic requirements for such application.

The different tests, realised in standard conditions, show the limits in precision as well as in reliability between *navigation* and *surveying,* see Figure 8. If the maximal difference remained always below the 10 m, it cannot be improved with the occurential approach and therefore its performance does not meet surveying requirements. On counterpart, the necessary repeated stops for the ZUPTs, are very constraining for navigation, showing simultaneously the functional limits of such approach. Future research will focus on the integration and complementarities of both approaches.

4. Handling magnetic disturbances

Once walking, magnetic disturbances have an important influence on the quality of the azimuth signal. These are sometimes identifiable thanks to the magnetic field itself, however, the simultaneous use of a gyroscope provides a heading, even in sensible areas.

4.1 Optimising the magnetic information

The Earth magnetic field can be considered as constant within the area normally covered by a pedestrian. All sudden variations of this field may be interpreted as disturbances. Unfortunately, when someone is moving, the environment causes small random variations. If low-pass filter and the occurential approach take care of the majority of these fluctuations, the determination of a threshold is indispensable. Ideally this should be determined in a magnetically neutral area. This stage being unfortunately too constraining, the value of 3µT has been empirically defined as threshold for the root mean square of the magnetic field during three steps. Passed this value, the last good azimuth is held constant until the field variation becomes stable again. The error introduced with such a simplification is directly associated with the sinuosity of the path during the disturbed period. As the effect of a disturbance decreases with the square (even the cube) of the distance from the source, most effects are visible only over tens of meters. Considering that people walk straight sections, especially in a built environment, this approach provides a much better result than considering indistinctively disturbed and undisturbed azimuths.

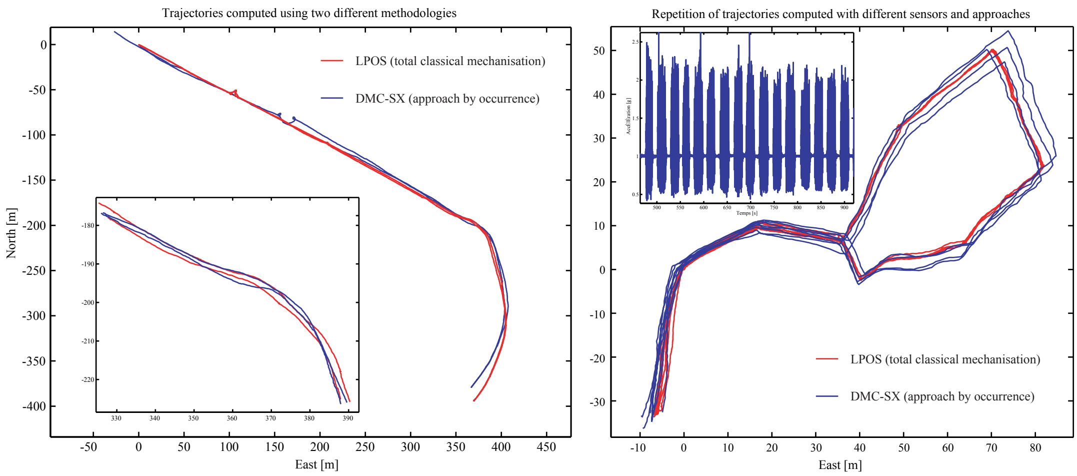

Figure 8: Comparison of the trajectories obtained with the two LPOS and PNM approaches. On the left, a rectilinear return walk of 1'331.5 m. The end-loop position error computed by the occurential approach is 21.4 m (1.6 %) and -6.4 m on the travelled distance. On the right, the repetitions of the same trajectory (304.8 m) show the perfect reproducibility of the classical approach. On 4 trials with the occurential approach, the dispersion on the travelled distance is 7.8 m (from 299.4 m to 307.2 m), that is an error of 2 cm/step. The inserted box presents the vertical accelerations bringing to the fore the frequent ZUPTS (10 s each 30 s).

4.2 Using gyroscope

Although the gyroscopic azimuth is broadly used in dead reckoning navigation, the intention here is to use it only as a back up system in definite situations when the compass is confused, Figure 11, or during quick turns. The exclusive use of the gyroscope during these periods, even if they are reasonably short (one to two minutes maximum) requires its permanent and complete calibration. Therefore bias and scale factor are continuously up-dated by the compass data or/and with GPS data when the signal is available. The use of non-aligned sensors forces the gyroscope angles to conform to the compass. In a second time only, the misalignment value towards the direction of walk can be defined if given absolute directions are known or if satellites signals are present.

Numerous tests (Moix 2002) using a low cost directional gyroscope, Figure 9, have shown a scale factor error of 1%. For 90° turn, keeping the scale factor to unity would cause an error of 0.9°. That matches the precision of the azimuth obtained from the compass. Therefore, the parameter of a scale factor will be neglected under the hypothesis that the gyroscope is set perpendicularly to the plane of movement. However, the bias determination is of major importance and requires an initialisation phase before each run. This is done while standing or by walking along a line, important being that the gyroscope doesn't sense any angular velocity (Earth rate neglected). The simplified model is the following:

Figure 9: The latest prototype also integrates a gyroscope, necessary for indoor navigation as well as navigating in magnetically disturbed areas.

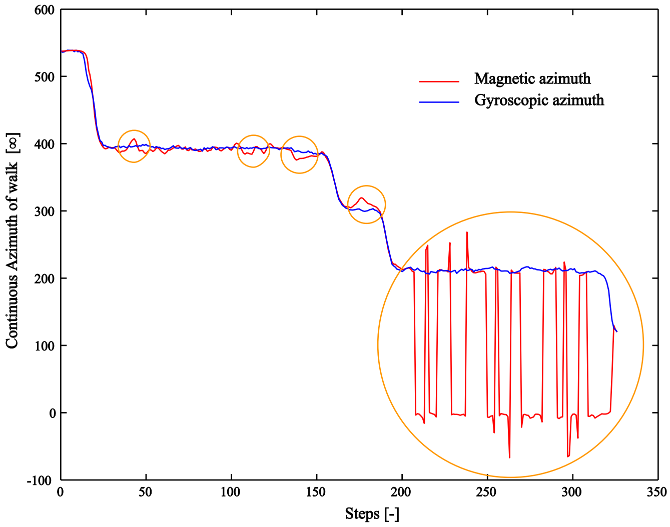

Figure 10 : Comparison of the continuous azimuth of walk computed from both, compass and gyroscope. This shows in evidence the magnetic disturbances and the important effect they can have, if not-detected, on the computation of the azimuth

$$\check{\omega}_i = \omega_i - b_i + \varepsilon_i \tag{4.1}$$

where $\check{\omega}_i$ is the true angular velocity value, ω_i the measured angular velocity value, b_i the instantaneous bias and ε_i a zero mean white noise affecting the measurements.

If we consider the azimuth to be fix during the interval we can write:

$$\varphi^{gyro}_{begin} - \varphi^{gyro}_{end} = \sum_{i=1}^{n}(b_i)\cdot\Delta t \tag{4.2}$$

where n is the number of time interval considered and Δt is the time interval itself (here 1/30 s). If we assume that the bias is constant during this initial phase, its value can be approximated by:

$$\bar{b} = \frac{1}{n}\cdot\sum_{i=1}^{n} b_i = \frac{\varphi^{gyro}_{begin} - \varphi^{gyro}_{end}}{\Delta T} \tag{4.3}$$

where $\Delta T = n \cdot \Delta t$. As long as no magnetic disturbance is detected, this value $\bar{b}$ is continuously updated. As the value of the bias varies with time, an estimation of the error of both azimuths in required. Magnetic disturbances are continuously checked to avoid bias update and use of the compass information during these periods, Figure10.

Figure 11 : Indoor navigation: In presence of strong magnetic disturbances caused by apparent iron pillars and reinforcement, the trajectory using compass only (red) provides fancy results. The solution integrating gyroscope and compass azimuth is more stable and fits the real trajectory even in small details, allowing the identification of the room in which the pedestrian stepped in (blue).

4.4. Unweighted bias update and error propagation

Considering the azimuth of the compass as true, the bias will be computed bringing the gyroscope heading on the compass azimuth. At the update, this is expressed by:

$$\varphi_{j+1}^{gyro} = \varphi_{j}^{compass} + \sum_{i=j}^{j+1} (\omega_i - b_j) \cdot \Delta t = \varphi_{j}^{gyro} + \sum_{i=j}^{j+1} (\omega_i - b_j) \cdot \Delta t \qquad (4.4)$$

where *j* represents the epoch of bias update. Such modelisation requires a constant bias between updates. This is unfortunately not the case but considering the short time between updates, such assumption can be made. The azimuth of the compass can also be written as:

$$\varphi_{j+1}^{compass} = \varphi_{j}^{compass} + \sum_{i=j}^{j+1} (\omega_i - b_i) \cdot \Delta t \qquad (4.5)$$

where $b_i = b_j + \Delta b_i$ and Δb_i is the bias increment by unit of time *i*. Subtracting (4.5) from (4.4), the average bias correction is

$$\overline{\Delta b}_{j+1} = \frac{1}{n} \sum_{i=j}^{j+1} \Delta b_i = \frac{\varphi_{j+1}^{gyro} - \varphi_{j+1}^{compass}}{\Delta T} \quad [°/s] \qquad (4.6)$$

with $\Delta T = n \cdot \Delta t = t_{j+1} - t_j$. By correcting simultaneously the bias $b_{j+1} = b_j + \overline{\Delta b}_{j+1}$, the azimuth of the gyroscope becomes

$$\varphi_{j+1}^{gyro*} = \varphi_{j}^{gyro*} + \sum_{i=j}^{j+1} (\omega_i - b_{j+1}) \cdot \Delta t = \varphi_{j+1}^{gyro} - \overline{\Delta b}_{j+1} \cdot \Delta T \qquad (4.7)$$

Logically, an error on the bias will influence the error on the gyroscopic azimuth. The evolution of this value is computed applying the error propagation to (4.6)

$$\sigma_b^2 = \sigma_{\Delta b}^2 = \frac{\sigma_{\varphi^{compass}}^2 + \sigma_{\varphi^{gyro}}^2}{\Delta T^2} \qquad (4.8)$$

As $\sigma_{\varphi^{gyro}}^2$ is dependent of the precision of the bias, both errors are not independent. In order to remedy to this problem, the equation (4.8) allows writing

$$\overline{\Delta b}_{j+1} = \frac{1}{n} \sum_{i=j}^{j+1} \Delta b_i = \frac{\varphi_{j}^{compass} - \varphi_{j+1}^{compass}}{\Delta T} + \overline{\omega}_i - b_j \quad \text{i.e.} \quad b_{j+1} = \frac{\varphi_{j}^{compass} - \varphi_{j+1}^{compass}}{\Delta T} + \overline{\omega}_i \qquad (4.9)$$

The variance on the bias is

$$\sigma_b{}^2 = \frac{2 \cdot \sigma_{\varphi^{compass}}^2}{\Delta T^2} + \frac{1}{n} \cdot \sigma_\omega^2 \qquad (4.10)$$

that leads to the variance on the gyroscopic azimuth itself

$$\sigma^2{}_{\varphi_{j+m}^{GYRO}} = \sigma_{\varphi^{compass}}^2 + m \cdot \Delta t^2 \cdot \sigma_\omega^2 + m^2 \cdot \Delta t^2 \cdot \sigma_b^2 \qquad (4.11)$$

m is the number of samples since the last update. At this stage, the assumption of the constancy of the bias can influence the results. The larger the *m* value becomes, the greater the influence of the bias drift on the azimuth. The maximal time interval is directly related to the quality of gyroscope used. In the given conditions, tests show that pure gyroscope dead reckoning is achievable up to a time interval of 120 seconds.
As the magnetic azimuth is not perfect, it should not be considered as true in the updating process. A weighting of its value can be obtained with the use of either an exponential or a Kalman filter.

4.4. Weighted bias update and error propagation

Using an exponential filter has the advantage of taking into account an evolution of the bias without forgetting its past values. This can be seen as a security in environments where undetected magnetic disturbances could influence its value. The updated bias can be expressed as

$$b^*_{j+1} = (1-\alpha)\, b_{j+1} + \alpha\, b^*_j \tag{4.12}$$

where the parameter α regulates the influence of the new measurement on the bias value.
The expression (4.7) becomes

$$\varphi^{gyro*}_{j+1} = \varphi^{gyro*}_{j} + \sum_{i=j}^{j+1} (\omega_i - b^*_{j+1}) \cdot \Delta t \tag{4.13}$$

The gyroscopic azimuth is corrected by the value

$$\Delta\varphi^{gyro*}_{j+1} = \varphi^{gyro*}_{j+1} - \varphi^{gyro}_{j+1} = (\alpha - 1) \cdot \Delta T \cdot \overline{\Delta b}_{j+1} \tag{4.14}$$

Applying the law of variance propagation to (4.12)

$$b^*_j = \alpha^j b_0 + \sum_{i=1}^{j+1} \alpha^{(j-i)} \cdot (1-\alpha)\, b_i \tag{4.15}$$

Assuming a constant time interval between the updates as well as a white noise on the average value of the measured angular velocities, the variance on the bias is

$$\sigma^2_{b^*_j} = \frac{2 \cdot (1-\alpha)^2}{\Delta T^2} \cdot \left(\sum_{i=0}^{j+1} (-\alpha)^i \right) \sigma^2_{\varphi^{compass}} + \alpha^{2j} \cdot \sigma^2_{b_0} \tag{4.16}$$

Considering (4.14) the variance of the azimuth given by the gyroscope becomes

$$\sigma^2_{\varphi^{gyro*}_{j+m}} = \sigma^2_{b_0} \left(\Delta T^2 \left(\sum_{i=1}^{j} (\alpha^i) \right)^2 + m^2 \Delta t^2 \alpha^j \right) + \sigma^2_{\varphi^{compass}} \left(2\sum_{i=1}^{2j} (-\alpha)^i + 1 + \frac{2m^2 \Delta t^2 (1-\alpha)^2}{\Delta T^2} \sum_{i=0}^{j+1} (-\alpha)^i \right) \tag{4.17}$$

4.5. Update of the bias using a Kalman filter

A commonly used approach to integrate different sources of information is a Kalman filter, as described in Gelb (1971). The parameters considered are the gyroscope bias and the azimuth. The bias is modelled as a first order Markov process (Ladetto et al 2001) that leads for the equations of movement to

$$\begin{pmatrix} d\dot{\varphi}_k \\ d\dot{b}_k \end{pmatrix} = \begin{pmatrix} 0 & -1 \\ 0 & -\beta \end{pmatrix} \cdot \begin{pmatrix} d\varphi_k \\ db_k \end{pmatrix} + \begin{pmatrix} 1 \\ a \end{pmatrix} w \tag{4.18}$$

Here, the increment *k* represents a step occurrence and not a time interval. The values of 0.05 for *a* and 0.05 [^{o2}/s] for the spectral density of the driving noise have been empirically determined for the employed gyro.

Figure 12 presents the two different methods of integration with their precision. The initial value of 3° takes into account that residual magnetic disturbances might have not been identified during the bias determination. This value is empirical and reflects the precision one can expect in such application. The differences between the two approaches are very small and, in the majority of the tests done, inferior to the precision of the compass. The main distinction is in the precision of the gyroscopic azimuth. In the exponential filtering, the precision becomes weaker from one update to the next, because the uncertainty in the previous biases is maintained present thanks to the factor α. The opposite is observed with the Kalman filter, where the gain matrix tends to become smaller and smaller, thus trusting the model. The uncertainty in the prediction must be artificially increased in order to prevent the gain from reaching zero, which would result in ignoring any new measurement. Even if the exponential approach doesn't converge, it fits the reality better than the Kalman filter. The magnetic field may

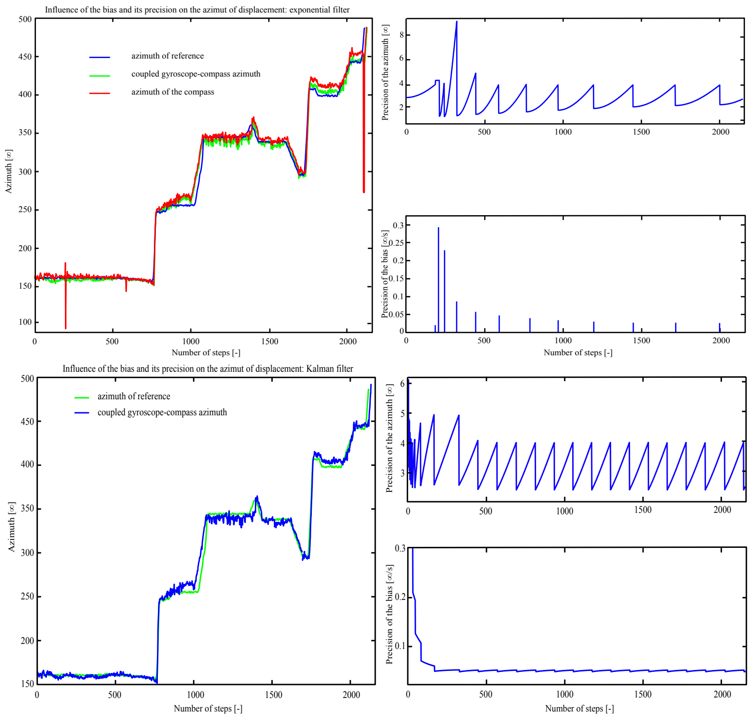

Figure 12: Update of the bias of the gyroscope using the two different approaches and their consequence on the precision of the gyroscope azimuth. In the Kalman filter, the frequent updates of the beginning result from by the hypothesis of an unknown bias (precision of 100°). The threshold for the updates is set to 4°.

present undetectable disturbances. When the bias updates are done using the compass data only, the imprecision of the gyroscope azimuth also augments with time. The presence of satellite signals improves the precision of the updates, as with the Kalman filter.

5. Altitude: the third component

The continuous knowledge of the altitude opens not only possibilities for a tri-dimensional positioning but also for physiological and energetical analysis. The trajectory in planimetry is also improved by considering the cosine of the slope for the projection of the different part of the journey.

In pedestrian navigation, three main actors will occasion altitude changes. Each of them has its own particularity that allows identification.

1. **slopes**: small or large, the vertical change will be regular and continuous
2. **stairs**: present a gradient in altimetry of +/- 1 m for every 5 steps.
3. **elevators**: no detection of movement is seen on the accelerometers but the barometer sense the changes in pressure.

As for planimetry, relative information is more precise than the absolute one and GPS or known altitude updates are necessary. The resolution of the barometer can be improved by an appropriate treatment of the pressure. As 0.1 mb represents more or less 1 m in height, oscillations between two altitudes, only caused by the sensor resolution, are very common, even on flat ground. A temporal filter takes into consideration the possibility and probability of the 3 kinds of movement described previously before applying different treatment following the situation. An exponential filter is applied afterwards in the case of slopes and elevators. This allows having continuous changes more precise than the resolution of the sensor itself. In the stairs situation, the step height is mainly normalised (between 16.25 cm and 19.6 cm in Switzerland). Progressive altitude change is modelled as soon as the action is detected. Figure 13 presents two different indoor and outdoor situations where altitude is computed specifically to the detected situation.

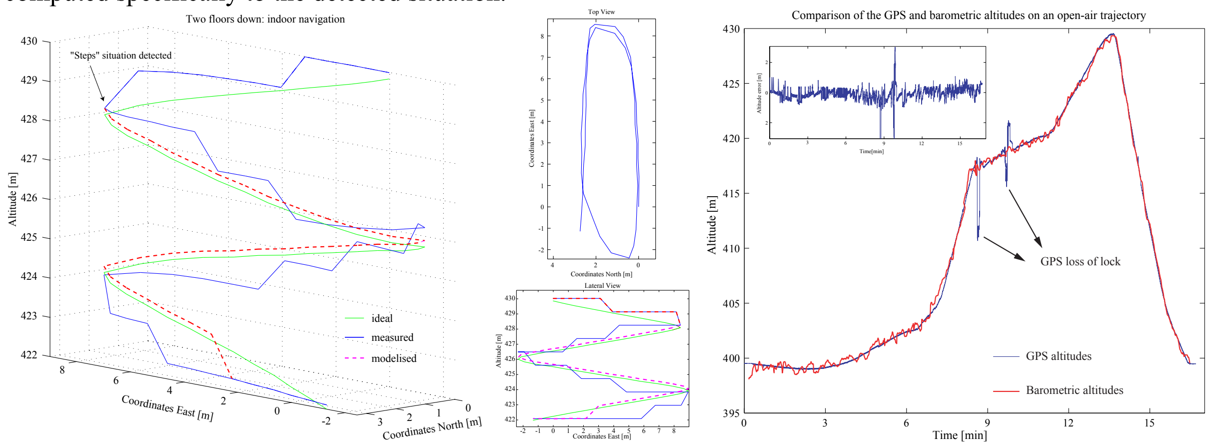

Figure 13 : (left) 3-D representation of downward walking for a stair scenario inside a building. The altitude change of 7.8 m is modeled here after filtering the pression by 7.28 m. The improvement of the sensor resolution is possible here thanks to the detection of the situation and an appropriate pressure treatment. (right) Comparison of GPS and barometric altitudes for an outdoor trajectory. No update of the barometric altitude is done, showing the absence of short-term drift for this solution. The average difference is 0.71 m with a maximum to 2.1 m, ignoring the part of the track where a loss of lock occurred and a re-acquisition of the GPS signal degrade the altitude.

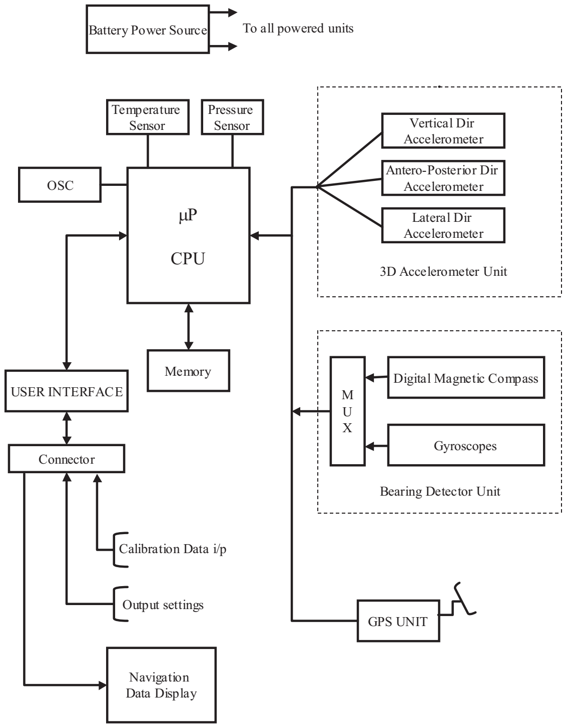

Figure 14: Schematic representation of the Pedestrian Navigation Module (PNM). The different sensors work in parallel at a frequency that can be individually chosen in function of the specificity of the application.

6. Reliability concept in pedestrian navigation

The concept of reliability used mainly to predict industrial process failures has been introduced in geodesy by Baarda (1968) and can be adapted to the particularity of pedestrian navigation. The integration of various measurements from several sensors allows, because of the redundancy in the information, the detection of a bad calibration as well as mistakes and systematic errors in the models. The developed Pedestrian Navigation Module (PNM) offers in different forms: 3 azimuths (compass - gyroscope - GPS), 2 altitudes (barometer - GPS), 2 travelled distances (dead reckoning - GPS). Figure 14 presents the structure of the PNM.

The indicators should take into account the degradation of precision (spatial or temporal) depending on the chosen technologies. Accuracy and reliability are theoretically well distinct notions, and the evolution of the first one does not necessarily affect the second. If this is true for well-defined models, generally fixed and constant in time, such statement in the context of walk, is less categorical. The precision of the compass may be so bad in magnetically disturbed areas, that its reliability can be questionned. A similar conclusion can be deduced for a gyroscope azimuth after a long time without bias control. Two indicators will be set to reflect the situation in which the azimuths and positions are computed.

6.1. The first indicator expresses the part of redundancy of the information. This represents the degree of certitude of one observation against the presence of an error. This notion is called the **redundancy number**. For the azimuth, compass, gyroscope (and GPS), provide orientations that control one-another. The considered values are shown in Table 2. The given percentages take the different filtering stages into account. For example, even if the gyroscopic azimuth cannot be relied on because of a too long time without bias update, the angular velocity data helps to validate or invalidate the magnetic azimuth. A similar argument can be applied to the other measurements.

Value	Situation of computation of the azimuth
0 %	Magnetic disturbances / Long period without any gyroscope bias update
25 %	Magnetic disturbances / Recent bias update of the gyroscope
50 %	Area magnetically stable / Long period without any gyroscope bias update
75 %	Area magnetically stable / Recent bias update of the gyroscope
+25 %	Add to each case if a GPS azimuth was computed

Table 2: Empirical weighting of the different scenarios allowing the computation of the azimuth of walk

6.2. The second indicator is closer to its geodetic use. It presents the effect on the coordinates of the biggest non-detected error in the different observations. The term of **external reliability** is commonly used. In the given application, only the indicator relative to the azimuth of walk presents a real meaning. As magnetic disturbances are detected using an empirical threshold, each disturbance inferior to this value will induce an error. The latter will propagate on the East and North components according to the azimuth of walk as presented in Figure 15. An imprecision in the bias will also cause cumulated errors that are difficult to identify over a short time period.

It is important to mention that in pure dead reckoning mode, one single non-detected disturbed area could have important consequences on the following positions. Without any absolute update, the error will tend to remain constant for the trajectory. The measured path after the disturbances is parallel to the true one at a distance that is proportional to the number of steps done during the disturbed period. The use of satellite signals allows bounding the influence of such an error. Therefore, the time interval between two GPS positions will influence the external reliability of the system.

Indicator of reliability	Value	Situation of computation of the position
	0 %	No satellite available
Altimetry: 50 %	50 %	Altitude measured by barometer, calibrated at a known point
	50 %	Calibrated step model
Planimetry: 50 %	50 %	Compass valid but no recent update of the gyroscope bias

Table 3: Typical solution provided by the Pedestrian Navigation System in Dead Reckoning mode. The notion of time will be present for the altimetry. If no update can take place within a given interval, the reliability indicator falls to 0 to account for possible atmospheric variation will not permit to give a reliable absolute altitude.

The use of these two indicators is already present inside the algorithms for navigation, mainly with the use of numerous plausibility tests. However, an indicator is computed with the cumuli of the percentages according to a conditional logic. Its value doesn't have any precise mathematical meaning but allows for an intuitive assessment of the computed coordinates. As it is common in geodesy, planimetry and altimetry are separated. Table 3 shows a typical solution provided by the PNM during a dead reckoning period.

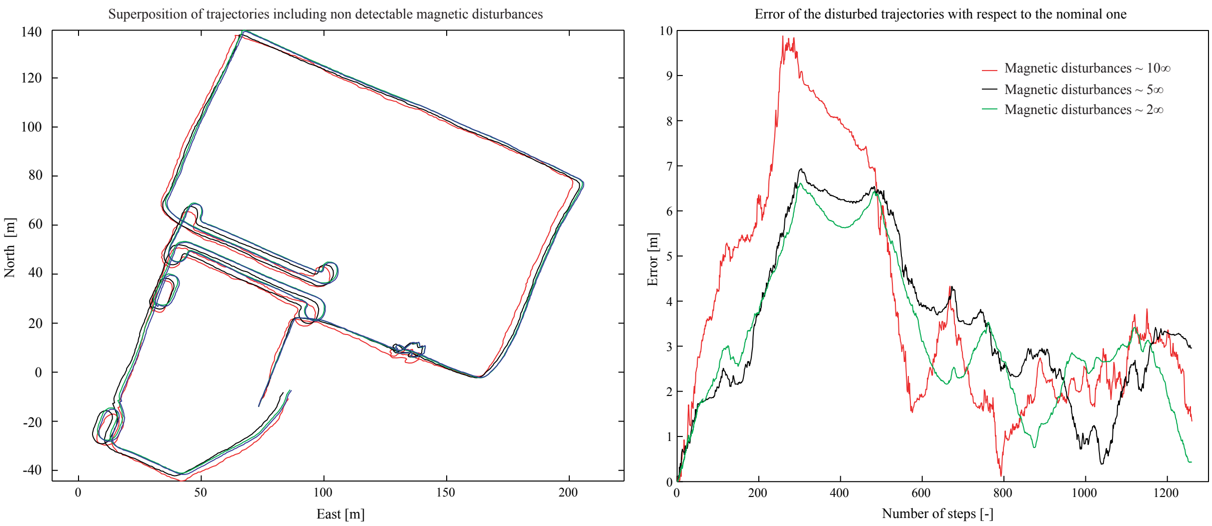

Figure 15: Representation of the notion of internal reliability. As the thresholds are empirically fixed for the determination of a magnetic disturbance, the non-detected disturbances will induce errors in positions. Disturbances from 2° to 10° have been introduced in the measurements. Superior disturbances are detected. It is of interest to mention that in general, the considered error in position is inferior to the precision of the so-called GPS navigation solution.

7. Specific GPS antenna for Pedestrian Navigation

If the tuning of the GPS receiver needs to be done to match the specific dynamic of pedestrian navigation, the antenna will play a major role in the computation of a fix. As the majority of antennas available on the market are done for car navigation, they all take advantage of the metal structure (ground plane) of the car to improve the reception of the satellite signals. As this structure is not available on a person, the efficiency of such antennas is generally strongly reduced. In order to remedy to this aspect, the PNM uses a specific antenna designed especially for pedestrian navigation. Figure 16 & Figure 17 present a true example of the GPS availability downtown a city using 3 different antenna technologies and the necessity of DR capabilities for a reliable continuous positioning. As pedestrians mainly walk on sidewalks, more than 50% of the sky is totally obstructed by buildings and requires therefore the use of every available GPS signal, even the weakest ones as presented in Table 4.

Antenna	Number of Satellites Used		
	min	average	max
Patch (commercial)	0	2	6
Helicoïdal	0	3	8
Linear	0	5	9

Table 4: Number of satellites used for computations of fixes all around the trajectory.

Figure 16: : Left : Trajectory downtown Lausanne with simultaneously 3 GPS receivers from u-blox AG, Switzerland, using 3 different antennas. In blue, a commercial patch antenna, in red a special helicoïdal antenna made by Sarantel Ltd (UK) and in green a specific linear antenna developed by Vendôme Technologies (France). Right: The author during the tests, wearing two PNMs (in the front and in the back) as well as two single GPS receivers.

Figure 17: Left: This specific GPS antenna for pedestrian navigation has been developed by Vendôme Technolgies (France). It is a miniaturized plate antenna with controlled impedance. Its characteristics allow remaining in the frequency workspace, even when the central frequency is shifted because of the presence of the human body or other disturbing objects. For the testing purposes, the antenna has been adapted and coupled with a modified 20dB amplifier from Sarantel Ltd (UK). Right: Continuous and unique representation of the Figure 13 trajectory output by the PNM. Only 5 GPS positions were used during the whole run to calibrate the different models and bound the statistical error.

Conclusion

This paper shows the achievable precision and reliability of the occurential, stride-dependent, approach that replaces the temporal, double integration, evolution. The development of a Pedestrian Navigation System based mainly on a digital magnetic compass was tested against the 3D inertial navigation. In non-magnetically disturbed areas, the results are close to each other and errors in position are below 10 meters. The addition of a gyroscope helps bridging the gaps when the compass is strongly disturbed and improves the reliability of the system. No operational ZUPTs constraint is required by the approach. The analytic error propagation of the gyroscope bias and its consequence on the azimuth determination are described. Two indicators on reliability are presented, providing information about the quality of the computed position.

The numerous tests realised prove the validity of the concept and of the PNM for a navigation system. They also stressed the necessity to tune the GPS receiver as well as the improvement in position that can be achieved by selecting application dedicated GPS antenna.

Dismounted Soldier Navigation/Positioning requirements appear to be inversely proportional to the availability of conventional navigation solutions, i.e., the more sever the environment the less likely currently relied upon navigation aids will be available. One of the most critical positioning requirements is expected for dismounted soldiers within buildings. In building operation typically implies poor GPS reliability and degradation associated with multi-path problems for ranging systems. A desire to locate and distribute position information for small dismounted soldier units to enable reliable situational awareness to determination of each soldier's location not only to indicate what floor and what room but to the ability to tell which side of the wall the soldier is on is a most challenging requirement. Integrating gyro technology with a digital magnetic compass begins to address the magnetic anomalies corrupting digital magnetic based dead reckoning systems inside buildings, urban areas, and in close combat with Armour and Mechanized vehicles and thus improving the positioning performance.

In combat there is strength in Situational Awareness – when dismounted soldiers are in difficult environments Dead Reckoning Navigation enables Situational Awareness!

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