DIGITAL MAGNETIC COMPASS AND GYROSCOPE INTEGRATION
FOR PEDESTRIAN NAVIGATION

Q. Ladetto*, B. Merminod**
Faculté ENAC - Institut du Développement Territorial, Geodetic Laboratory (TOPO)
CH-1015 Lausanne, Switzerland.
WWW: http://topo.epfl.ch
E-mail: quentin.ladetto@epfl.ch

Abstract

Keywords: Pedestrian Navigation, Dead Reckoning, Magnetic Compass, Gyroscope

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.

Introduction

A nice aspect of human walking is the freedom of motion. The worst hypothesis in modelling human trajectories is precisely this liberty of movements. Such aspect 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 factual approach 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 1).

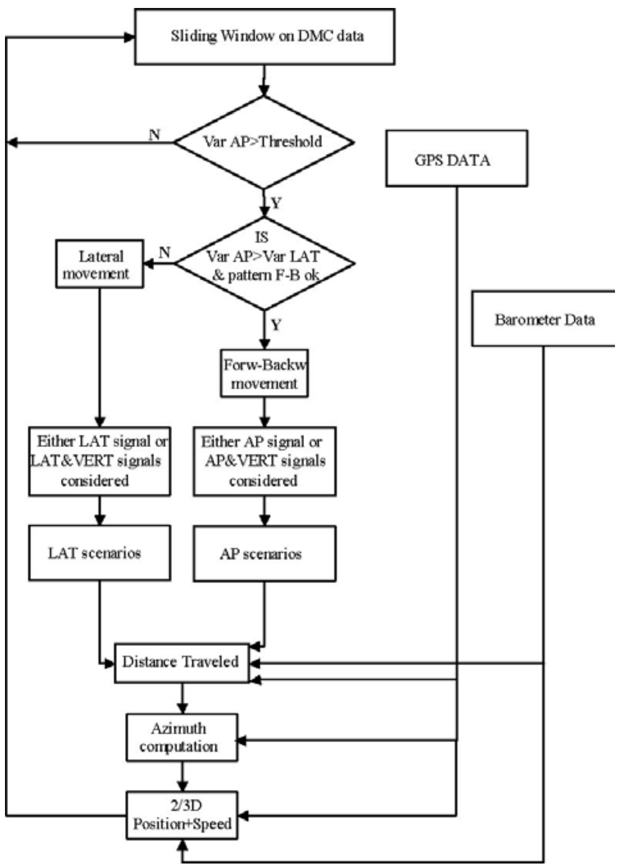

Figure 1: Flow chart of the factual approach considering each step occurrence instead of a double integration of the acceleration

This paper will present a calibration procedure necessary to compensate magnetic apparent

* PhD Student, Research Scientist
** Professor, Head of Laboratory

disturbances induced by human motions. The comparisons of trajectories in a non-disturbed area between the factual 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. Finally, a reliability concept complementing the indicator of precision is presented.

1. 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

$$H_x = b_x \cos\varphi + b_y \sin\varphi \sin\Theta + b_z \sin\varphi \cos\Theta \tag{1.1}$$
$$H_y = b_y \cos\Theta - b_z \sin\Theta \tag{1.2}$$

where b_i are the components measured by the sensor. 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

$$\alpha + \Delta\alpha = \arctan\left(\frac{-H_y}{H_x}\right) + \frac{\partial\left(-\arctan\left(\frac{H_y}{H_x}\right)\right)}{\partial H_y}\Delta H_y + \frac{\partial\left(-\arctan\left(\frac{H_y}{H_x}\right)\right)}{\partial H_x}\Delta H_x \tag{1.3}$$

Simplifying (1.3) and taking into account that

$$H_e = H_h \begin{bmatrix} \cos\alpha \\ -\sin\alpha \\ \tan\delta \end{bmatrix} \text{ where } \delta \text{ is the inclination of the magnetic vector} \tag{1.4}$$

The error produced can be written as

$$\Delta\alpha = -\Delta\theta \cdot \tan\delta \cdot \cos\alpha - \Delta\varphi \cdot \tan\delta \cdot \sin\alpha \tag{1.5}$$

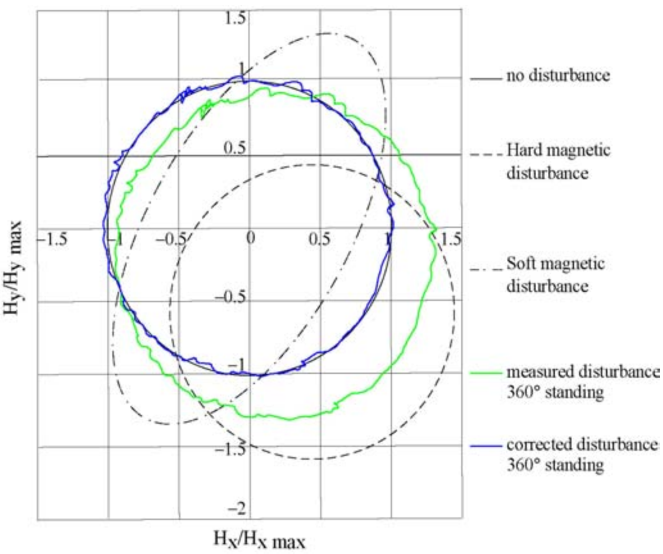

Figure 2: Description of the different effect of magnetic disturbances. The result of the simplified procedure adapted for pedestrian navigation corrects the disturbances caused by clothes and accessories.

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

$$H_x = X_{sf} \cdot H_{xmes} + X_0 \text{ and } H_y = Y_{sf} \cdot H_{ymes} + Y_0 \quad (1.6)$$

The result of the calibration procedure to determine the disturbances caused by the clothes and accessories of a person is illustrate in Figure 2.
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 3 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 3.92 for the roll angles. Without any calibration process, these values are impossible to retrieve from the data.

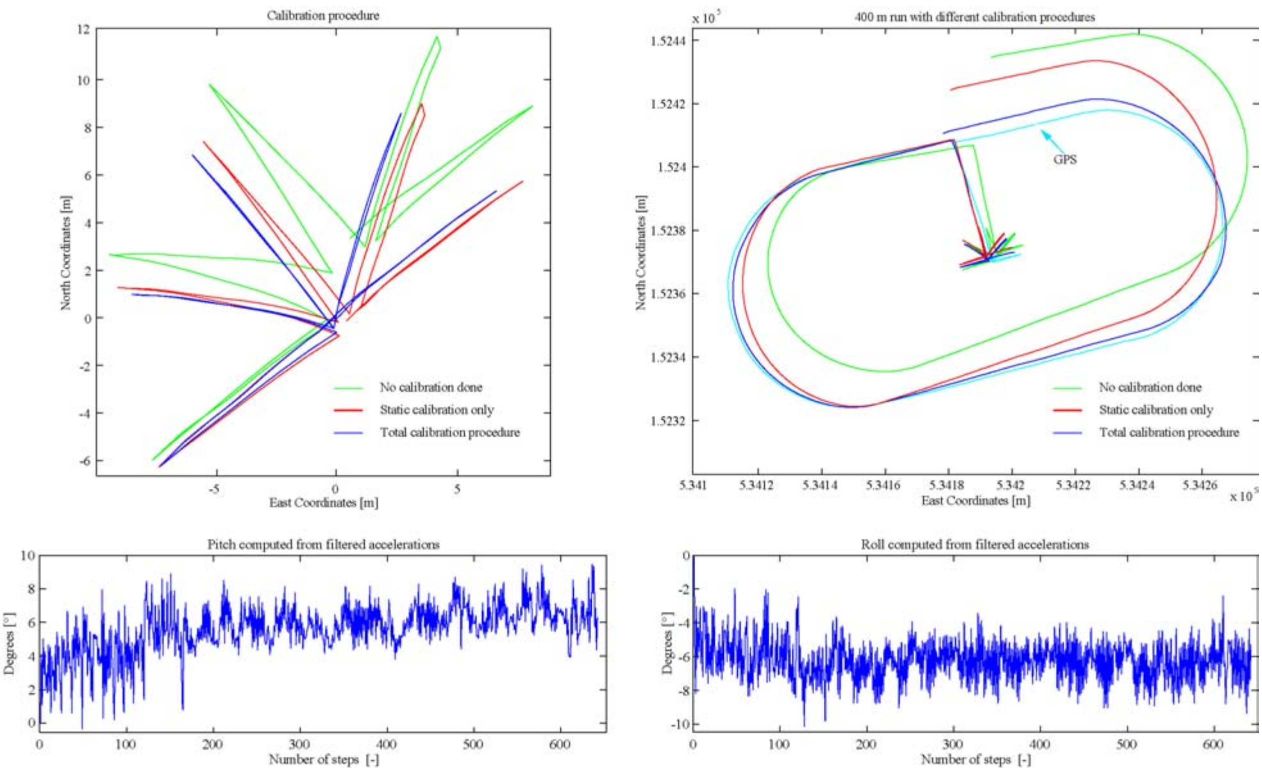

Figure 3: Effects of the different and complementary calibration phases (up). The pitch and roll angle values computed directly from the filtered acceleration don't provide the optimal attitude values to find the horizontal projection plane (down).

2. Factual vs. total mechanization approach

In order to test this approach versus a golden standard, trajectories were covered using two different devices (Figure 4). The measurement procedure as well as the data integration are completely different. 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 during 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.

The different tests, realised in standard conditions, show the limits in precision as well as in reliability between *navigation* and *surveying,* see Figure 5. If the maximal difference remained always below the 10 m, it cannot be improved with the factual 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.

Figure 4: Pedestrian Navigation System (PNS) (left) developed together with Leica Vectronix. With a size of 73.7 mm x 48.3 mm x 18 mm and a weight inferior to 50 grams, it fulfills all ergonomic requirements for such application. Right, the POS/LS^{TM} (Position and Orientation System for Land Survey) system of Applanix for high precision surveying.

3. 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.

3.1 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 factual 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.

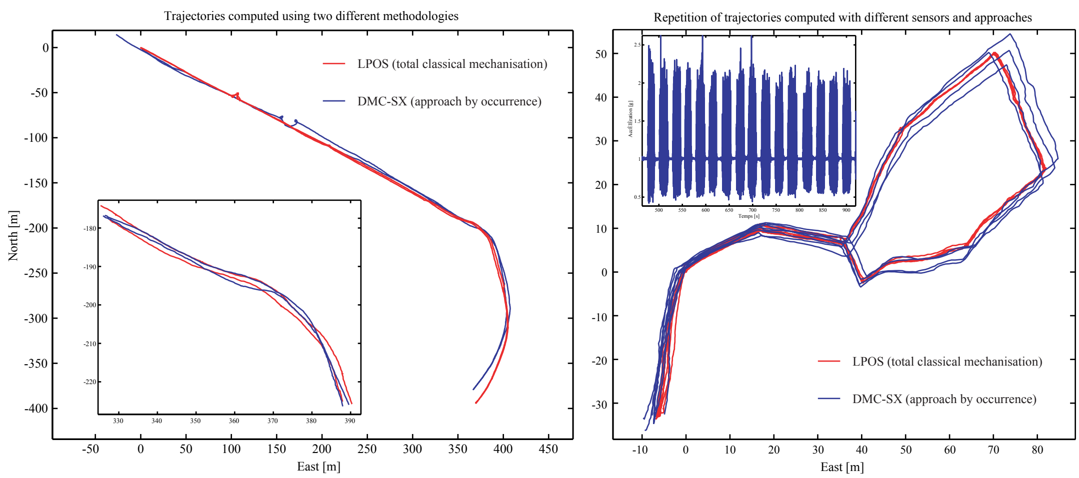

Figure 5: Comparison of the trajectories obtained with the two LPOS and PNS approaches. On the left, a rectilinear return walk of 1'331.5 m. The end-loop position error computed by the factual approach is 21.4 m (1.6 %) and -6.4 m on the travelled distance. On the right, the repetitions of the same trajectory (304.8 m) show the perfect reproducibility of the classical approach. On 4 trials with the factual 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).

3.2 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 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 with 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 vertical gyroscope 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

$$\check{\omega}_i = \omega_i - b_i + \varepsilon_i \tag{3.2}$$

where $\check{\omega}_i$ is the true value, ω_i the measured value and ε_i a white noise affecting the measurements.

If we consider the azimuth we can write:

$$\varphi_{begin}^{gyro} - \varphi_{end}^{gyro} = \sum_{i=1}^{n} (b_i) \cdot \Delta t \tag{3.4}$$

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:

$$\bar{b} = \frac{1}{n} \cdot \sum_{i=1}^{n} b_i = \frac{\varphi_{begin}^{gyro} - \varphi_{end}^{gyro}}{\Delta T} \tag{3.5}$$

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.

3.3. 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:

$$\varphi_{j+1}^{gyro} = \varphi_{j}^{compass} + \sum_{i=j}^{j+1} (\omega_i - b_j) \cdot \Delta t = \varphi_{j}^{gyro} + \sum_{i=j}^{j+1} (\omega_i - b_j) \cdot \Delta t \tag{3.6}$$

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:

$$\varphi_{j+1}^{compass} = \varphi_{j}^{compass} + \sum_{i=j}^{j+1} (\omega_i - b_i) \cdot \Delta t \tag{3.7}$$

where $b_i = b_j + \Delta b_i$ and Δb_i is the bias increment by unit of time i. Subtracting (3.7) from (3.6), the average bias correction is

$$\overline{\Delta b}_{j+1} = \frac{1}{n} \sum_{i=j}^{j+1} \Delta b_i = \frac{\varphi_{j+1}^{gyro} - \varphi_{j+1}^{compass}}{\Delta T} \ [°/s] \tag{3.8}$$

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

$$\varphi_{j+1}^{gyro*} = \varphi_j^{gyro*} + \sum_{i=j}^{j+1} (\omega_i - b_{j+1}) \cdot \Delta t = \varphi_{j+1}^{gyro} - \overline{\Delta b}_{j+1} \cdot \Delta T \tag{3.9}$$

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 (3.8)

$$\sigma_b^2 = \sigma_{\Delta b}^2 = \frac{\sigma^2_{\varphi^{compass}} + \sigma^2_{\varphi^{gyro}}}{\Delta T^2} \tag{3.10}$$

As $\sigma^2_{\varphi^{gyro}}$ is dependent of the precision of the bias, both errors are not independent. In order to remedy to this problem, the equation (3.8) allows to write

$$\overline{\Delta b}_{j+1} = \frac{1}{n} \sum_{i=j}^{j+1} \Delta b_i = \frac{\varphi_j^{compass} - \varphi_{j+1}^{compass}}{\Delta T} + \overline{\omega}_i - b_j \quad \text{i.e. } b_{j+1} = \frac{\varphi_j^{compass} - \varphi_{j+1}^{compass}}{\Delta T} + \overline{\omega}_i \tag{3.11}$$

The variance on the bias is

$$\sigma_b{}^2 = \frac{2 \cdot \sigma^2_{\varphi^{compass}}}{\Delta T^2} + \frac{1}{n} \cdot \sigma_\omega^2 \tag{3.12}$$

that leads to the variance on the gyroscopic azimuth itself

$$\sigma^2{}_{\varphi_{j+m}^{GYRO}} = \sigma^2_{\varphi^{compass}} + m \cdot \Delta t^2 \cdot \sigma_\omega^2 + m^2 \cdot \Delta t^2 \cdot \sigma_b^2 \tag{3.13}$$

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.

3.4. 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

$$b_{j+1}^* = (1-\alpha)\, b_{j+1} + \alpha\, b_j^* \tag{3.14}$$

where the parameter α regulates the influence of the new measurement on the bias value.
The expression (3.9) becomes

$$\varphi_{j+1}^{gyro*} = \varphi_j^{gyro*} + \sum_{i=j}^{j+1} (\omega_i - b_{j+1}^*) \cdot \Delta t \tag{3.15}$$

The gyroscopic azimuth is corrected by the value

$$\Delta\varphi_{j+1}^{gyro*} = \varphi_{j+1}^{gyro*} - \varphi_{j+1}^{gyro} = (\alpha - 1) \cdot \Delta T \cdot \overline{\Delta b}_{j+1} \tag{3.16}$$

Applying the law of variance propagation to (3.14)

$$b_j^* = \alpha^j b_0 + \sum_{i=1}^{j+1} \alpha^{(j-i)} \cdot (1-\alpha)\, b_i \tag{3.17}$$

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

$$\sigma^2_{b_j^*} = \frac{2\cdot(1-\alpha)^2}{\Delta T^2} \cdot \left(\sum_{i=0}^{j+1} (-\alpha)^i \right) \sigma^2_{\varphi^{\text{compass}}} + \alpha^{2j} \cdot \sigma^2_{b_0} \tag{3.18}$$

Considering (3.16) the variance of the azimuth given by the gyroscope becomes

$$\sigma^2_{\varphi^{\text{gyro*}}_{j+m}} = \sigma^2_{b_0} \left(\Delta T^2 \left(\sum_{i=1}^{j} (\alpha^i) \right)^2 + m^2 \Delta t^2 \alpha^j \right) + \sigma^2_{\varphi^{\text{compass}}} \left(2 \sum_{i=1}^{2j} (-\alpha)^i + 1 + \frac{2m^2 \Delta t^2 (1-\alpha)^2}{\Delta T^2} \sum_{i=0}^{j+1} (-\alpha)^i \right) \tag{3.19}$$

3.5. 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

$$\begin{pmatrix} d\dot{\varphi}_k \\ d\dot{b}_k \end{pmatrix} = \begin{pmatrix} 0 & -1 \\ 0 & -\beta \end{pmatrix} \cdot \begin{pmatrix} d\varphi_k \\ db_k \end{pmatrix} + \begin{pmatrix} 1 \\ a \end{pmatrix} w \tag{3.20}$$

Here, the increment k represents a step occurrence and not a time interval. The values of 0.05 for a and 0.05 [$°^2$/s] for the spectral density of the driving noise have been empirically determined for the employed gyro.

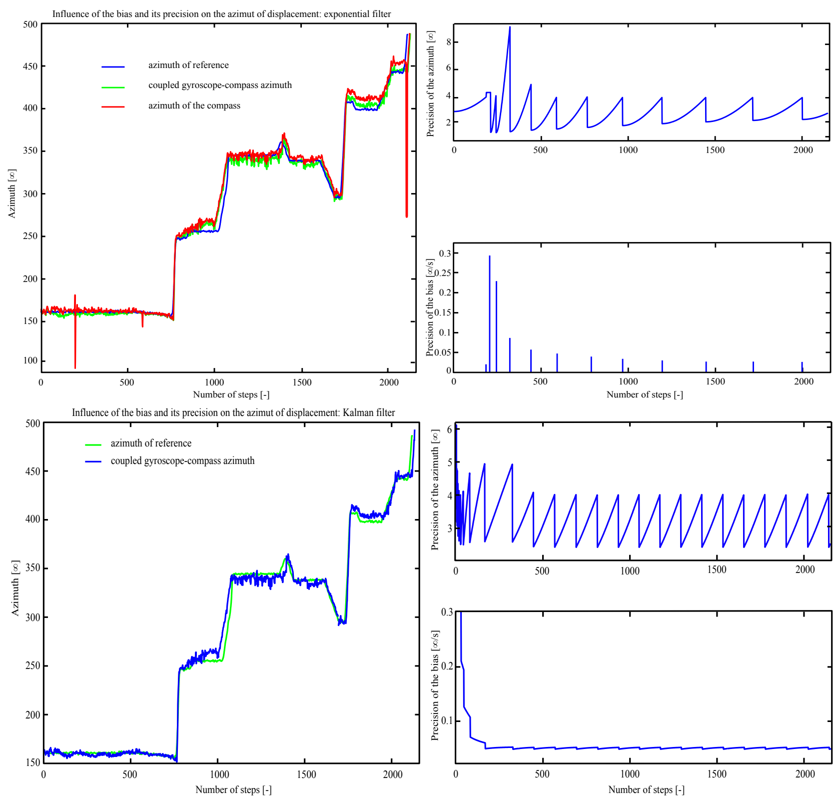

Figure 6: Update of the bias of the gyroscope using the two different approaches and their consequence on the precision of the gyroscope azimuth. In the Kalman filter, the frequent updates of the beginning result from by the hypothesis of an unknown bias (precision of 100°). The threshold for the updates is set to 4°.

Figure 4 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 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.

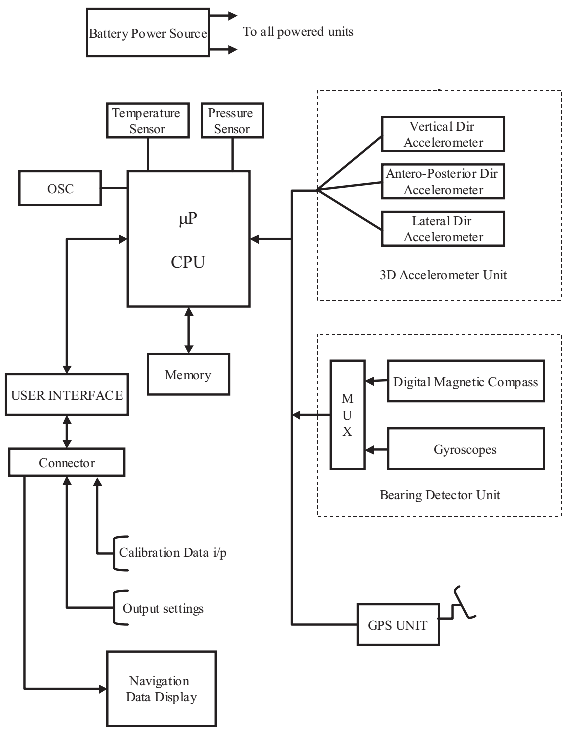

Figure 7: Schematic representation of the Pedestrian Navigation System. The different sensors work in parallel at a frequency that can be individually chosen in function of the specificity of the application.

4. 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 System (PNS) offers in different forms: 3 azimuths (compass - gyroscope - GPS), 2 altitudes (barometer - GPS), 2 travelled distances (dead reckoning - GPS). Figure 7 presents the structure of the PNS.

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.

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 1. 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 1: Empirical weighting of the different scenarios allowing the computation of the azimuth of walk

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 8. 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 2: 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 2 shows a typical solution provided by the PNS during a dead reckoning period.

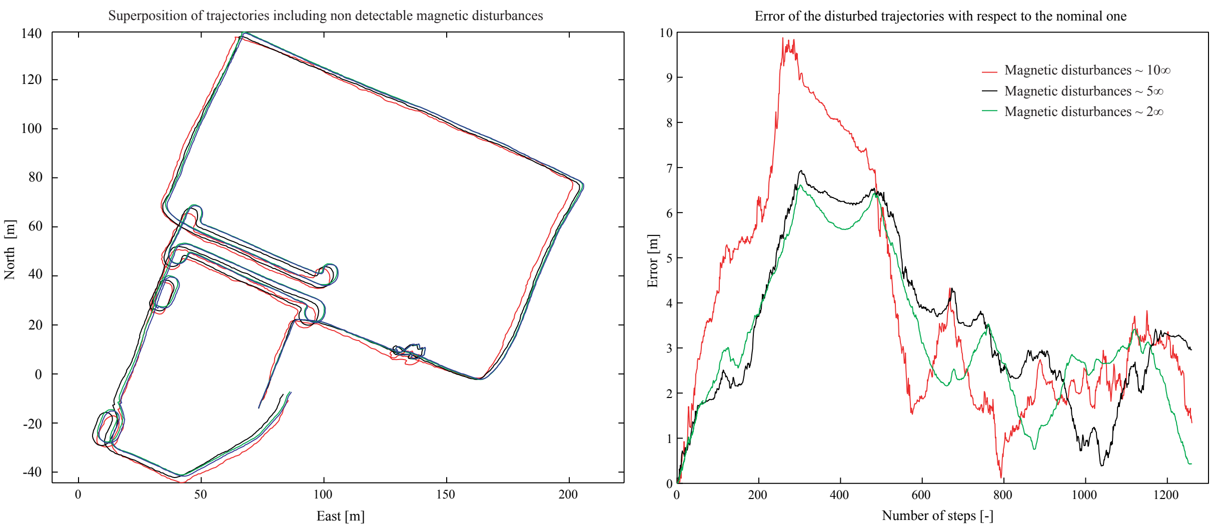

Figure 8: Representation of the notion of internal reliability. As the thresholds are empirically fixed for the determination of a magnetic disturbance, the non-detected disturbances will induce errors in positions. Disturbances from 2° to 10° have been introduced in the measurements. Superior disturbances 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.

Conclusion

This paper shows the achievable precision and reliability of the factual, 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. Finally, two indicators on reliability are presented, providing information about the quality of the computed position.
The numerous tests realised proved the validity of the concept for a navigation system that aims at offering an accuracy of a few meters in all kinds of environments.

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