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AN ALTERNATIVE APPROACH TO VISION TECHNIQUES: PEDESTRIAN NAVIGATION SYSTEM BASED ON DIGITAL MAGNETIC COMPASS AND GYROSCOPE INTEGRATION

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ABSTRACT

Over the last few years, research had been conducted on how to develop basic mobility aid for visually impaired and blind people using vision and image processing techniques. However, our research at Geodetic Engineering Laboratory has taken a different view to this problem. We have been looking at some alternative approaches to tackle the navigation problem for the visually impaired and blind people.
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 decentralized low-cost gyroscope, the advantage of one device compensates the drawback of the other. If we compare the rate of change of both signals continuously while measuring the strength of the magnetic field, it is possible to detect and compensate magnetic disturbances. When these disturbances do not take place, the continuous measurement of the azimuth allows computing and updating the bias and scale factor of the gyroscope. Thus, reliability of indoor and outdoor navigation is, because of the redundancy of information, significantly improved. Numerous tests conducted with different subjects in various environments validate this approach.

1. INTRODUCTION

The nice aspect about human displacements is its total and unpredictable freedom of motions. The worst hypothesis when modelling human trajectories is precisely this liberty of movements. Such aspect will play a major role in the filtering of the azimuth of displacement. 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 must change. Some examples show that this condition might be sufficient but not necessary and that it is not so straightforward as it firstly appears. In order to improve the reliability of the azimuth determination, a gyroscope will be used. The motivation doesn't come to navigate with a gyroscope heading only, as presented in [Gabaglio, 2002], but to use it to bridge the gaps when the compass is out. 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, opening therefore the use of a gyroscope that has multiple tasks. Azimuth, however, is only one component in the determination of the trajectory. The step length determination is done here using a occurrential approach rather than a double integration of the acceleration. In order to detect the direction of displacement of the person, we perform pattern recognition on the 3D acceleration. This allows a distinction between forwards-backwards movements as well as side-stepping, frequently done by the blind to bypass obstacles. This paper will present the occurrential approach capabilities for pedestrian navigation as well as the combination of compass and gyroscope data for this specific application.

2. 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 modeling of a step *occurrence* but to reliably reproduce a traveled 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 centered 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	7	3	3
3	10	3	5
4	11	1	5
5	13	3	4
6	8	5	4
7	9	4	6
8	10	3	5
9	13	7	4
10	12	3	6
11	9	2	2
12	6	6	8
13	8	3	6
14	10	5	8
15	11	4	5

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 3.6 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.

		Peri-Urban	Urban
Person with view	f	1.78	1.85
	s_0	0.06	0.09
1^{st} **blind**	f	1.52	1.59
	s_0	0.12	0.20
2^{nd} **blind**	f	1.70	1.81
	s_0	0.08	0.24
3^{rd} **blind**	f	1.66	1.72
	s_0	0.11	0.17

Table 2. Comparison between step frequencies for two free trajectories in residential and downtown areas. The person with view is representative of a group of 13 people who participated to tests. Frequency variability is higher for the blind. This can be explained by the trust towards the instantaneous situation. In case of hesitation, a higher frequency will be adopted to quickly adapt to any unexpected event. Direct consequence will be to shorten the steps.

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 1 shows the influence of the slope on the step length, simultaneously to the individuality of the approach towards changes in the terrain. In order to check if the developed theory is also applicable to the blind, several tests took place downtown Lausanne. It is important to note that the blind were not guided by anybody but were moving freely, only helped by their walking stick, TABLE 2. Results show that the walking frequency is strongly correlated to the knowledge of the path as well as to the congestion of the sidewalk. The frequency changes are in harmony with the previous theory, and the physiological models, once calibrated, can be

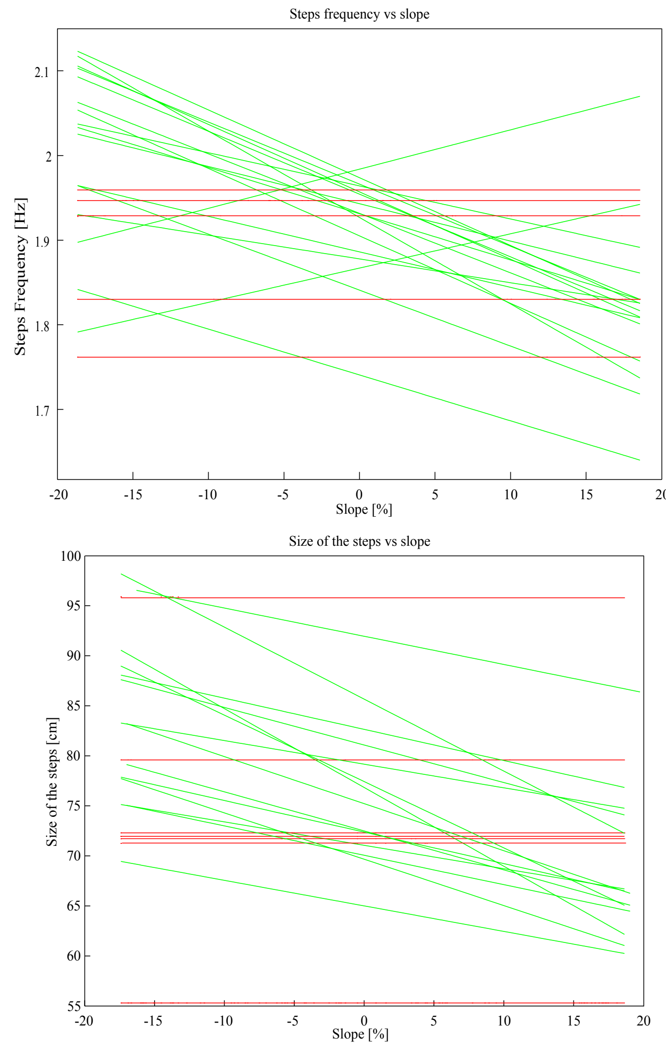

Figure 1. The influence of the slope on the step frequency (up) and the step length (down). More than every other parameter, the fitness of a person influence in the short time these parameters. The augmentation or maintenance of the step frequency/length by people, express the tentative to maintain a constant speed independently of the slope.

used as for people with view. The different obstacles (advertising plate, display rack) cause lateral movements that have to be detected. This is done by directly analyzing the pattern of the tridimensional acceleration signals. Several movements of interest were discretized in order to get a dictionary of patterns to match [Steiner, 2002, Ladetto, 2002]. Corrections to the measured azimuth of walk will then be applied according to the displacement. FIGURE 2 shows the detection of different ways of walking.

3. COMPASS NAVIGATION

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

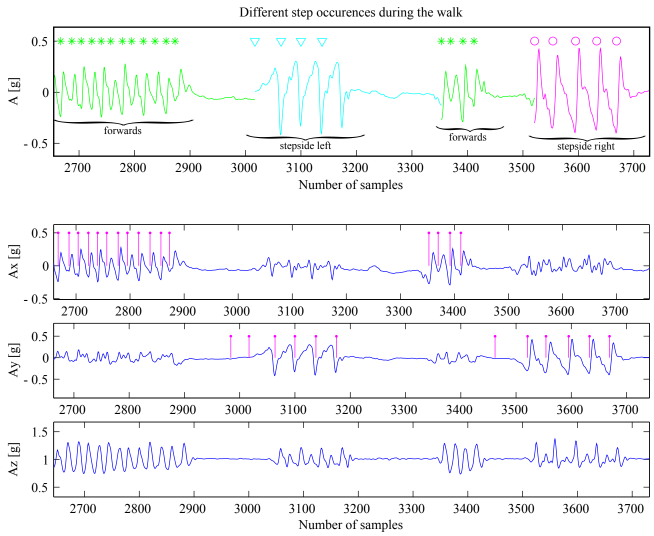

Figure 2. Example of a person walking with different attitudes. The side-stepping displacements are important in applications for the blind. These movements occur mainly when by-passing an obstacle, and concern only one to three step occurrence.

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

$$\begin{aligned} H_x &= b_x \cdot \cos\varphi + b_y \cdot \sin\theta \cdot \sin\varphi + b_z \cdot \cos\theta \cdot \sin\varphi \\ H_y &= b_y \cdot \cos\theta - b_z \cdot \sin\theta \end{aligned} \qquad (1)$$

where b_i coefficients are the components measured by the sensor. The azimuths (Eq. 2) 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, it value and uncertainty becomes

$$\alpha = \arctan(\frac{-H_y}{H_x}) \qquad (2)$$

$$\begin{aligned} \alpha + \triangle\alpha &= \arctan(\frac{-H_y}{H_x}) + \frac{\partial\left(-\arctan\left(\frac{H_y}{H_x}\right)\right)}{\partial H_y}\triangle H_y \\ &+ \frac{\partial\left(-\arctan\left(\frac{H_y}{H_x}\right)\right)}{\partial H_x}\triangle H_x \end{aligned}$$

Simplifying and taking into account that

$$H_e = H_H \begin{bmatrix} \cos(\alpha) \\ -\sin(\alpha) \\ \tan(\delta) \end{bmatrix} \qquad (3)$$

we get the error produced that can be written as

$$\triangle\alpha = \frac{H_y \triangle H_x - H_x \triangle H_y}{{H_x}^2 + {H_y}^2}$$

The use of relations (Eq. 1) and (Eq. 3), together with some trigonometric manipulations, leads to

$$\triangle\alpha = -\triangle\theta \cdot \tan\delta \cdot \cos\alpha - \triangle\varphi \cdot \tan\delta \cdot \sin\alpha \qquad (4)$$

This relation shows that the error in determining the attitude angles directly affects the azimuth. 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 space dimensions. A rigorous approach for calibration and removal of these disturbances would require the determination of 12 parameters at known elevations, which, considering the previous remark, would also be affected by some errors. A simplified 4 parameters calibration [Caruso, 1997] consists of determining only the corrections in the horizontal plane. This is more convenient for this particular application considering that the pedestrian navigation system is generally worn vertical 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 (3) become

$$\begin{aligned} H_x &= X_{fe} \cdot H_{X_{mes}} + X_0 \\ H_y &= Y_{fe} \cdot H_{Y_{mes}} + X_0 \end{aligned}$$

FIGURE 3 illustrates the results of the calibration procedure determining the disturbances caused by the clothes and accessories of a person.

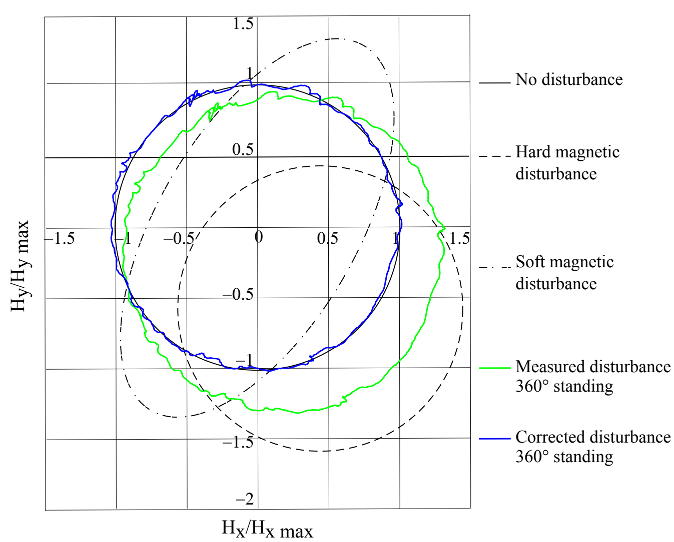

Figure 3. Description of the different effects of magnetic disturbances. The result of the simplified procedure adapted for pedestrian navigation corrects the disturbances caused by clothes and accessories.

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 allows providing a heading when navigating in sensible areas.

4.1. Optimising the magnetic information

The Earth magnetic field can be considered as a constant within the area normally covered by a pedestrian. All sudden variation of this field will be logically and indicator of a disturbance. Unfortunately, when someone is moving, the magnetic ambient is always changing and small random variation are caused by the environment.

If a low-pass filter and the occurrential approach take care of the majority of these fluctuations, the determination of a threshold is indispensable. Ideally this should be determined in a magnetic neutral area. This stage being unfortunately too constraining, the value of 3mT has been empirically defined as threshold on 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 simplification is directly correlated to the sinuosity of the path during the disturbed period. As the effect of a disturbance decreases with the square (even cube) of the distance from the source, the majority of effects are visible only over tens of meters. Considering the way people walk and the strong influence of the cadastre (straight line along sidewalks between buildings), this approach provides a much better result than considering indistinctively disturbed and undisturbed azimuths.

4.2. Using gyroscope

Although 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. Bias and scale factor are therefore continuously up-dated by the compass data or/and with GPS data when the satellite signal is available. The use of non-aligned sensors force the gyroscope angles to virtually harmonize themselves with the compass. The misalignment towards the direction of walk can in a second time only be defined if given absolute directions are known or if satellites signals are present.

Numerous tests [Moix, 2002, Ladetto and Merminod, 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 is in the same order of precision as the azimuth we get from the compass. The parameter of a scale factor will therefore be neglected under the hypothesis that the gyroscope is set perpendicularly to the plane of movement. The bias determination, however, is of major importance and requires an initialisation phase before each run. This will be done while standing or along a line because it is important that the gyroscope doesn't sense any angular velocity (Earth rate is neglected). The simplified model is the following

$$\breve{\omega}_i = \omega_i - b_i + \varepsilon_i$$

where $\breve{\omega}_i$ is the true angular velocity, b_i is the instantaneous bias and ε_i is a white noise with zero mean. Considering the azimuth from the gyroscope, it is possible to write

$$\varphi^{gyro}_{start} - \varphi^{gyro}_{end} = \sum_{i=1}^{n}(-b_i) \cdot \triangle t$$

where n is the number of time interval and $\triangle t$ is the time interval itself (here 1/30 s). Doing the hypothesis of a constant bias during the initial phase, an approximated bias value is given by

$$\bar{b} = \frac{1}{n} \cdot \sum_{i=1}^{n}(b_i) = \frac{\varphi^{gyro}_{start} - \varphi^{gyro}_{end}}{\triangle T}$$

where $\triangle T = n \cdot \triangle t$. The value $\bar{b}$ is then automatically updated when no magnetic disturbance is detected. This can be done via a Kalman or an exponential filter. FIGURE 4 presents the effects of magnetic disturbances on the compass.

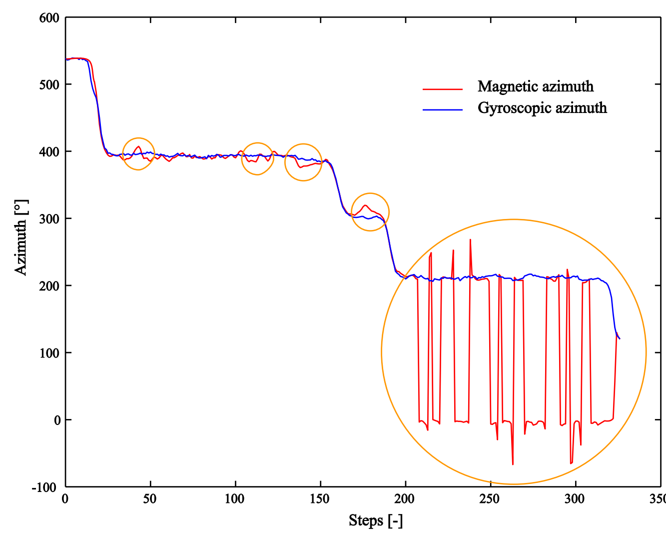

Figure 4. Comparison of the azimuth computed from both, compass and gyroscope. This shows in evidence the magnetic disturbances.

5. DISPLACEMENT IN TRAVERSE

The displacement of a person can be seen as a traverse as it is commonly called in geodesy. The distance between two summits corresponds to a stride and the angle between one point and the other is the azimuth of displacement. The two start and end points that need known coordinates will be either survey points or GPS fixes. The mathematical expression of a trajectory is expressed by

$$\begin{aligned} East_{final} &= East_{initial} + \sum_{i=1}^{n} d_i \cdot \sin\alpha_i \\ North_{final} &= North_{initial} + \sum_{i=1}^{n} d_i \cdot \cos\alpha_i \end{aligned}$$

where n is the number of steps, d is the computed step length and α_i is the measured azimuth.

The precision of the final position is computed by applying the variance-covariance propagation law to the previous equation:

$$\begin{aligned}\sigma^2_{East_i} &= \sigma^2_{East_{i-1}} + \sin^2\alpha \cdot \sigma^2_{d_i} + d_i^2 \cdot \cos^2\alpha_i \cdot \sigma^2_{\alpha_i}\\ \sigma^2_{North_i} &= \sigma^2_{North_{i-1}} + \cos^2\alpha \cdot \sigma^2_{d_i} + d_i^2 \cdot \sin^2\alpha_i \cdot \sigma^2_{\alpha_i}\end{aligned}$$

At this stage we can clearly see the difference in evolution of the precision between the occurrential approach and the 3D inertial navigation. Using the first approach, no degradation of the position occurs if no movement is detected. On the contrary, continuous time integration is sensible to every bias present in the acceleration, even if the person is standing still. FIGURE 5 represents the general flow-chart of the information. Before any azimuth determination, several tests are done to check if the person is moving, and which kind of movement is being done. Once this is done, the dead reckoning solution is computed and compared, if available, to the GPS position. This latter will also help updating the different parameters used in the step and speed estimation, the misalignment as well as the altitude models.

When walking downtown cities, satellites signals are generally

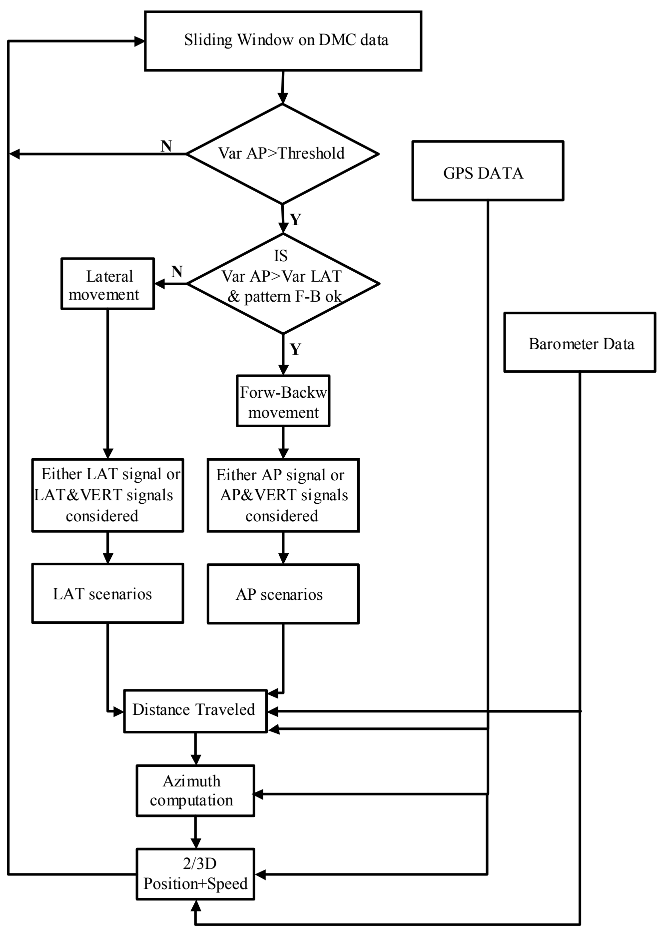

Figure 5. Flow chart of the developed approach considering each step occurrence instead of a double integration of the acceleration.

not continuously available and positions might only be computed at crossroads. The specific update procedure takes this intermittent particularity into account by sequentially updating the parameters. It can therefore take the best advantage of the configuration of the previous and present GPS positions. The precision of the satellite solution of navigation (10-20 m) also influences the update. Even if consecutive GPS fixes can be computed, their proximity might not be suitable enough to accurately deduce the azimuth. On counterpart, relative positioning can take advantage of the strong correlation between successive GPS epochs to compute speed and traveled distance. Special care should however be taken concerning multipath and thus, solutions require reliable testing before being used for update.

6. 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.

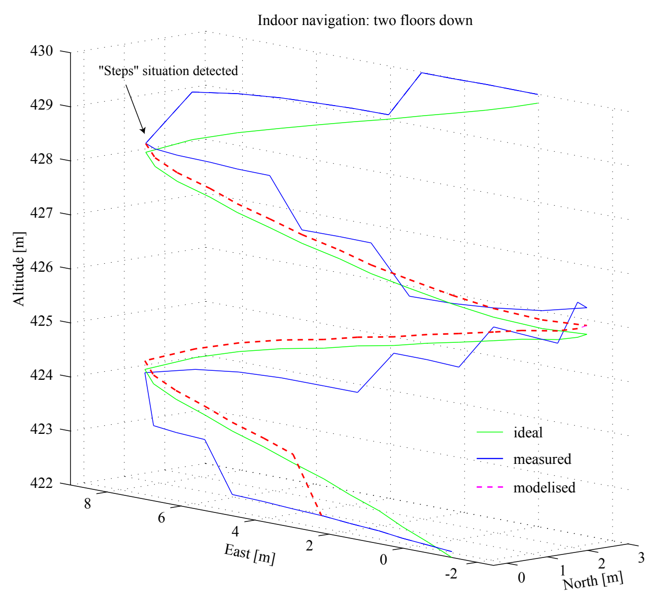

Figure 6. 3-D representation of downward walking for a stair scenario inside a building. The altitude change of 7.8 m is modeled here after filtering the pression by 7.28 m. The improvement of the sensor resolution is possible here thanks to the detection of the situation and an appropriate pressure treatment.

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 modeled as soon as the action is detected. FIGURE 6 presents the typical downward sloping stair inside a building.

7. PNS: A NEW CHALLENGE

To measure, synchronize and filter all the necessary data, a system was conceived and realized together with Leica Vectronix. The Pedestrian Navigation System (PNS), FIGURE 7, is composed of a high performance, commercial grade GPS receiver, a barometer, a digital magnetic compass (3 accelerometers & 3 magnetic sensors). The integration of a gyroscope is in progress.

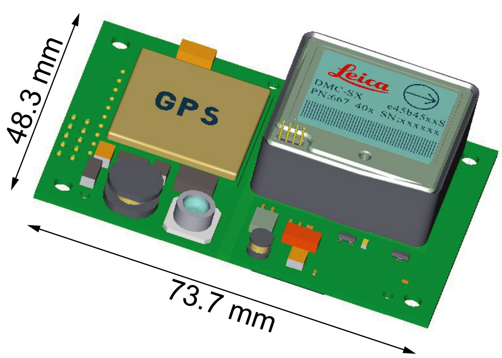

Figure 7. Pedestrian Navigation System (PNS) developed together with Leica Vectronix. A total 3-D positioning capability for less than 50 grams.

8. CONCLUSION

This paper showed the achievable accuracy and reliability of the occurrential, stride-dependant, approach that replaces the temporal, double integration, evolution. The development of a Pedestrian Navigation System (PNS) based mainly on a digital magnetic compass was done in order to fulfill the specific ergonomic requirements of the application. In non-magnetically disturbed areas, the errors in position are below the 10 meters. In order to improve the reliability of the system, the addition of a gyroscope helps bridging the gaps when the compass is strongly disturbed. No operational ZUPTs constrain are required by the approach. This new product and approach open the door to a new data capture form in GIS, navigation for the blind, FIGURE 8, as well as projects where individual's position is of interest.

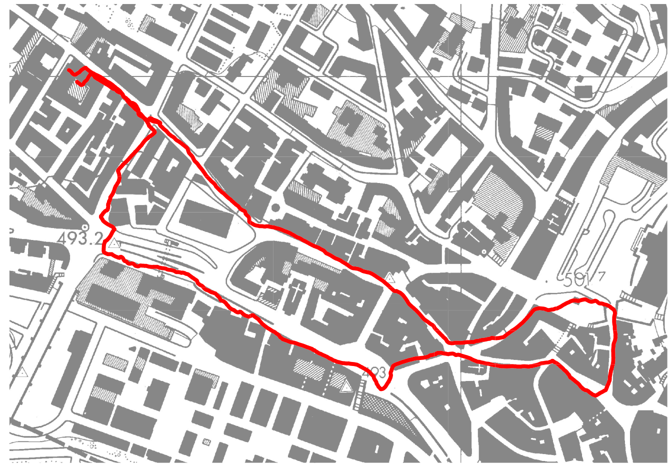

Figure 8. Pure Dead Reckoning Navigation by a blind downtown Lausanne (CH). The different models were calibrated and took into account the sidestepping as well as the snap movements of the blind. Reported on a site plan, the trajectory (1'905 m) shows small discrepancies but determine reliably the real path followed. The power line of the bus as well as the numerous parked cars influence negligibly the computed trajectory.

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