Two Different Approaches for Augmented GPS Pedestrian Navigation

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BIOGRAPHY

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ABSTRACT

This paper present the calibration of the different models used for pedestrian navigation. Information on travelled distance and azimuth sensed by inertial sensors is merged with GPS observation through Kalman filtering. All models use GPS positions without differential corrections to calibrate systematic errors present in inertial sensors.

Different prototypes have been developed. They integrate a digital magnetic compass or gyroscopes, tri- or bi-axial accelerometers, an altimeter and a mono-frequency GPS receiver.

The results show that an integrated system improves the reliability and precision of the trajectory, as compared with GPS only. Absolute accuracy of under 5 meters are achieved and maintained even in pure Dead Reckoning (DR) mode, i.e. when no satellite signal is available. Taking advantage of the strong correlation between epochs, there is no need to use DGPS corrections to calibrate the DR models.

The numerous challenges of this research domain are actually investigated at the Institute of Geomatics (IGEO-TOPO) of the Swiss Federal Institute of Technology (EPFL) in close collaboration with the Swiss Center for Electronics and Microtechnology (CSEM) as well as Leica AG.

1. INTRODUCTION

According to the needs and specificity of pedestrian navigation, the classical GPS/INS approach used for vehicle navigation is not suitable. Limitations apply to the weight, size and ergonomy of the device. The system must be able to determine the trajectory of a person in both presence and absence of GPS measurements. The main challenge is to maintain a good accuracy of the position even when no satellite data are available.

The increasing demand in positioning people for medical applications, GIS, fire rescue or military requires adapted technologies. New miniaturised low power Inertial Measurement Units (IMUs) coupled with satellites receivers can provide accurate position in indoor and outdoor situations. IMU are generally built to provide 3D acceleration and rotation information. One IMU based on gyroscopes and another one using magnetometers to compute the azimuth will be considered in this paper.

As satellite signals are not always available, the development of Dead Reckoning (DR) strategies is necessary to provide continuous positions. The nature of human walking varies greatly and is difficult to predict. This characteristic suggest the implementation of navigation models that are quite different from the "classical" vehicle applications. Physiological aspects have to be taken into account and require on-line calibration. In an effort to overcome the limitation of the models performing only in "standard" walking conditions, research has been carried out to detect forward/backward displacements as well as side-stepping automatically.

Pedestrian applications require mostly real time information. Thanks to the improvement in the GPS accuracy since the suppression of the selective availability, the computed absolute position, the so-called "navigation solution", has been considered as precise enough for the foreseen applications. Differentiating and filtering positions epoch by epoch to deduce the speed and the azimuth also allowed for a very good calibration of the parameters used in DR-mode.

This paper provides a brief background on the pedestrian navigation principles and the problems encountered. Then it presents two different low cost GPS-INS prototypes that have been developed at our laboratory with their specifications and foreseen applications. Finally, several results as well as comparative tests under different circumstances are also analysed.

2. PEDESTRIAN NAVIGATION OVERVIEW

Classical inertial mechanisation to deduce speed position and orientation is not optimal for pedestrian navigation. (Judd 1997, Soehren and Keyes 2000, Gabaglio and Merminod 1999, Ladetto and al. 1999, 2000). A step detection procedure counting each occurrence and multiplying it by an average step length gives much better results than a mathematical integration of the accelerometrical signal. The logical relationship between step size and walking speed is well explained in the literature (Cavagna, 1969, Margaria 1976, Perrin and al 2000). The enhancement and modification of some formulae according to the available measurement data, provide an accurate model to compute the travelled distance independently of the person doing the tests. Therefore the distance travelled is estimated mainly by means of accelerometers.

Having the travelled distance computed, the walking line of sight must also be continuously determined in order to provide a position in dead reckoning mode. This is accomplished using magnetic sensors or gyroscopes.

Satellite data are mainly used to correct the azimuth bias of the magnetic sensors as well as the bias and drift of the gyros. The data integration is done via different Kalman filter algorithms and will be discussed later.

3. TWO COMPLEMENTARY LOW COST INS-GPS APPROACHES

Taking advantage of the industrial production of miniaturised sensors, two directions of investigation are pursued: First sensing the North direction by means of the magnetic field sensors, the second deducing it with the help of gyros. Both systems have their strengths and weaknesses and they may complement each other. These aspects will be discussed at the end of the article.

3.1 GPS and DMC

The core of the first prototype is the Leica Digital Magnetic Compass (DMC-SX) that combines three micro-electromechanical (MEMs) accelerometers and three magnetometers. To be rigorous, the azimuth is defined as the angle between the horizontal projection of the line of sight of the person walking and the horizontal component of the earth's magnetic field. Knowing the direction where a person is pointing, the azimuth is computed by the projection of the earth magnetic field vector sensed by the output of the three orthogonal magnetic field sensors and two inclination sensors. At present, the specifications of the Leica DMC-SX regarding the precision, size, weight and power-consumption make it the best candidate for such applications. According to the author's knowledge, the survey community uses this sensor in several oil research projects and in mobile mapping systems (MMS) (Ellum and El-Sheimy 2000).

In order to compare the azimuth output by the DMC-SX with the one derived from two consecutive GPS position, the former must be corrected for magnetic declination. The declination is the difference angle between the geographic North and the magnetic North. The latter varies with time and geographical location. Global or regional models are currently available and are known as the International Geomagnetic Reference Field (IGRF) (National Geophysical Data Center). Some countries have their own mathematical representation of the magnetic field with superior accuracy. For pedestrian navigation, a precision of 1° is sufficient and global models are usually adequate.

Figure 1: Leica Digital Magnetic Compass (DMC-SX)

For absolute positioning and calibration of the different DR algorithms, the system uses the output of a mono frequency GPS receiver produced by μ-blox AG. Up to now air pressure and temperature were recorded separately on a meteo station commercialised by Revue Thommen AG. All data were synchronised subsequently. The integration of a miniaturised air pressure transducer is actually realised on the second generation of prototypes.

Methodology overview

The different autonomous signals that are going to be analysed are strongly influenced by the placement of the unit on the body. To maintain the stability during the walk, the unit is placed at the waist level of the person. The output azimuth will therefore correspond to the line of

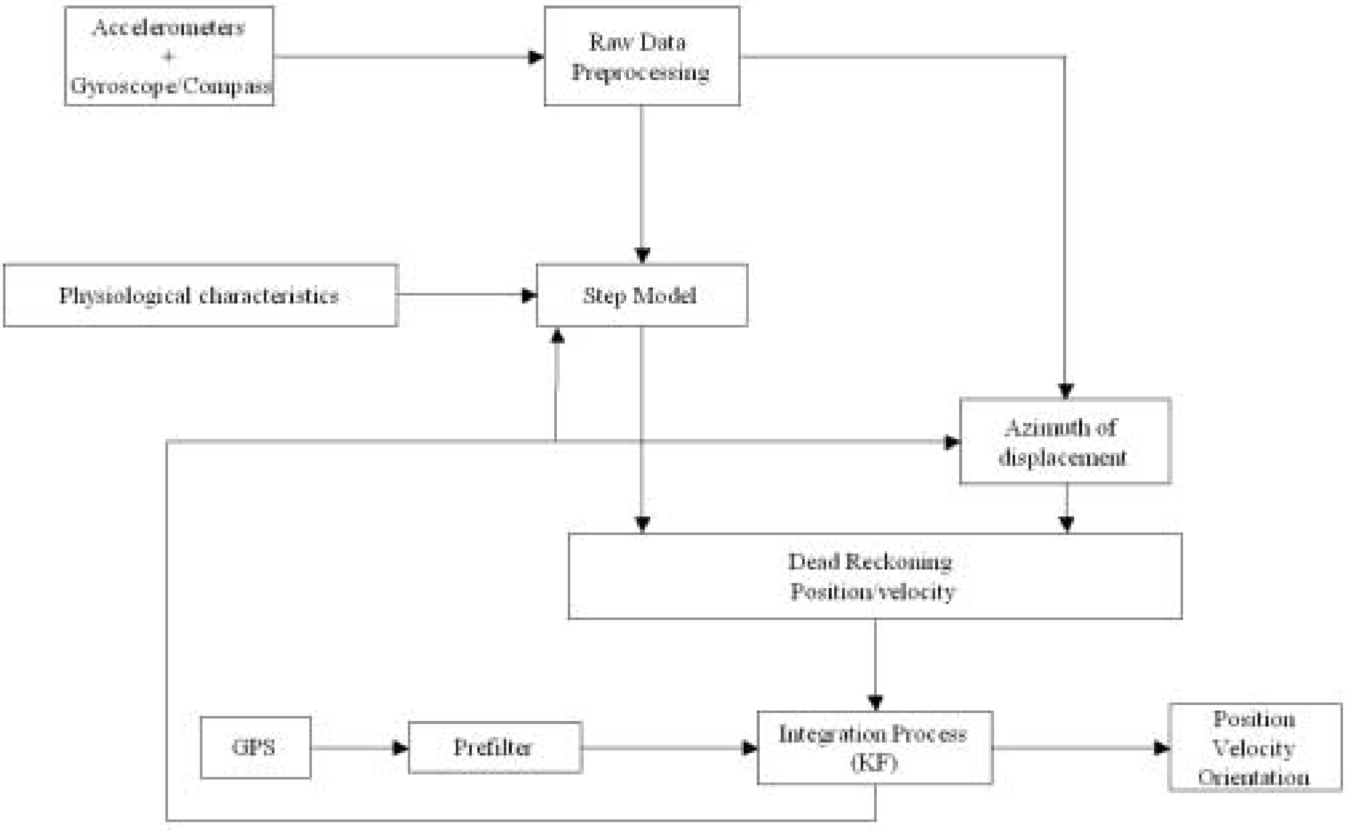

Figure 2 : Structure of the algorithms for pedestrian navigation

sight of the waist which, most of the time, is in the direction of walk.

The accuracy of the azimuth angle depends strongly on the local disturbances of the magnetic field. Such disturbances can be characterised as two types: hard-magnetic and soft-magnetic. Hard-magnetic perturbations are caused by permanent magnets and electrical currents which add changes to the earth field irrespective of its strength and orientation. Soft-magnetic disturbances are caused by magnetic material distorting the earth field and are therefore dependent on the strength and position of this field. More complete explanation of this phenomenon can be found in Gnepf 1999 and Caruso 2000.

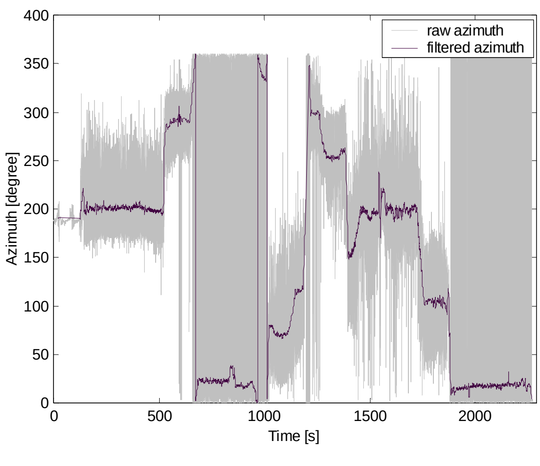

Figure 3: raw and filtered azimuth. The variation of the signal is mainly caused by the physiological swing of the hips while walking.

Different calibration routines are implemented in the DMC-SX which are performed before placing it on the person. However, in a day-to-day life, the magnetic field is permanently disturbed by a variety of sources such as computers, power-lines, iron objects, reinforcement in buildings, etc. The azimuth error caused by these disturbances depends on the inverse of the second power $1/d^2$ (possibly on the third power $1/d^3$) of the distance d to the object. Some of these effects are eliminated by filtering the azimuth, but in the absence of external input such as GPS or gyros, the disturbances cannot be compensated. Particular care must be taken not to filter out the motion when smoothing the noise in the azimuth signal.

As the perturbations tend to be reasonably constant for a given environment, magnetic correction maps can be created for areas such as campuses, commercial centres and any other particular place of interest. A typical application could be to find one’s way out of a building, situation fairly common for blind people or fire fighters in conditions of reduced visibility (smoke) inside a building.

If the repeatability of a trajectory is the main interest, no particular compensation is required.

After several trials, the location of the sensor has been chosen at the lower back, which can be considered as relatively stable while walking. This stability will mainly influence the azimuth signal as well as the reliability of the step detection procedure. However the orientation of the waist does not always correspond with the walking direction as for backward displacements and side-stepping. Such movements are detected through filtering and pattern recognition of the tri-dimensional accelerometric signal of the IMU. Once the correct direction of the displacement is known, the azimuth is computed.

The combination with GPS data is done via different Kalman filters. When GPS is available, individual models for the step length are calibrated as well as the magnetometer outputs. Particular attention is given to the azimuth derived from the GPS positions. The error in position influences the azimuth. In consequence, the computed heading will depend strongly on the distance between two considered epochs. This aspect will have a major influence on the azimuth-bias calibration. A block diagram of the integration approach is presented in Figure 2.

3.2 GPS and gyroscope

The second approach consists in using a gyroscope to determine the walking line of sight. The tests and investigations have been made with the Crossbow DMU. This Motion Unit measures acceleration in three orthogonal axes as well as rotation rate about each axis. This is accomplish by three MEMS accelerometer (surface micro-machined silicon) and three gyroscopes. The gyros consist of vibrating ceramic plate that utilise Coriolis forces to output angular rate (Lawrence, 1998). The DMU employs an internal processor and a temperature sensor to compensate for deterministic errors. This device has been chosen at the beginning of the studies for its relatively low cost and its integration of the six sensors. It is not suitable for hardware development but offers good capabilities for investigations. The previous research at the Geodetic Engineering Laboratory shows that 2 accelerometers and one gyro are enough to compute a 2D trajectory of a walking person (Gabaglio and Merminod 2000). All the methodology presented below is built around the use of these inertial sensors.

The inertial sensors provide the output signal in response to the physical input (acceleration or rotation) through the use of a bias and a scale sensor:

$$\text{output} = \text{bias} + \text{scale\_factor} \cdot \text{physical\_input}$$

Bias is the signal given by the sensor when there is no input. The scale factor is the ratio between a change in the output signal and a change in the input (Lawrence, 1998).

Those two parameters are changing over time (especially the bias) and must be calibrated before and/or during the use. The influence of the accelerometer bias is negligible due to the way the distance computation is done. This is not the case for the gyroscopes. The bias induces a drift of the azimuth and then of the position. As the gyroscopes provide only the angular rate, an initial orientation has to be found. Then single integration yields the absolute orientation which goes into the DR mechanisation.

For absolute positioning, the system uses a mono frequency GPS receiver manufactured by BAE systems (formerly Canadian Marconi): the Allstar. It provides positions at 2 Hz. The absolute position is computed with the GPS code smoothed by the carrier phase (Hatch, 1982). Differencing two successive GPS positions provides precise azimuth and velocity. A special care must be given to the cycle slip detection during the count of the carrier cycle. This azimuth is used for the initialisation of the orientation and the calibration of the bias.

Methodology overview

The sensors are placed on the thorax. This choice allow to use the same sensors as for a fall detection system developed by the CSEM for emergency applications. One accelerometer is placed vertically (pseudo-vertical), the second one is mounted perpendicular to the first and oriented along the walk direction (anterio-posterior). The gyro measures the angular rate about the axis of the first accelerometer. The orientation information is then "pseudo-horizontal". Default of the horizontality can be taken in account by the scale factor.

During a straight walk, the gyro produces a signal where the periodicity of the step rate is clearly visible. Additionally, random errors degrade the signal (Figure 4). The accuracy of the angular rate is 0.1 ^{o}/s. The raw signal is firstly processed to eliminate this periodicity and the random errors through a low pass filter. The filter has been designed through wavelet analysis. This technique allows to study the raw data in different situations during a path (short turn, long turn, straight line, change in velocity, etc.). The goal is to eliminate the noise and the periodic changes while keeping the significant changes of the walking line of sight. Furthermore the length of the filter must stay short (not more than two seconds) to minimise the delay for the computation of the position (near real time).

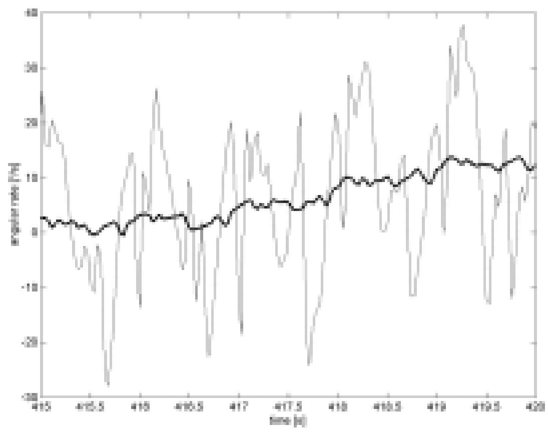

Figure 4 : gyro raw and filtered data during a 10^{o}/s turn.

The low-pass filtered gyro data still contain additional errors that influence the orientation. The scale factor and the bias have to be determined and the angular rate integration requires an initial orientation. Concerning the scale factor, the calibration is performed in laboratory for each sensor. This parameter remains relatively stable as compared to the bias. Moreover the change in the scale factor during a walk is not easily observable as long as a good determination of the bias is not achieved. An on-line calibration of the scale factor is therefore inappropriate.

The determination of the bias is accomplished using the GPS derived azimuth. The inertial azimuth given by the gyro is compared with the azimuth derived from GPS positions through a KF. This filter distributes the difference between both azimuths to the change in orientation and to the change in bias. The difference is also propagated to the estimated position. It means that when GPS is available and when an azimuth update is performed, the following parameters are changed: the bias of the gyroscopes, the orientation as shown in the Figure 4 but also the position (Figure 5). The same filter is used for both the initialisation and the on-line calibration of those parameters.

To achieve a better accuracy of the observed GPS azimuth, a local KF is used. When the gyro azimuth needs to be initialised or needs to be recalibrated, then the GPS azimuth is filtered and smoothed to be compared with the gyro azimuth (Figure 5). The choice of the update time is driven by the accuracy of the orientation given by the gyro.

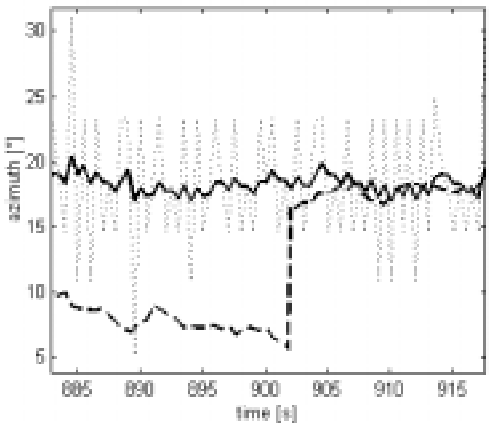

Figure 5 : Azimuth update: the filtered GPS azimuth (bold line) updates the INS azimuth (dashed line). The azimuth is changed, as well as its slope (i.e. the bias of the gyro). GPS raw azimuth is shown as dotted line.

The GPS positions are processed with the same filter. With minimal change, any type of position provided by another system (GSM, Loran, ..) can be implemented in the filter. Thus the developed algorithms can be quite easily extended to include other positioning systems. The structure of the algorithms is presented in Figure 2.

4. RESULTS

To evaluate the GPS-accelerometer-gyro system, tests took place on an athletic ring. Concerning the travelled distance estimated by the accelerometers, the error is about 4m for the 400m really travelled. Other tests show that the accuracy of the travelled distance can be estimated at 2%. The next figure shows the integrated position, its accuracy and the standard deviation of the azimuth.

At the beginning of the track, neither the initial orientation, nor the bias are known. Therefore the system needs a few updates of azimuth and position. All the updates are computed each time the azimuth accuracy reaches 5°.

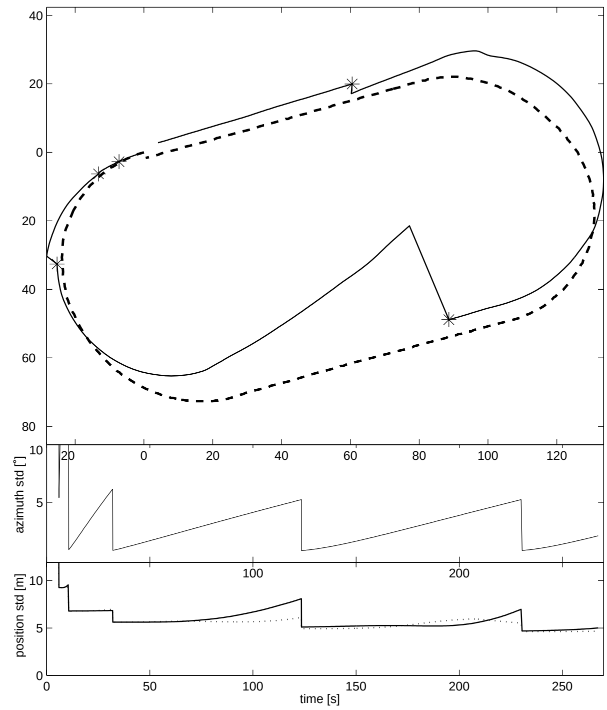

Figure 6: Athletic ring test. Up: the GPS (dashed) and the GPS-gyro trajectory. Down: the standard deviation of azimuth and position (east: dotted, north: full line).

After the first updates, the bias estimation my contain a large error (Figure 6). However, after 400m, the bias is determined with a precision of less than 0.1°/s. The position error at the end of the track is 4m. The standard deviation of the azimuth and of the position increase between updates (due to error propagation in the DR model) but globally decrease at each update. By example for the position, the accuracy is 15m at the first update (GPS accuracy) and 5m at the last update. This shows that the integration of GPS with other sensors not only to fills the GPS gaps but also improves the accuracy and the reliability.

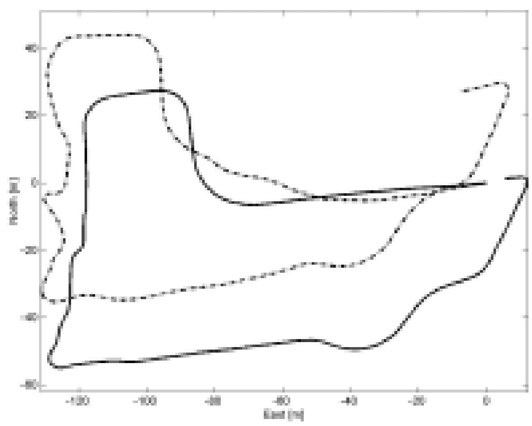

Figure 7: Gyro (full line) and DMC (dashed line) trajectories in a magnetically disturbed environment.

If only an azimuth update is performed, using azimuth information coming from other sensors such as the DMC, the accuracy of both the azimuth and position are improved. But the position accuracy cannot decrease more than the one reached at the last position update.

In order to analyse the influence of hard- and soft-magnetic disturbances on the trajectory, tests were conducted in a zone with strong iron concentration and electrical currents (Figure 7). Local perturbations of the compass appear very clearly, affecting the trajectory. The gyroscope solution, as expected, is not influenced by the environment. It can be stressed that once the magnetically disturbed zone is passed, the computed azimuth returns to its previous, undisturbed value.

Another test took place in a residential area where it was possible to experience the loss of some satellite signals as well as "normal" magnetic disturbances (Figure 8). The total length of the trajectory, measured by carrier phase differential GPS, is 1840 m. The variation of altitude during the run is 31 m. The maximal slope is 13%.

The maximal error between the computed trajectory and the true one is 5.2m for the GPS-DMC system and 25 m for the GPS-gyro module.

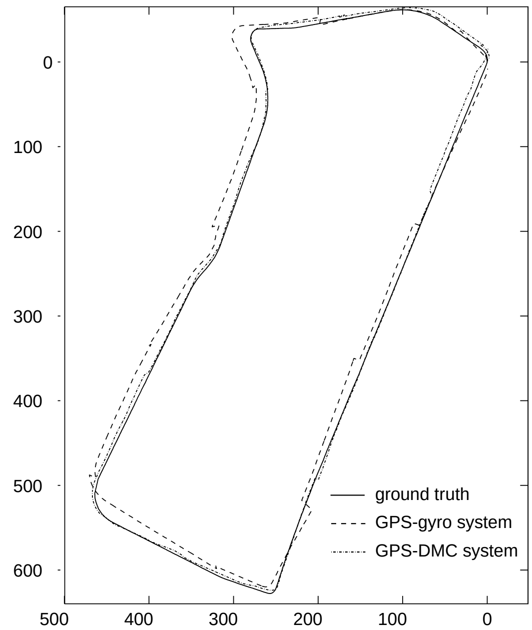

Figure 8: Comparison of the GPS–DMC/gyro integration on a path in a residential area.

A pure Dead Reckoning test using the magnetic compass was done along a tortuous path. The scope was to see if the models used are accurate enough to distinguish on what side of the street a person was walking. A person walked along both side of the road in a closed loop over a distance of 3019 m. The computed travelled distance matches the true one within 1.3% (2979 m), and the difference in position between the start and the end points is 5.6 m (0.2%). The trajectory, reported in Figure 9 show that the expectations have been fulfilled.

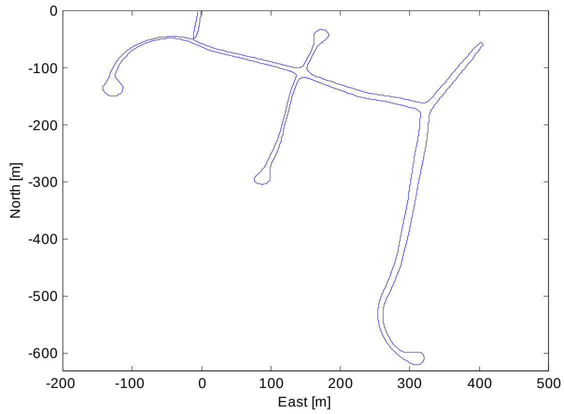

Figure 9: Pure DR test of a person walking on both side of the street.

5. CONCLUSION

The different tests conducted in parallel with the two sensor systems show clearly that the weaknesses of one system are the advantages of the other one. According to this remark, an optimal and more reliable system will be obtained by coupling the gyroscopes with the magnetic compass. Once again, the information we get with the synergy of two different systems will be superior to the one obtained from each module separately.

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

Table 1 : comparison between compass and gyro

The gyroscope will provide a useful indication to identify magnetic disturbances, while the compass will be useful to determine the bias of the gyros and the initial orientation, even when no GPS is available.

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