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# Real Time Pedestrian Navigation System

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## BIOGRAPHY

Damien Kubrak is a Ph.D. student at the signal processing lab of the Ecole Nationale de l'Aviation Civile (ENAC) in Toulouse, France. He graduated in 2002 as an electronics engineer from the ENAC, and received the same year his Master of research degree in signal processing. His work focuses on the hybridization of MEMS sensors with a GPS receiver to face personal positioning issues.

Christophe Macabiau graduated as an electronics engineer in 1992 from the Ecole Nationale de l'Aviation Civile (ENAC) in Toulouse, France. Since 1994, he has been working on the application of satellite navigation techniques to civil aviation. He received his Ph.D. in 1997 and has been in charge of the signal processing lab of the ENAC since 2000.

Michel Monnerat graduated from the ENSICA (Ecole Nationale Supérieure d'Ingénieur de Constructions Aéronautiques) engineering school. After being involved within Alcatel Space in many radar programs, in charge of the onboard processing of the ARGOS / SARSAT payload, he has been involved in the Galileo program since 1998, for the signal design and performance aspects. He is currently involved in Alcatel Alenia Space LBS programs.

## ABSTRACT

This paper presents a real time pedestrian navigation system that combines different type of GPS receivers (namely High Sensitivity GPS and Assisted GPS) with several low-cost inertial sensors to face GPS outages and provide a reliable and continuous position solution.

The off-the-shelf inertial module from Xsens is made of several low-cost MEMS type sensors contained in a very small package (58×58×22 mm W×L×H). This unit is composed of a triad of gyroscopes, a triad of accelerometers and a triad of magnetometers as well as a temperature sensor. The measurements of the different sensors are combined to provide an autonomous

Pedestrian Navigation System that does not rely on GPS measurements. This navigation method is based on the analysis of the dynamic of the pedestrian, as performed in [1], in order to limit the impact of accelerometer biases that systematically degrades the position accuracy. The remaining gyro drifts are estimated and compensated dynamically through the implementation of an attitude filter that combines the different sensors data. The magnetic interference issue is also addressed with a mitigation technique based on gyros measurements.

The Assisted GPS or High Sensitivity GPS receiver and the Pedestrian Navigation System are combined in real time to provide more reliable position solutions and also augment the overall availability especially in deep urban canyons and indoor environments. The coupling methodology follows a loose integration scheme.

The Integrated Navigation System is software implemented on an ultra portable PC. The inertial unit is connected to the ultra Portable PC using the serial RS-232 link through the USB serial port.

Results show that the real time combination of both navigation systems improves tremendously the availability of the position solution, especially in harsh environments. The accuracy of the position solution during GPS outages is also augmented, and stays within acceptable limits according the trials that are exercised during long GPS outages. It is also shown that the analysis of the coefficients used to model the velocity of the pedestrian allows the detection of bad GPS measurements that prevent the Pedestrian Navigation System from being inaccurately initialized for further standalone navigation.

## INTRODUCTION

Over the past few years, major progresses have been made on the processing of GNSS signals. High sensitivity and assisted techniques have indeed tremendously improved the acquisition and tracking of GNSS signals with very low C/N<sub>0</sub>. The main consequence of these advances is that position solutions

are far more available than those of receivers available few years ago. Location Based Services (LBS) benefit these improvements, as it can be seen for example in land vehicle navigation or personal navigation systems products.

The increase of both position solutions availability and sensitivity is not an end in itself. Indeed, the weaker the signals are, the more the acquisition process is likely to detect wrong peaks due to cross correlations, pure multipath replica... making pseudoranges very affected by noise. This consequently leads to position solutions accurate to only several hundreds of meters. In deep urban canyons or deep indoor environments, no position can furthermore be computed because signals are even too weak.

Therefore, in order to provide a position solution whatever the environment in which the user requires its location, augmentations have to be associated to the main positioning system. Several philosophies exist, the one using local wireless networks such as GSM or Wifi, the other using rather self contained sensors to reduce the augmentation infrastructure cost. The latter is the methodology followed throughout this study.

In a first time, both AGPS and HSGPS basic principles are described and a rough performance assessment is done through typical real acquisition and tracking tests. The augmentation system made of a low-cost IMU is then described in detailed as well as the mechanization used to limit the impact of the measurements errors. An optimization of the pedestrian mechanization is also proposed through the use of a drift-free attitude filter capable of estimating the gyroscopes bias, even when the IMU is moving. The integration methodology is then presented as well as the integrated pedestrian navigation system that fuses whether HSGPS or AGPS with the low-cost IMU. The performance of the developed navigation system is finally assessed through actual tests done in urban canyons like environments as well as indoors. A method using the mechanization properties is also proposed to detect and exclude GPS measurements very affected by noise and multipath in order to increase the accuracy of the navigation system.

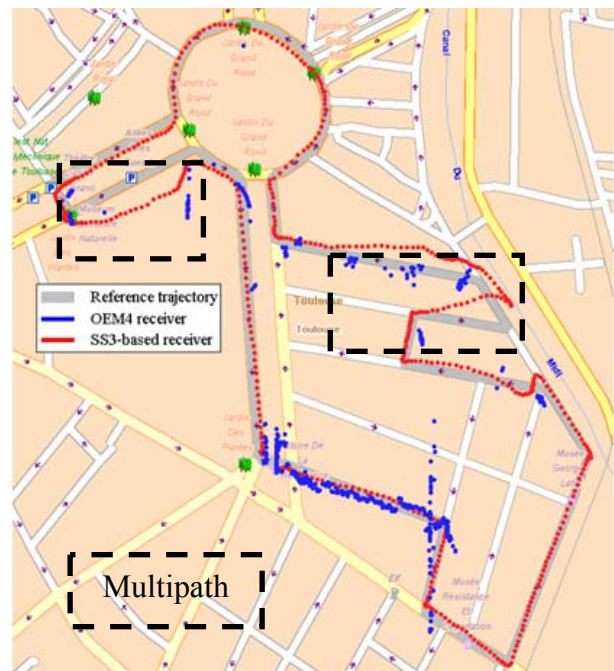
## GPS MODULES

### High Sensitivity GPS:

HSGPS has been one of the major improvements brought to the processing of GPS signals. Its basic principle relies on the use of long dwell times as well as robust filtering techniques to fight perturbing signals such as cross-correlations and multipath. As a result, both sensitivity and position availability are increased.

There are however some limitations to such processing techniques. The accuracy of the position solution is indeed quite inaccurate indoors and in some cases experiences very large dispersion, which makes the hybridization with inertial sensors inefficient and unreliable. The multipath sensitivity is also dramatically increased inside buildings, since a non Line-of-Sight signal is very likely to be acquired, tracked and integrated in the measurements used to compute the position solution. There is moreover a need to track signals with a minimum power in order to be able to demodulate the ephemeris of the satellite, and as a consequence to compute the position of the user.

Despite all these limitations especially in harsh environments, the HSGPS tremendously extend the GPS position solution in urban areas. As an illustration of the performance of such a receiver, Figure 1 presents the trajectories computed in a typical urban test. A geodetic grade GPS receiver whose trajectory is plotted in blue is used as a comparison. The HSGPS position solution is plotted in red. Prior to the test, the HSGPS is statically initialized under clear sky conditions in order to get the ephemerides and the almanacs of the satellites in visibility. As it can be seen in the figure, the HSGPS position solution is far more relevant of the true path followed during the test, which is plotted in gray, even if sometimes the solution is very affected by multipaths.



**Figure 1 – Urban Environment HSGPS test Results.**

### Assisted GPS:

The Assisted GPS shares the same basic processing principle as HSGPS. The GPS chipset is

however aided by assistance data mainly composed of the navigation model (ephemeris, clock corrections) and various corrections that are broadcast by an assistance data server through a wireless connection [5], as given in Table 1.

Such architecture has three major impacts on the processing of GPS signal as compared to the HSGPS one. First, the transmission of the data needed to be able to compute the position of the user is much more rapid than what is currently achievable with the GPS navigation message. Second, the acquisition stage is tremendously improved by the processing of the assistance data that reduces both Doppler frequency and code phase uncertainties. As a result, the Time-to-First-Fix (TTFF) is no more limited by the update time of the signal in space (i.e. at least 30 seconds). Finally, as soon as the GPS time has been recovered, there is no need to demodulate the ephemeris of the satellites that are tracked to compute the position of the user since all code ambiguities can be solved using the rough position broadcast in the assistance data. Such an improvement decreases the dilution of precision which in turn increases the position solution accuracy.

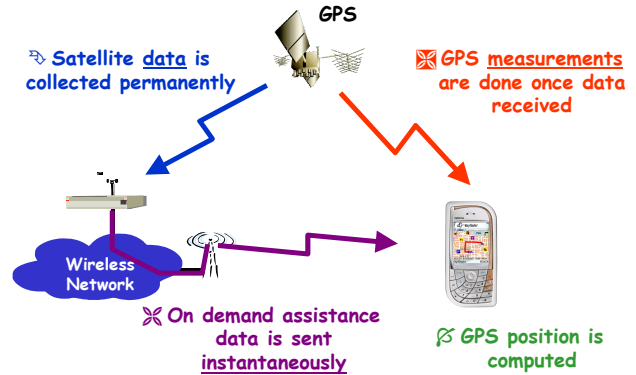
Reference location :	Pre location of the mobile generally deduced from cellular information
Reference time	Reference time relative to the GPS time
Navigation model	Visible satellites ephemeris and clock corrections
Ionosphere corrections	Klobuchar model broadcast by the GPS signal in space
Differential correction	Standard differential corrections
Real time integrity	List of bad satellites
Almanacs	Almanacs of the GPS constellation
UTC model	Model UTC broadcast by the Signal in space
Acquisition assistance	List of assistance to improve the acquisition

**Table 1 – Assistance data.**

Figure 2 summarizes the basic principle of the Assisted GPS. The assistance server is permanently collecting and processing GPS signals in order to get the ephemeris of each satellite. On demand of the user, the assistance server sends back to the user’s mobile phone the required data and the embedded AGPS chipset process them together with GPS signals in order to compute the position solution.

Two types of location are allowed. It could be the so-called “MS-Based” mode or the “MS-Assisted” mode. In the first case, the mobile thanks to the assistance data performs the pseudo ranges measurement, then computes its location and sends it back to the server. In

the second case, the mobile thanks to the assistance data performs the pseudo ranges measurements and sends them back to the server which performs the location computation.



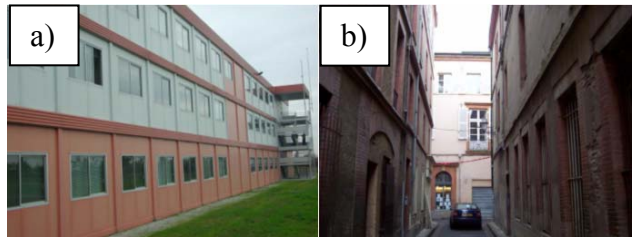
**Figure 2 – Functioning of the assistance mode.**

In the tests conducted hereafter, a real assisted GPS architecture developed by Alcatel Alenia Space has been used together with the assisted GPS module.

The assistance server is permanently processing GPS signals to form the assistance message. It is also capable of including EGNOS corrections, even if this feature is not used in the following of the study. The wireless connection used for data transmission is supported by the GPRS protocol of the European GSM cellular network.

Performance Assessment:

As an illustration of both HSGPS and AGPS performance, several TTFF tests have been conducted in light indoor and urban canyon environments, as shown in Figure 3. Several handsets have also been tested: 2 AGPS based and 1 HSGPS based. The results given hereafter are to be understood for a cold start positioning mode.



**Figure 3 – Light indoor (a) and urban canyon (b) test environments.**

The different TTFFs obtained during the tests are summarized below in Table 2. They clearly demonstrate the improvements brought by the assistance data on the processing of GPS signals.

Parameter	TTFF		
	AGPS	AGPS	HSGPS
type	AGPS	AGPS	HSGPS
Handset	Motorola A835	HP 6515	GlobalSat BT 338
Outdoor	20	14	38
Light Indoor	21	16	42
Urban Canyon	42	35	150

Table 2 – TTFF results of typical tests conducted in the environments of Figure 3.

The tracking results of a pedestrian going inside and outside buildings are shown below. Figure 4 presents the tracking made by a HSGPS, whereas Figure 5 illustrates the results obtained with an AGPS. The reference trajectory is plotted in yellow in both figures. At the beginning of the two trials, the pedestrian is outside and keeps walking outside buildings until he arrives at point A. He then enters the building and keeps walking inside until point B when he gets outside until the end of the trial.

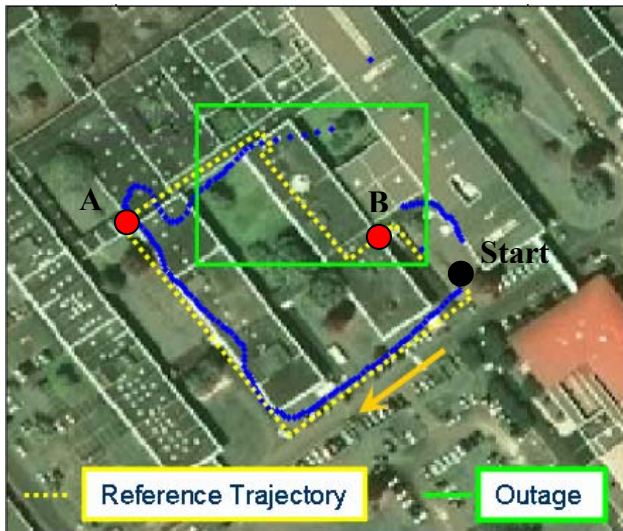


Figure 4 – HSGPS tracking result of a pedestrian going inside and outside buildings.

The AGPS position solution is smoother than the HSGPS one. It is less affected by multipath especially when the pedestrian is close to the buildings while walking outside. The reacquisition of the GPS signals is also faster in the case of the AGPS, and the position solution more accurate.

As it can be seen in the two figures, both AGPS and HSGPS experience outages which makes impossible the continuous tracking of pedestrian inside buildings and consequently justify the need of an augmentation system.

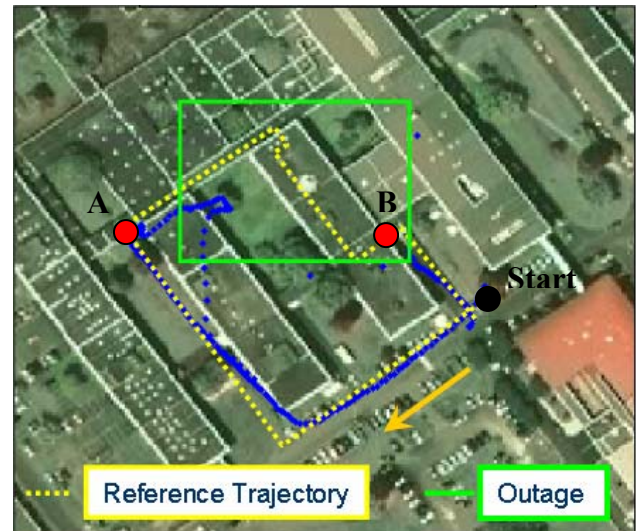


Figure 5 – AGPS tracking result of a pedestrian going inside and outside buildings.

## PEDESTRIAN NAVIGATION SYSTEM

In this study, we managed to augment the GPS-based positioning method in order to increase the position availability wherever the user is. The use of a low-cost IMU is more specifically addressed in the following.

The measurement unit used throughout this study is the off-the-shelf MTi from Xsens, which is composed of a triad of accelerometers, gyroscopes and magnetometers, whose technical characteristics are given below in Table 3. Since the sensors are low-cost (about \$10 each if bought in large volume) their respective performance can be expected to be low as well. Calibration procedures must then be done in order to improve the quality of the measurements which in turn decreases the impact of the errors in the inertial navigation algorithm. However, such calibrations procedures have a non negligible impact onto the final cost of the sensors unit. The Xsens MTi cost including the software development kit is indeed about \$1600.

	rate of turn	acceleration	magnetic field	temperature
Unit	[deg/s]	[m/s <sup>2</sup> ]	[mGauss]	[°C]
Dimensions	3 axes	3 axes	3 axes	-
Full Scale	(units) +/- 300	+/- 17	+/- 750	-55...+125
Linearity	(% of FS) 0.1	0.2	0.2	<1
Bias stability	(units 1σ) 5	0.02	0.5	0.5
Scale factor stability	(% 1σ) -	0.05	0.5	-
Noise density	(units √Hz) 0.1	0.001	0.5 (1σ)	-
Alignment error	(deg) 0.1	0.1	0.1	-
Bandwidth	(Hz) 40	30	10	-

Table 3 – MTi Sensors Specifications [2].

As biases may dramatically impact the classical inertial navigation, the mechanization used to propagate

the position of the user using inertial measurements is rather based on the modeling of the pedestrian velocity together with an estimation of its heading [1]. The velocity model used in this study is given below in equation (1). It is composed of three parameters computed on the basis of a time window of 2 seconds.

$$v_{pedestrian} = A \cdot MEAN + B \cdot FREQ + C \cdot STD \quad (1)$$

where:

- $v_{pedestrian}$  is the modeled velocity of the pedestrian.
- MEAN, FREQ and STD are respectively the mean, the characteristic frequency and the standard deviation of the acceleration magnitude
- A,B,C are coefficients computed through regression

The coefficients A, B and C are computed through regression whether on-line when GPS velocity measurements are available or off-line using special calibration procedures. The trajectory of the pedestrian is then reconstructed using the usual Dead Reckoning approach as given in equation (2).

$$\begin{aligned} N_k &= N_{k-1} + \Delta d_{[k-1,k]} \cos(\psi_k) \\ E_k &= E_{k-1} + \Delta d_{[k-1,k]} \sin(\psi_k) \end{aligned} \quad (2)$$

where:

- $N_k$  and  $E_k$  are the north and east components of the user's position at epoch k
- $\Delta d_{[k-1,k]}$  is the travelled distance between epochs k-1 and k
- $\psi_k$  is the mean heading of the pedestrian between epochs k-1 and k.

Equation (2) clearly shows the close relationship of the mechanization performance and the accuracy of both the heading and the estimated traveled distance of the pedestrian. Even if the mechanization principle limits the impact of the accelerometers bias, the gyroscopes errors still degrade the overall performance. Improvement is thus possible to complete the optimization of the mechanization in the particular case of the pedestrian navigation.

Given these statements, an attitude filter capable of estimating the gyroscopes bias has been developed. Accelerometers can indeed be used to sense the local gravity, which allows the estimation of the measurement unit inclination. Magnetometers measurements, once rotated into a horizontal plane, can be used to sense the Earth's magnetic field, allowing the estimation of the measurement unit heading.

However, the implementation of such correction principles is not as straightforward as it seems. The

motion of the IMU indeed disturbs the correction of the inclination by the accelerometers, and consequently the heading as well. Interferences may moreover disturb the measurement of the Earth's magnetic field, making the magnetic heading no more reliable for correction purposes of the gyroscope-based heading bias. Another issue that must be handled deals with the Euler's angles singularity that occurs when the pitch angle reaches  $\pm 90^\circ$ . In such a use case, both roll and heading angles are no more defined so that the output of the attitude computation algorithm is completely erroneous. As the IMU may be placed with a random attitude onto the body of the pedestrian to track, this issue is of tremendous importance.

Figure 6 summarizes the principle of the attitude filter taking into account all the aforementioned issues. The attitude is computed using two separate Kalman filters for inclination and heading estimation. Both the rotation rates and the acceleration of the user are estimated in the inclination filter.

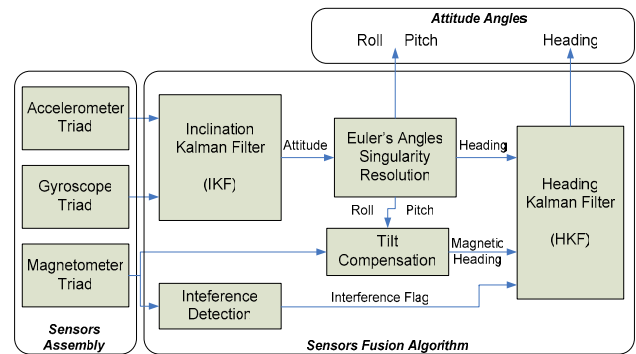


Figure 6 – Attitude Filter Principle.

The optimized pedestrian navigation system used in the following of the study to propagate the position of the pedestrian is illustrated below in Figure 7. It is referred in the following as the standalone Pedestrian Navigation System (i.e. the PNS relying only on IMU data).

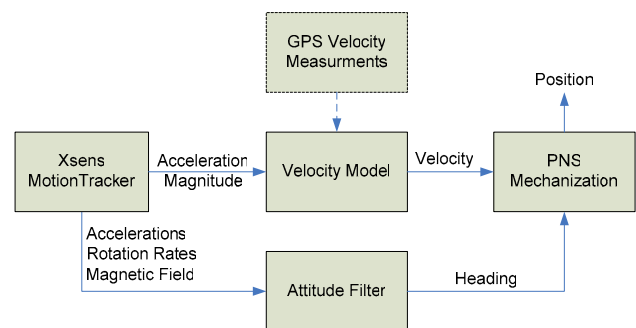


Figure 7 – Pedestrian Navigation System Principle [6].

## INTEGRATED PEDESTRIAN NAVIGATION SYSTEM

To be able to track a pedestrian whatever its location, we fused both GPS-based positioning modules with the Pedestrian Navigation System developed around the low-cost IMU. The integration methodology followed is a loose coupling integration using a Kalman filter, as described in Figure 8.

The filter is composed on 7 states. The estimates are the north and east position errors  $\partial N$  and  $\partial E$ , the velocity error  $\partial v$ , the heading error  $\partial \psi$  and the regression coefficients errors  $\partial A$ ,  $\partial B$ ,  $\partial C$ .

All the filters as well as the pedestrian mechanization are implemented in C/C++ for real time purposes. The software application is also able to store all raw data as outputted by the different sensors for post processing perspectives.

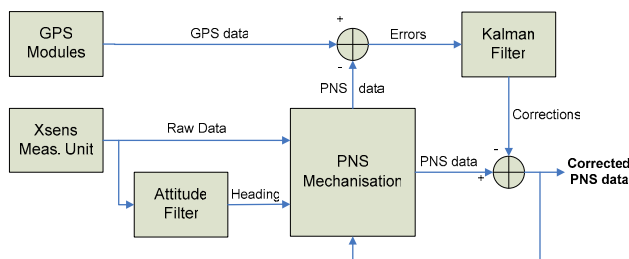


Figure 8 – Sensor Fusion Architecture.

The GPS-based positioning modules are designed to increase the availability of the position solution. As a consequence, even if weak signals are tracked, the modules are able to compute the location of the user. However, such measurements (namely position and velocity) are very noisy and affected by multipath in harsh environments. In such conditions, the initialization of the pedestrian navigation algorithm may be unreliable, which consequently will degrade the positioning performance of the integrated navigation system.

To avoid such use cases, a decision logic is added into the sensor fusion acquisition. This condition has been found empirically. She characterizes the quality of the GPS measurements as follows: if the C/N0 of the 4th satellite used to compute the position solution is below 25dBHz, the integrated system deliberately relies exclusively on the IMU data. RAIM techniques could have been implemented to detect and exclude bad GPS measurements as discussed for example in [3] and [4], but the integration level chosen in the frame of this study is too high (position and velocity level). Nevertheless, such quality monitoring techniques do not provide reliable results due to the limited amount of data available for analysis purposes.

Figure 9 illustrates the integrated pedestrian navigation system developed within the scope of this study. The off-the-shelf MTi is connected via the USB port to the processing unit (Dialogue FlyBook) and provides accelerations, rotation rates and magnetic field measurements. The GPS module we used is Bluetooth capable and can be configured whether in a high sensitivity or assisted mode. Data are provided through NMEA frames to the processing unit. The Alcatel Alenia Space assistance server processes the GPS signals to elaborate the assistance data that are transmitted to the processing unit on the demand of the user through a wireless connection (in the test conducted, the wireless connection is the GPRS, which is supported on the GSM cellular network). The data are then uploaded into the assisted GPS chipset for further processing. The processing unit computes and displays the position of the user on a map that can be whether on its screen or a distant one.

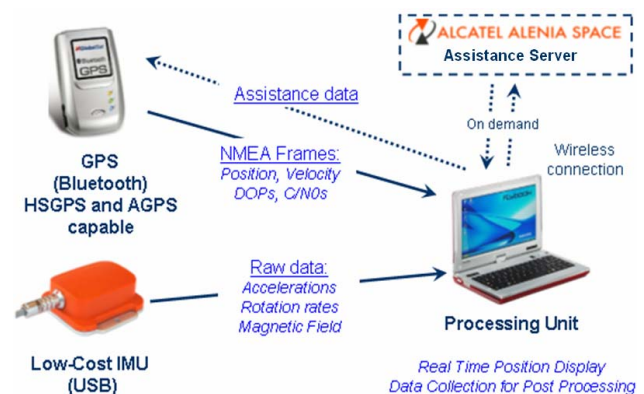


Figure 9 – Integrated Pedestrian Navigation System.

## TEST RESULTS

The integrated pedestrian navigation system described in the previous section has been tested in actual conditions. Test results are presented in this section.

First, the hybridization result of a HSGPS with the low-cost IMU is shown. The test is the same as those presented earlier and shown in Figure 4. In green is plotted the output of the integrated navigation system using both information of the PNS and the HSGPS module, whose measurements are used to correct the PNS errors. In red is plotted the position solution of the integrated navigation system relying exclusively on the MTi data. In that case, the GPS measurements are whether declared not reliable according to the empiric decision logic added in the sensors fusion filter, or simply not available (outage). As it can be seen in Figure 10, the hybridization tremendously improves the position availability and accuracy, especially when the pedestrian is inside the building.



**Figure 10 – HSGPS/IMU Hybridization Results.**

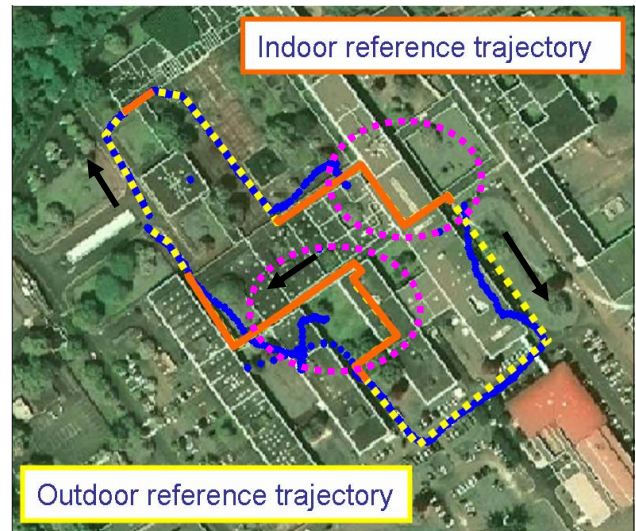
The same conclusions can be drawn in the case of the hybridization with the AGPS module, as shown in Figure 11.



**Figure 11 – AGPS/IMU Hybridization Results.**

One interesting point to notice according to the results shown in the two above figures is that there are more epochs where the navigation system relies exclusively on the IMU in the HSGPS hybridization case than in the AGPS hybridization case. This suggests that AGPS is more suited to hybridization purposes. The measurements are indeed less noisy and more reliable according to our decision logic. The position solution is also more accurate thanks to a better dilution of precision due to the availability of the ephemeris of all the satellites that are tracked (as compared to the HSGPS case where data need to be demodulated for each satellite).

A longer test using only the AGPS module has been conducted. The reference trajectory and the AGPS position solution are plotted below in Figure 12. The reference trajectory is plotted in yellow to show the outdoor path followed by the pedestrian and in orange when the pedestrian walks indoors. Two outages in the AGPS single point solution can be observed (identified as the magenta circles), which makes impossible the tracking of the pedestrian inside the buildings.



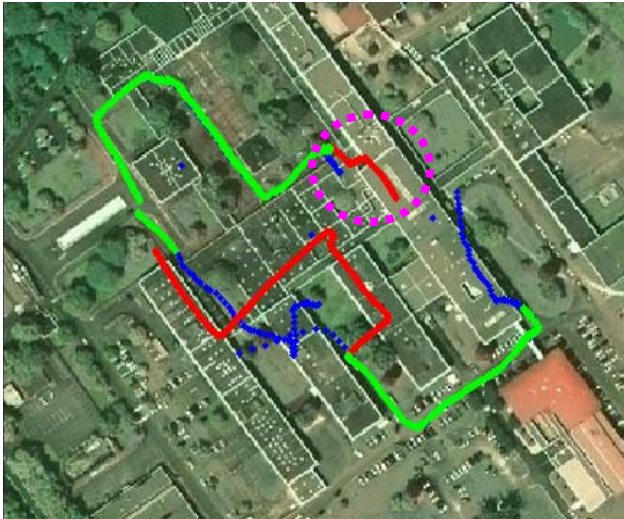
**Figure 12 – Pedestrian trial inside and outside buildings. AGPS Single Point Position Solution (blue) and Reference Trajectory (yellow outdoors, orange indoors).**

The hybridization results are plotted in Figure 13 using the same color legend as in the previous graphs. The hybridized position solution is far more relevant of the true trajectory followed during the trial. There are two main periods where the integrated navigation system relies exclusively on the IMU data, which corresponds approximately to the outages experienced by the AGPS. The estimation of the heading is quite good, but the traveled distance is sometimes very badly estimated, as for example during the first outage (identified by the magenta circle in Figure 13).

To analyze the reason of this bad traveled distance estimation, Figure 14 presents the regression coefficients as corrected by the Kalman filter as well as the availability of the GPS measurements (which includes the epochs when the GPS measurements are declared unreliable). Just before the first outage (around time 2 min), the regression coefficients experience very large variations due to very noisy GPS measurements that have not been excluded according to the first decision logic implemented in the sensors fusion filter (in other words, the 4<sup>th</sup> satellite used to compute the position solution is higher than 25 dBHz). When the first GPS outage occurs,

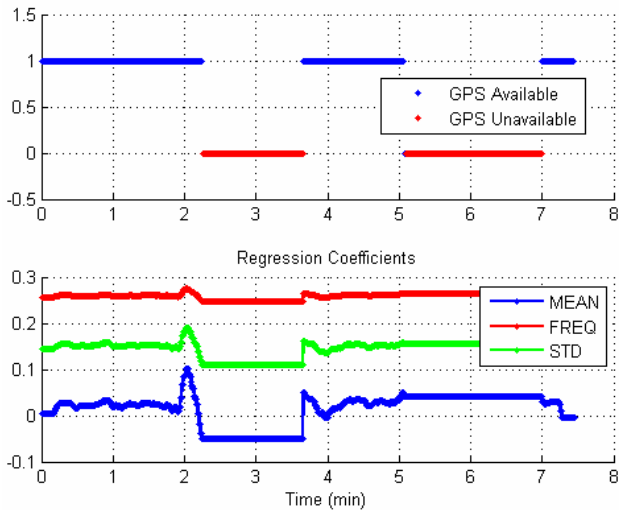


the inaccurate regression coefficients are kept constant leading to a bad estimation of the traveled distance. In the case presented hereafter, the coefficients are lower than their value estimated with good GPS measurements, which explains why the estimated traveled distance is so short. The first decision logic is not efficient enough to prevent bad GPS measurements from degrading the initialization of the PNS for further standalone navigation.



**Figure 13 – AGPS/IMU Hybridization. Long Test.**

In order to enhance the monitoring of the quality of the GPS measurements, another condition is added to the sensors fusion filter according to the conclusions that have just been drawn.

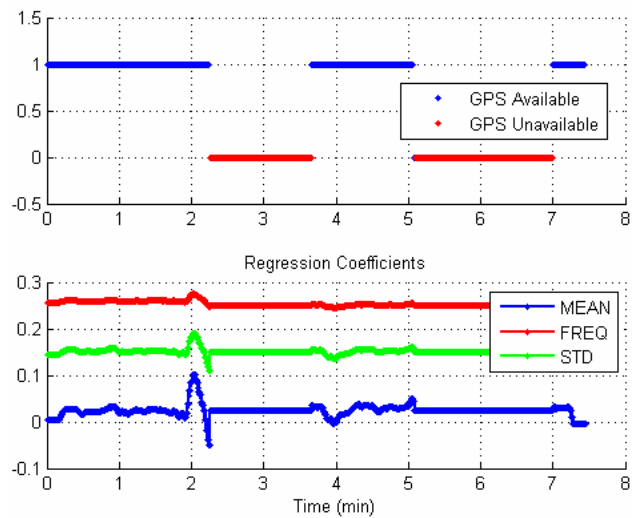


**Figure 14 – GPS measurements availability and Regression Coefficients**

If a strong variability in the regression coefficients is detected (which obviously does not reflect a real change in the pace of the pedestrian), then the GPS

measurements are assumed unreliable. The regression coefficients are furthermore corrected by their mean value over the previous minute, which is an approximation of their actual values.

The effect of the correction brought to the regression coefficients is illustrated in Figure 15. The method is clearly efficient as compared to the previous estimation. It also allows the detection of bad GPS measurements. Such a quality test on the estimated regression coefficients has been found enough reliable to remove the first decision logic based on the  $C/N_0$  of the 4<sup>th</sup> satellite used in the computation of the user's position. As it can be seen in Figure 15, the regression coefficients have a smoother shape with is consistent with the typical pace of a pedestrian



**Figure 15 – GPS measurements availability and Corrected Regression Coefficients after Variability Detection (Post Processing Results).**



**Figure 16 – AGPS/IMU Hybridization Results. Long Test with Corrected Regression Coefficients (Post Processing Results).**

The impact of correction method onto the accuracy of the position solution as provided by the integrated pedestrian navigation system is illustrated in Figure 16. The traveled distance accuracy is tremendously increased during the first GPS outage and the position solution is clearly relevant of the true path followed inside the building. The RMS horizontal accuracy stays within 10 meters from the true trajectory for the whole test, even during the two outages which both last about 2 minutes.

## CONCLUSION

A real time pedestrian navigation system has been developed based on the combination of GPS modules with a low-cost IMU in order to face the typical GPS outages that occur inside buildings and increase the position solution availability whatever the location of the pedestrian. An optimized pedestrian mechanization has been used to limit the impact of both accelerometers and gyroscopes bias and consequently improve in the same time the performance of the navigation system during outages. Both integrations with HSGPS and AGPS have been tested

Results have shown that AGPS provides measurements less noisy than HSGPS does, which makes it more suited to hybridization purposes. A method aimed at detecting unreliable AGPS measurements through the dynamic of the estimated regression coefficients has also been described. Its implementation and test on real data collected during the different trial exercised has demonstrated its efficiency. It finally has been shown that the accuracy of the developed integrated pedestrian navigation system stays within 10 meters (RMS horizontal position error) from the true trajectory according to the trial exercised.

## ACKNOWLEDGMENTS

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