DEMONSTRATION OF UBIQUITOUS POSITIONING WITH WIFI, INS AND ASSISTED HS-GNSS HYBRIDIZATION

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1. INTRODUCTION

In the recent years, GNSS applications and services have experienced an incredible growth due to the authorities' commitment to providing free, reliable and uninterrupted GNSS signals to civil users around the world. In parallel with this decision, the issue of legal mandates on location identification such as the US FCC E911 and the European E112 recommendation has certainly become the primary driver for the industry of GNSS receivers. The results of these efforts and investments on GNSS receiver technology have allowed the introduction of GNSS receivers in many areas, but especially, in those related with small, portable and lightweight technological equipment. However, and despite of these efforts, many challenges still remain for the widespread deployment of GNSS services. This is the case of seamless and ubiquitous positioning applications for which difficulties arise when working scenarios differ from clear sky outdoor conditions. In the presence of either urban or indoor scenarios, the reception of satellite signals is seriously degraded and it becomes very difficult for traditional GNSS receivers to keep track of the visible satellites.

The problems encountered when operating GNSS receivers is harsh environments has motivated the development of the so-called high-sensitivity (HS) receivers. HS-GNSS receivers adopt a two-fold strategy: the use of advanced signal processing techniques for detecting weak GNSS signals and the incorporation of alternative positioning technologies to GNSS. These alternative technologies may be already incorporated in the user's terminal (e.g. inertial sensors) or may be already deployed in the user's environment (e.g. access points of wireless local area networks). Based on these premises, the present paper presents the system architecture of a hybrid indoor positioning demonstrator platform developed under the ESA DINGPOS project. The objective of this project is to study, develop and test the most promising state-of-the art indoor positioning techniques. The result is an indoor demonstration platform that combines HS-GNSS with MEMS sensors, UWB and WiFi measurements. Data fusion is then implemented by a hybridization module based on the extended Kalman filter whose output is further refined by using map matching techniques.

Although the DINGPOS platform is still under development, now entering the integration phase, this paper provides an overall description of the indoor positioning demonstrator from a system level perspective. Preliminary results are also presented to illustrate the goodness of WiFi, MEMS and HS-GNSS hybridization for solving the challenges of ubiquitous positioning.

2. THE HYBRID INDOOR NAVIGATION PARADIGM

The main problem to be solved for allowing seamless and ubiquitous positioning is the signal degradation when operating in urban or indoor scenarios. The most important degradation comes from the severe signal attenuation, especially when operating indoors, due to the presence of walls, ceilings, and other obstacles. Attenuation levels on the order of 20 to 70 dB can easily be experienced, exceeding by large the admissible power fluctuations of traditional GNSS receivers. Apart from this effect, the presence of diffuse multipath and near-far interferences from strong satellites further complicates the acquisition of GNSS signals. In these circumstances, the development of advanced signal processing techniques for the detection of very weak signals becomes a must. Acquisition of such a weak signal is theoretically feasible, but it imposes stringent demands in terms of integration time and thus, in terms of precise knowledge of synchronization errors such as Doppler and clock instabilities [1]. Moreover, such a long integration interval prevents the receiver to keep track of the navigation message, since more than one navigation bit durations have to be integrated to produce a reliable detection metric. In these circumstances, indoor GNSS receivers have no choice but to resort to external sources with the aim of retrieving the required data and time stamps for determining the PVT solution. This necessity leads to the concept of assisted-GNSS, where the information concerning the navigation message and other extra data are provided by a location server [2]. This configuration constitutes the fundamentals of the indoor navigation paradigm, where both high-sensitivity techniques and assisted-GNSS information are combined to allow the ubiquitous operation of GNSS receivers.

Further improvements can be obtained if GNSS takes advantage of other existing technologies within the user's reach to improve the overall reliability of GNSS measurements. These alternatives can be classified into two main categories depending on whether they require some degree of infrastructure (e.g. WLAN or cellular communication networks) or they can be used in stand-alone mode operation (e.g. inertial sensors). The latter are of particular interest because they do not need any kind of infrastructure and thus, they can easily be incorporated in the receiver at a reduced cost. However, non-infrastructure positioning technologies do often have the drawback of exhibiting drifts in their output measurements. For this reason non-infrastructure positioning technologies such as inertial sensors have to be carefully hybridized by properly weighting the information they provide in time. This hybridization can be further refined by using 3D map matching techniques to correct the estimated user's route according to urbanistical and topographical information. The overall result of this combination of technologies configures the concept of advanced positioning platform to be presented in this paper.

3. DINGPOS PLATFORM DESCRIPTION

The DINGPOS platform is based on the system architecture shown in the block diagram of Fig. 1. Each of the positioning technologies is associated to a navigation module that behaves as a state machine with status: "offline", "configuration", "idle" (ready) and "processing". The control of these statuses and of the whole platform is implemented via a man machine interface (MMI) where the user can select the navigation modules to be used and the system configuration.

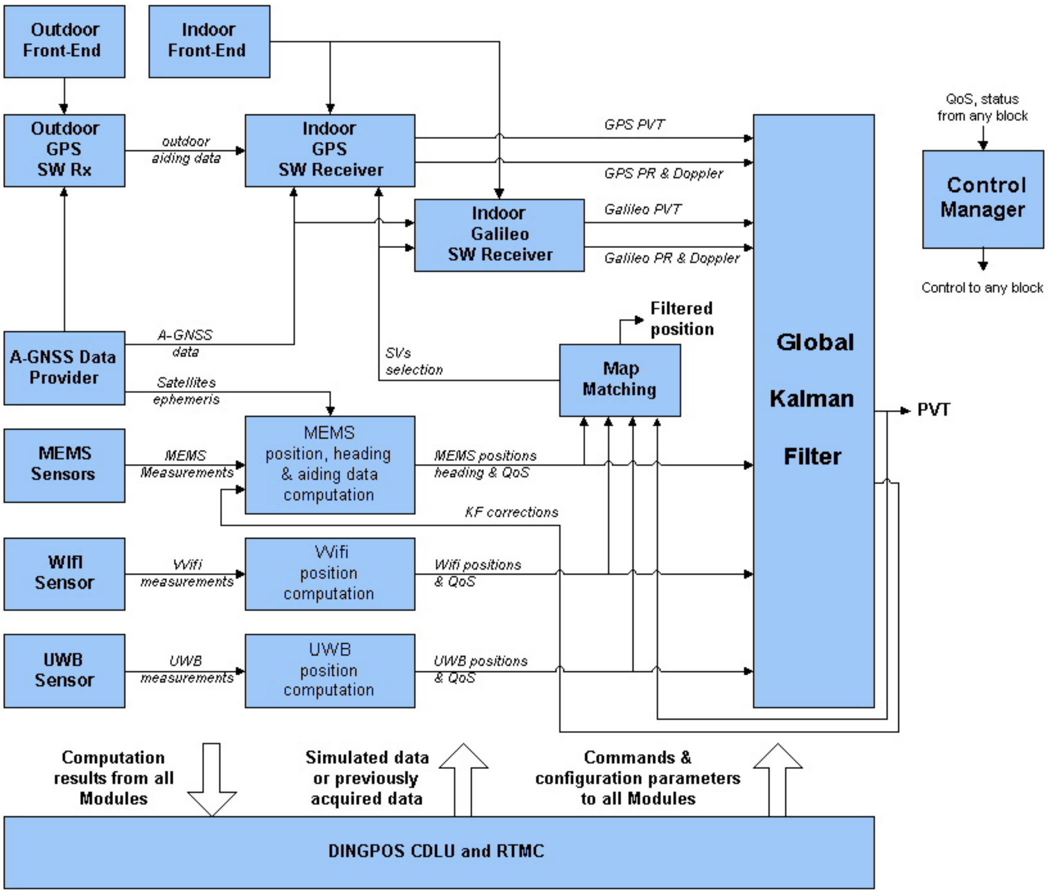

Fig. 1 DINGPOS demonstration platform architecture.

In order to manage all platform modules and the communication between them, a real time monitoring and control unit (RTMC) is implemented behind the MMI. The RTMC manages the configuration and monitoring of each module, the interfacing protocol between different modules, the retrieval and storage of output data and the visual display through the MMI. Next, a short description is provided for the main elements of this platform.

3.1. Assisted/HS-GNSS

The DINGPOS platform incorporates assisted-GNSS capabilities that are used in connection with the Thales Alenia Space location server. The assistance data comprises information regarding the reference time and location, DGPS corrections, ephemeris data, ionospheric and UTC models, almanac, acquisition assistance data and real time integrity. This information is downloaded via an XML file according to the 3GPP defined RRLP protocol and exchanged within OMA defined SUPL transactions. This assistance data is then used by the HS-GNSS software receiver to detect and acquire visible satellites.

The HS-GNSS receiver operates in snapshot mode and is able to detect GPS L1/L5 as well as Galileo E1/E5a signals in rather hostile indoor environments. To do so, advanced signal processing techniques have been implemented such as the double-FFT acquisition method, and near-far detection strategies to avoid interference from undesired strong satellites. The acquisition module is certainly the core of the HS-GNSS receiver and it is based on the double-FFT algorithm [3], which can be understood as the optimal implementation of the time-frequency matched filter to the received signal. This algorithm consists of two FFT stages: the first one for correlating the input signal with the local code, and the second one for a fine Doppler search. The results are stored in a three dimensional matrix with dimensions corresponding to the number of samples per code, the number of fine frequency bins and the bit transition (or secondary code) hypothesis. This matrix is then noncoherently integrated with the aim of extending the overall correlation interval. This will allow reliable signal detection in the presence of residual frequency errors and possible clock instabilities. After noncoherent integration, noise floor normalization is undergone for equalizing all frequency bands and thus avoiding false detections due to the different spectral power levels. The entries of the accumulated and normalized acquisition matrix are then compared with a threshold for signal detection. In case of declaring the presence of signal, one more step must be performed to ensure that acquisition was not due to near-far effects from strong visible satellites. This near-far validation stage consists on determining whether the underlying statistics of the despreaded samples correspond to the expected statistical distribution (i.e. absence of near-far effects) or not [4]. Once signal acquisition has been validated, the user's position is determined via the Peterson method [5], which incorporates the information regarding the satellites Doppler for solving the 1ms pseudorange ambiguity. This ambiguity appears when the navigation message cannot be accessed, that is, when the correlation time exceeds the bit duration, as it occurs in indoor environments.

3.2. Inertial sensors

Using sensors as an augmentation to GNSS-based positioning systems is all the more interesting as their integration into consumer products has been constantly increasing for the last two years. Single-die sensors capable of providing measurements along three orthogonal axes can now be found in large volume (as for instance accelerometers and magnetometers [6]), whereas other sensors are likely to follow (currently two axis gyroscope into one single-die [7]). Sensor-based positioning methods have been widely studied. Traditional navigation algorithms may have very different performance in terms of accuracy depending on the quality of the sensors embedded in the measurements unit. Two typical mechanizations can be used to navigate, namely the Inertial Navigation System mechanization [8] or the Pedestrian Navigation System mechanization [9].

3.3. Wireless networks

During the last few years, Wireless LANs have experience a huge growth in popularity, mainly due to widely available low cost standardized commercial solutions, interoperability between equipment manufacturers, easy installation and maintenance and freedom to access data anytime, anywhere. The Wifi positioning technology takes benefit of this development together with mobile network location technologies. Most of the Wifi-based positioning techniques relies on Cell Identification (CI), Received Signal Strength (RSS), Wifi Time of Arrival (TOA), Wifi Time Difference of Arrival (TDOA). Angle of Arrival (AOA) techniques are not really applicable as highly directional antennas are not used in Wifi equipments. UWB technology is another example of wireless technology which is especially indicated for precise positioning in indoor environments. Except for the physical layer advantage of using a very large bandwidth, positioning algorithms for UWB signals do follow the same reasoning as for conventional narrowband positioning systems and, in practice, significant advantages have been reported for the combined used of signal strength and time-of-arrival measurements.

3.4. Real-time implementation

Phase 1 of the DINGPOS project was dedicated to the navigation and integration algorithms development and evaluation. The processing of the data from the different sensors was performed in post-processing using Matlab software and the interfacing between the different modules in the platform was carried out by means of data files. The goal for the DINGPOS platform is to operate in real or near real time for the different configuration modes with minimal operator supervision. This is most significant for the high-sensitivity Galileo and GPS software receiver modules due to the very high computational burden associated to the long coherent and non-coherent signal integration proposed to recover the weak signals specified. Interfacing between the processing modules and to the assistance data server, data synchronization, data logging and monitoring and control aspects for the different types of sensors being integrated also need to be resolved.

To this purpose it was planned that, once the individual and joint performance of the proposed algorithms had been evaluated, the different processing modules would be implemented in a compiled programming language, C or C++, to optimize the system requirements and running time on a PC platform. The implementation of the GPS and Galileo software receivers based on algorithms proposed by UAB is being undertaken in a closely coordinated manner by TAS and ADI, respectively.

The DINGPOS platform was initially scoped around a high specification desktop PC running MS Windows OS. A quad-core microprocessor with 4 GB of RAM specification was originally envisaged. The processing software will make the best possible use of the multiple processing cores with parallel thread processing and taking advantage of the SSE extended microprocessor instruction sets Single Instruction Multiple Data (SIMD) capabilities.

In pursuit of maximum performance on a standard PC, the possibility of utilising the power of the Graphics Processing Unit (GPU) has been explored. The GPU is increasingly being used for applications that are non-graphics related. This has been aided with the introduction of GPU SDKs by graphics hardware companies, which allow the GPU resources to be tapped into using language constructs that are familiar to application programmers. The system that was seen to provide the most mature and ease of use was nVidia's CUDA (Compute Unified Device Architecture).

Graphics chips have been developed and refined over the years to cope with the demands of high polygon count graphical applications (typically games). The computations involved with transposing polygons from the 3D world to the 2D screen space, with the associated texture and shading computations, have led to highly parallel SIMD architectures. A typical modern graphics card can have hundreds of processor cores, each of which is able to run hundreds of threads concurrently. The result is a situation where thousands of threads are able to run in parallel. This is ideal for computations that involve repetitive operations performed on large data sets, such as matrix computations. The processing required from the initial FFT through to the required output in the proposed double-FFT acquisition algorithm is all highly suited to being run on the GPU architecture.

4. HYBRIDIZATION TECHNIQUES

In the context of the DINGPOS project, by hybridization is understood the process of blending all the observations and measurements available in a particular epoch in order to optimally estimate a set of states. In other words, DINGPOS shall be able to process all the available information for vector state estimation every epoch.

The Extended Kalman Filter is the selected technique for the DINGPOS project. The Extended Kalman Filter (EKF) linearizes the measurements and the state vector dynamics around the last epoch. This is the case of indoor navigation where the user motion is not deterministic, where the outputs of sensors like an IMU are not lineal, and where the geometry of reception of the signal based measurements (either GNSS, Wifi, Bluetooth UWB or any other signal based mechanisms) changes with the time or the user motion.

It is well know that there are different strategies to combine or hybridise the measurements with Kalman type filters. There are mainly two different approaches based on whether the filter inputs are the positioning or state vector estimation by each sensor (loosely coupled approach) or raw measurements from each sensor (tightly coupled approach). It is out of the scope to explain the intricacies of each approach. The interested reader is referred to [10] for detailed information.

In the context of the DINGPOS project, the selected hybridization strategy is the tight-coupled approach. The reasons are the following:

- Accuracy: The GNSS pseudorange and Doppler measurements are introduced in the filter, obtaining a blended solution with the INS sensor data more accurate than with loose coupling.
- It can use GNSS information in a useful way even if less than 4 SVs are available.
- Tight coupling navigation solutions are more robust, since measurements subject to high errors can be more easily detected using the information from all sensors together.

In other words, due to the fact that the GNSS signal arrives with high multipath and attenuated, it was considered that the tight coupled approach best adapts to the context of indoor navigation with the DINGPOS sensor's platform.

Two implementations are possible regarding each integration strategy: open-loop or closed-loop mode. In open-loop mode the Kalman filter errors estimations are used to correct the sensors outputs, without feedback to the sensors. Without feedback, the mechanisation error grows rapidly, and thus can introduce large errors into the integrated system.

In a closed loop integration scheme, a feedback loop is used to correct the raw sensors outputs and other mechanisation parameters using the error estimates obtained from the Kalman filter. Sensors mechanization outputs are kept with small errors and outliers are more likely to be detected. Again, the interested reader is referred to [10] for further information.

In the context of the DINGPOS project, where the use of low-cost sensors (specially the inertial ones) it's one of the highlights, the use of a closed loop integration scheme is mandatory. Hence, the hybridization module of the DINGPOS platform implements a tight-coupled with closed-loop Extended Kalman Filter.

The authors are fully aware of other techniques for hybridization in indoor environment conditions. Levels, walls and doors impose constraints in the feasible motion and positioning solutions. The introduction of these domain considerations seems difficult to be introduced in a generic approach in the classical EKF and has driven the search of other algorithms. New alternatives recently introduced are the unscented filters (UFs) (see [11]), also known as sigma-point filters, and the particle filters (see [12] and [13]) which are being postulated recently for positioning estimation in indoor navigation (e.g., [14] and [15]) thanks to its suitability to manage the environment constraints. The use of these filters is, however, out of the scope of this paper and only performance with EKF will be presented.

5. PRELIMINARY PERFORMANCES

5.1. Insights into the use of GPU for GNSS processing

A preliminary test has been carried out to assess the potential and complexity of using a GPU for the Galileo software receiver. CUDA is shipped with two higher level libraries – CUFFT and CUBLAS. These are based on the well known libraries FFTW and BLAS respectively. These offer the benefits of these well known libraries but with the added benefit of gaining access to the GPU's power. The GNSS software receivers, and in particular the extended signal correlations over the code/Doppler/bit edge search space, are the most processor intensive tasks in the DINGPOS system. The one factor that can disrupt the performance gains obtained from the GPU is the memory transfer of data to and from the GPU. The inputs to the FFT must unavoidably be transferred to the GPU. However, it is then of great benefit to do all the processing possible after the FFT until the required answer is obtained so as to minimise the amount of data that is returned to the CPU.

Some prototyping programs have been written to test the premise that moving the FFT processing to the GPU will have performance benefits. The existing MATLAB code for the GPS has been analysed to get an idea of the processing required for each cycle of work. The initial FFT and inverse FFT operations are of a size of 32,768 data points. At this size of analysis the benefits of the GPU are starting to take hold. The run times for performing FFT and a subsequent inverse FFT on data blocks of 32,768 points repeated 5,000 times is summarized below:

- CPU time = 7.5 seconds.
- GPU time = 3.6 seconds.

For the GPU program the input array is copied to the GPU for every iteration (32,768 complex float) to include the received signal transfer delay. As can be seen, the run time is less than half that of the CPU. This a worthwhile improvement considering the ease of implementation, the future benefits if the rate of progress of graphics hardware remains at its high level, and the potential off-loading of work from the CPU that could be taken up by parallel software. It is thought that the performance gain could be improved upon. Combinations of parallel CPU/GPU processing will be considered for the most challenging signals.

5.2. HS-GNSS performance

Preliminary results are provided in this section to illustrate the HS-GNSS performance. Indoor scenarios were generated with a Spirent simulator and a power attenuator to reduce the output power levels down to the indoor range. A total of 8 visible satellites was generated, 4 of which being affected by a -6 dB specular multipath component. Based on this baseline configuration, Fig. 2 presents the HS-GNSS position fixes for a static scenario, and Fig. 3 for a dynamic scenario, both with C/N0=25 dBHz. For the static case, different integration intervals were considered: 300ms, 600ms and 100ms, corresponding to 15, 30 and 50 noncoherent integrations of one bit period, which is the default coherent integration length of the double-FFT algorithm. It is interesting to observe the reduction in the position fixes jitter when increasing the integration interval in Fig. 2. For the dynamic case in Fig. 3, the trajectory describes a series of loops in a squared area of approximately 40 meters width and 40 meters height. Even for the outdoor case of C/N0=45 dBHz (red solid line), there is a significant jitter in position fixes due to the reduced dimensions of the user's trajectory compared to the inherent jitter of GPS position fixes (e.g. ionospheric errors, unfiltered position fixes, etc). However, even in the presence of 20dB attenuation, position fixes for C/N0=25 dBHz still keep track of the user's trajectory and can indeed provide a valuable information for the hybridization with the rest of sensors.

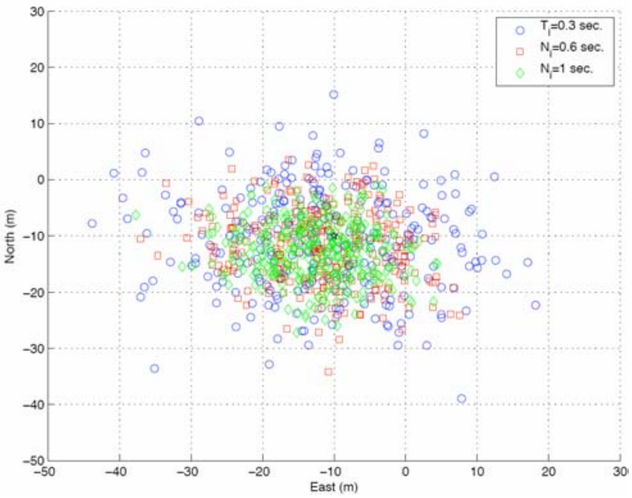

Fig. 2 HS-GNSS position fixes for a static scenario at C/N0=25dBHz.

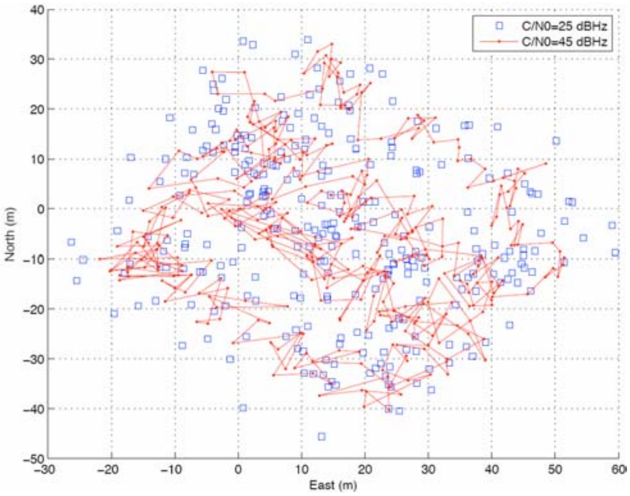

Fig. 3 HS-GNSS position fixes for a dynamic scenario following the reference trajectory.

5.3. MEMS and map matching performance

The DINGPOS platform comprises a Pedestrian Navigation System (PNS) module based on [16]. Accelerometer and gyroscope measurements are fed in a PNS to produce dead reckoning measurements. The PNS module is initialized off-line (initial position, initial heading) and the regression coefficients of the velocity model [16] are loaded before the test. These coefficients are taken from a previous test, which was conducted with another pedestrian in others conditions.

Fig. 4 shows the GPS reference trajectory (dashed curve) and the PNS trajectory (blue curve). The heading drift is clearly observable, accounting for 0.13 deg/s, which makes very difficult to reconstruct the user's trajectory.

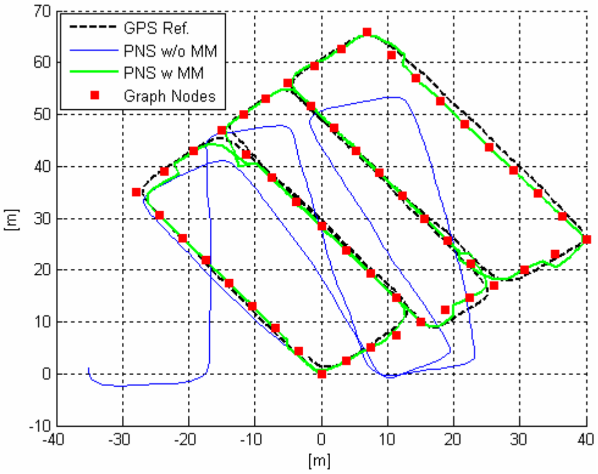

Fig. 4 MM results on PN positions.

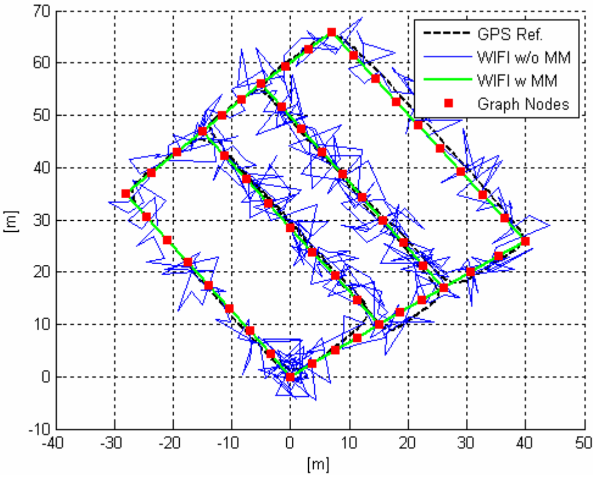

Fig. 5 MM results on WiFi positions.

However, the performance can be significantly improved by taking into consideration the aid of map matching techniques (MM). Two MM algorithms have been developed within the DINGPOS project: one for relative positioning system (PNS) and one for absolute positioning systems (WiFi, GPS). Both algorithms were tested on the data set generated for the integration test phase. Each MM algorithm uses a common diagram, built from the reference GPS measurements used to generate the reference trajectory. The results for the integration of MM with PNS and MM with WiFi are reported in the green curves of Fig. 4 and Fig. 5, respectively. The nodes of the diagram are shown as red squares. The WIFI positions in Fig. 5 are generated from the GPS reference trajectory on which a uniform distributed noise is added (5 m upper bound error). WiFi positions are very noisy and the Map-Matching filter enables to restrain these positions to the diagram. However, this not necessarily means that the accuracy is improved.

5.4. Hybridized performance: GNSS with MEMS and WiFi

As stated in Section 4, the hybridization approach finally considered in DINGPOS as the baseline case is a tight coupling navigation in closed loop Extended Kalman Filter. In this stage of the project, the filter processes as input measurements HS-GNSS pseudorange observables, WiFi positions and heading and velocity observations from a PNS model which processes IMU MEMS linear accelerations and angular rates. The hybrid filter processes one, several, or all the available sensors, each of them with different output rates. In this project phase the tuning of the EKF parameters (measurement noises and system dynamics uncertainty) has aimed to define a single configuration valid for any combination of input sensors. In order to assess the hybrid navigation filter performance several scenarios are considered. In a preliminary stage, these scenarios are addressing basically three different environments: soft indoor, urban and outdoor conditions. Deep indoor scenarios are to be considered in a subsequent stage by means of an outdoor-aided version of the HS-GNSS receiver. The environmental conditions are defined and characterized in terms of the signal-to-noise ratio.

The results of the soft indoor scenario are presented here. The pseudoranges observations have been generated with a software receiver in a soft indoor environment (C/N0 equal to 25 dBHz).

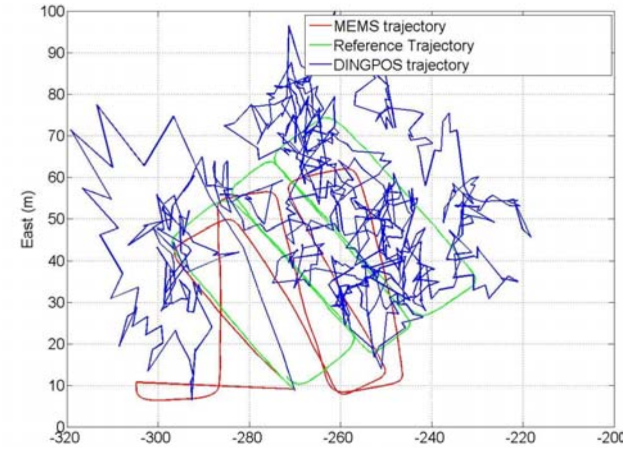

Fig. 6 EKF GNSS solution.

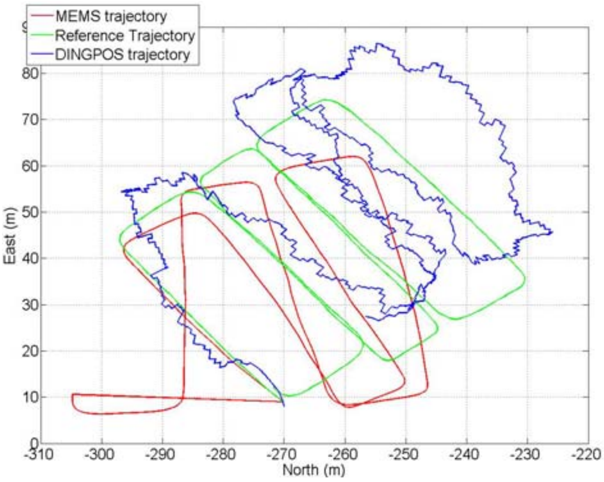

Fig. 7 EKF GNSS with MEMS solution.

Fig. 6 shows the EKF solution only with GPS measurements (pseudoranges observations with a frequency of 1Hz). In this case, the errors reach a maximum of 30 meters in the East component, and 16 meters in the North component. Nevertheless, the hybridization of GNSS with other sensors minimizes the errors; that is, improves the navigation solution. This enhancement can be seen in Fig. 7, where it is shown the trajectory obtained by the EKF with two different measurements: pseudoranges and the PNS speed and heading. The frequency of pseudoranges is 1Hz whereas the PNS speed and heading have a frequency of 50 Hz. In this situation, the maximum error has been reduced to 19 meters and 12 meters in East and North components, respectively.

Fig. 8 presents the EKF solution when three different measurements are used: GNSS pseudoranges with a frequency of 1 Hz, PNS heading and velocity with a frequency of 50 Hz and WIFI positions with 1Hz frequency. The maximum East error is 6.6 meters, while the North component is 5 meters away from the reference north component in the worst case. Again, the hybridization of GNSS and MEMS measurements with WIFI positions decreases the errors and makes the position solution follow the reference trajectory more accurately. To better understand the consequences of sensors hybridization, a comparison between the position errors in the three hybridization modes (GNSS, GNSS with MEMS and GNSS with MEMS and WIFI) is made in figure 6. Several conclusions can be drawn:

- The position error in GNSS mode and GNSS with MEMS mode has a drift (green and red plots) that does not appear in GNSS with MEMS and WIFI mode (black plot). This drift is caused by bad calibration. Only when WIFI is available is possible to estimate the calibration states, thus making the position error approach to zero.

- Comparing the GNSS mode solution (green plot) with the one obtained with GNSS and MEMS (red plot) it can be seen that the introduction of PNS heading and velocity in the EKF make the errors become smoother.

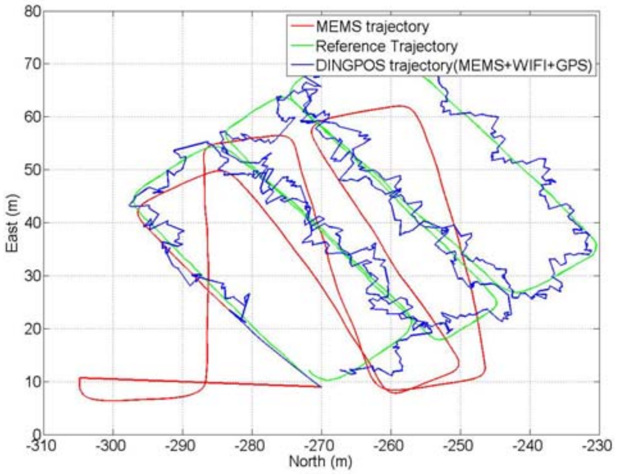

Fig. 8 EKF GNSS with MEMS and WiFi solution.

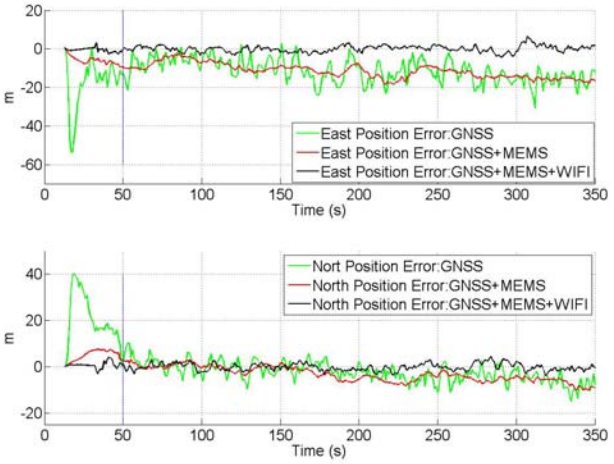

Fig. 9 East and North errors.

6. ACKNOWLEDGMENTS

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7. REFERENCES

[1] G. López-Risueño, G. Seco, “Measurement and Processing of Indoor GPS Signals Using One-Shot Software Receiver”, *Proc. IEEE Vehicular Technol. Conference*, Spring, May-June 2005.

[2] M. Monnerat, “AGNSS Standarization”, *Inside GNSS*, no. 4, pp.22-33, July-August, 2008.

[3] D. Jiménez-Baños, N. Blanco-Delgado, G. López-Risueño, G. Seco-Granados, A. García-Rodríguez, “Innovative Techniques for GPS Indoor Positioning Using a Snapshot Receiver”, *Proc. 19th ION Tech. Meeting*, 2006.

[4] G. López-Risueño, G. Seco, “C/N0 Estimation and Near-Far Mitigation for GNSS Indoor Receivers”, *Proc. IEEE Vehicular Technol. Conference (VTC)*, Spring, vol. 4, pp. 2624-2629, May-June 2005.

[5] B. Petterson, R. Hartnett, G. Ottman, “GPS Receiver Structures for the Urban Canyon”, *Proc. ION GPS* , 1995.

[6] Analog Devices ADXL330 datasheet and AKM 8970N 3D magnetic compass datasheet

[7] InvenSense IDG-1000 Integrated Dual Axis Gyroscope datasheet.

[8] J. A. Farrell, M. Barth, *The global positioning system and inertial navigation*, Mc Graw Hill, 1999.

[9] O. Mezentsev. “Sensor Aiding of HSGPS Pedestrian Navigation”. Ph.D. Thesis Report. 2005.

1319-1343, June 2002.

[10] C. Jekeli, *Inertial Navigation Systems with Geodetic Applications*, de Gruyter, 2001.

[11] S. J. Julier, J. K. Uhlmann, H. F. Durrant-Whyte, “A New Approach for Filtering Nonlinear Systems,” *Proc. American Control Conference*, IEEE Publications, Piscataway, NJ, pp. 1628–1632.

[12] A. Doucet, N. de Freitas, N. Gordan (ed.), *Sequential Monte Carlo Methods in Practice*, Springer, New York, Chap. 1.

[13] M. S. Arulampalam, S. Maskell, N. Gordon, et al., “A Tutorial on Particle Filters for Online Nonlinear/Non-Gaussian Bayesian Tracking,” *IEEE Transactions on Signal Processing*, vol. 50, no. 2, pp. 174–188.

[14] F. Gustafsson, F. Gunnarsson, N. Bergman, et al., “Particle Filters for Positioning, Navigation, and Tracking,” *IEEE Transactions on Signal Processing*, vol. 50, no. 2, pp. 425–437.

[15] F. Evennou and F. Marx, “Advanced Integration of WiFi and Inertial Navigation Systems for Indoor Mobile Positioning”, *EURASIP Journal on Applied Signal Processing*, Vol. 2006, Article ID 86706.

[16] D. Kubrak, C. Macabiau, M. Monnerat, “Performance Analysis of MEMS based Pedestrian Navigation Systems”, *Proc. ION GNSS* , 2005.