DINGPOS: INDOOR NAVIGATION DEMONSTRATION PLATFORM

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BIOGRAPHY

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INTRODUCTION

In deep urban and indoor environments the direct reception of the satellite signal is very often obstructed, making necessary to turn to alternative positioning technologies to GNSS. The optimum solution to overcome the challenges of indoor positioning should take advantage of existing infrastructure, such as communication networks that already provide indoor coverage, or local or autonomous elements implemented within the user terminal. This field is now maturing and is producing interesting technological solutions at reasonably accessible prices. It is not far-fetched to envision a single portable platform capable of incorporating a GNSS receiver embedded in a cellular device incorporating A-GNSS, WiFi, DVB or UWB and local MEMS, and combining all this information to provide the best possible positioning service in all environments.

Indoor navigation will lead to a significant improvement in Location Based Services for personal and professional applications, which will imply also important social benefits. The logistical monitoring and deployment of search and rescue teams, police corps, etc., would be improved significantly given the capability to continuously track each asset, not to mention the benefits to other sectors such as the transport of goods or hazardous materials. Innovative new applications will arise as the price of this technology comes down and within range of the general public.

In response to the obvious benefits of indoor positioning, the DINGPOS Project has been launched by ESA to study, develop and test the most promising state-of-the-art indoor positioning techniques . The project is studying innovative ways to combine different wireless technologies (WiFi, UWB, WiMax, GSM/EDGE y UMTS, Bluetooth, DVB) and sensors (baro-altimeters, gyroscopes, accelerometers) with indoor GNSS and other methods, such as 3D indoor Map Matching algorithms. Special effort is being placed on the development of high sensitivity algorithms for GPS and Galileo signal acquisition and tracking in indoor environments capable also of mitigating multipath, interferences and cross-correlation effects, taking advantage of the innovative features of the Galileo signal (pilot one, etc.) and assessing the benefits to be had with Galileo. Advanced data fusion techniques are also being investigated to best hybridise the available data from GNSS, MEMS and Wireless sensors, so as to provide seamless positioning in different environments.

After a performance assessment and architecture trade-off, the most promising technologies and techniques will then be implemented in the DINGPOS demonstrator platform, which will be kept open to future evolutions of indoor navigation.

1. CHALLENGES FOR INDOOR NAVIGATION

1.1 Environment and Signal Reception/Acquisition quality

The difficulties in using GNSS for indoor positioning, come from the fact that GNSS have been designed and dimensioned for outdoor environments. The propagation from the satellite to indoors presents many deleterious effects and therefore, indoor GNSS receivers have to operate in conditions that are much more demanding than the ones assumed in the nominal design of the system. In short, the demand of providing location information everywhere has lead us to the need of designing GNSS receivers able to work in environments for which GNSS had not been designed. Moreover, these indoor GNSS receivers are aimed at being embedded mainly in mobile phone and PDAs, where cost and power consumption are of paramount importance. All these aspects give rise to many challenges at signal processing and other levels in the design of such receivers.

The interest on indoor positioning was mainly initiated as a result of the US FCC E911 mandate in 1996, followed by a similar European recommendation called E112. The mandate required the mobile communication operators to be compatible with location determination in the 95% of all sold handsets. This implied that mobile terminals should be able to report their position during an emergency call with accuracy on the order of 50 or 100 meters. As the previous requirement was independent of the location (either indoors or outdoors) of the terminal, and only restricted by the coverage area of the mobile operator, it immediately became a technical and economical challenge, and the entry-into-force date has been postponed year after year, until December 2005

In the indoor environment, there is no LOS signal by definition and there is a rich multipath propagation. The absence of LOS signal goes against the basis of satellite-based positioning. However, in reality the signal energy reaches an indoor position delayed by the crossing of obstacles and spread in time due to the multipath-rich environment. It is then assumed that the delay introduced by obstacles is negligible; and the problem at the receiver turns into synchronizing the local code with the cluster of undistinguishable signal replicas having the smallest delay. Hence it is important to remark that indoor GNSS receivers are designed under the assumption that received signal model

$$x(t) = A_0 s\left(\left(1 + f_{d,0}/f_c\right)t - \tau_0\right)e^{j2\pi f_{d,0}t} + n(t)$$

is applicable, where and A_0, τ_0 and $f_{d,0}$ are the parameters characterizing the first significant aggregation of signal energy.

The most deleterious effect of indoor environments is obviously attenuation. Following to the results measurement campaigns, the conservative industry target is to receive GPS signals above an CNo of 20dBHz. Notwithstanding, in order to be able provide a positioning service with an unquestionable commercial appeal (i.e. with coverage in most building floors over the ground), reception down to CNo=10dBHz is pursued. The use of GNSS in this context has received the name of A-GNSS/A-GPS and HS-GNSS/HS-GPS, standing for Assisted or High Sensitivity GNSS/GPS

Before proceeding any further, the plausibility of achieving the required position accuracy at these low CNo values has to be checked. In order to avoid implementation details in the receiver, the Cramér-Rao Bound (CRB) on the estimation error in τ_0 is used (expressed in meters). For GPS, the CRB of τ_0 for CNo=10dBHz is 30m [RD. 1]. If the dilution of precision is equal to four and all satellites in view have CNo=10dBHz (which is a very pessimistic assumption), the position standard deviation will be 120m, which is on the order of the requirement. Although the analysis cannot be conclusive because it is based on a lower bound and only considers thermal noise errors, the assessment is positive and indicates that positioning at that low CNo may be possible.

The immediate effect of those low power levels is that the the bit energy to noise spectral density ratio, EbNo, falls well below the Shannon's limit. Therefore, the navigation message cannot be recovered and the time stamps on the signal are missed.

The availability of both the navigation message and the time stamps is essential for the computation of the position. The lack of the navigation message can be overcome with the use of the A-GPS concept, whereby the navigation message or equivalent information is sent to the GPS receiver by means of a terrestrial communication system, such as a cellular mobile system, a wireless local area network (WLAN), etc. The provision of the time stamps via the communication system is more problematic because it requires a very precise synchronization between the three parties involved: the navigation/communication receiver, the communication network and the GPS time. Although current (GSM) and third generation (CDMA2000 and UMTS) systems have the capability of providing this synchronization, it is feature that is preferably not implemented because it increases complexity and cost of the network. In the absence of time stamps or synchronization with the network, the receiver can still compute the position as long a rough estimate of the position (on the order of kilometers) and the time (on the order of seconds) is available. The computation is more complex than in a conventional receiver and, as we will see below, the use of more sophisticated signal processing algorithm can simplify the position computation.

Although the navigation message cannot be detected, it is still possible to measure τ_0. Attenuation has clearly the effect of increasing the estimation error in τ_0, which eventually translates into larger position errors. Moreover, attenuation differences among the signals coming from different satellites also have detrimental effects. This effect is called *near-far* effect in reference to the differences in received signal power experienced in cellular communication systems. In these systems, the power differences are due to the differences in distance from the mobile to the base stations. On the contrary, in GNSS the power differences are caused by the different attenuation of the propagation paths; for instance, one signal may be received through the window and another signal through the ceiling. The near-far effect may cause that weak signals from satellites in view are not detected or they are detected but the measured pseudorange has a huge error. In a general case, the near-far effect may also make the receiver detect a satellite that is not in view. However, this type of error is not considered here because the list of satellites in view is transmitted along with the assisting information.

It is well known that multipath is one of the main sources of error in GNSS-based outdoors positioning. The effect of multipath indoors is not well understood yet and remains an open topic of research. On the one hand delayed replicas tend to provide an overestimated value of the propagation delay, and on the other, they contribute to increase the average received energy, which facilitates signal detection.

The aspects conditioning GNSS-based indoor localization are not only arising from the propagation environment but also from the application requirements. First, the positioning receiver will most surely be included in a mobile phone or handheld, where the use of low-cost components is of paramount importance. Clocks used in this type of devices have stability on the other of 1ppm [RD. 2]. Note that 1ppm is equivalent to 1.5kHz in the L1 band. Second, as little additional hardware as possible should be needed for the navigation part of the receiver. Nowadays, there is the trend of using software-defined radio concepts for the implementation of the navigation functionality in the phone. Some manufacturers start to offer navigation receivers in which the signal processing is entirely executed in the processor (usually an ARM processor) already present in the phone. Next, mobile devices are power-constrained so the implementation of the navigation functionality has to be as power-efficient as possible. This fact leads to a snapshot or acquisition-only type of implementation. That is to say, the navigation receiver does not track the signals continuously, but only it process them when a position fix is needed. The industry target is to consume less than 100mJ per position fix. Every time the position is to be computed, the receiver has to acquire or synchronize the received signals. This process has to be done as quickly as possible because the time-to-fix (TTF) is an important performance metric at application level, where a TTF smaller than 10 seconds is sought. The A-GNSS concept contributes towards this objective because the transmission rate of the navigation message is much faster than that of the navigation signal.

1.2 Limitations of sensor only navigation

Generally, Users application require to have navigation means with **in-door and out-door** coverage. Definitely GNSS is the most appropriate to provide out-door wide range navigation. For In-door environments, two families of location techniques exist, one based on local networks means (Wifi, ad hoc deployed UWB or DVB-H…), or inertial sensors. Inertial sensors are interesting since they do not need any infrastructure. Nonetheless they drift quickly with time in distance but also in heading), and provide a relative position only. For these reasons inertial sensors need to be combined/hybridised with GNSS or network based location techniques, that provide absolute position.

2. STATE OF THE ART

2.1 Signal processing

The objective of the signal processing techniques is to address the main challenges posed by the indoor environment and described above: extremely low received signal energy, absence of time stamps and near-far problem.

It is clear that in order to be eventually able to detect weak signals, the signal power has to be accumulated during long time intervals. This is the so-called HS-GNSS principle. The correlation between the incoming signal and a local replica of the code for each of the satellites in view is computed for different trial values of the delay, τ, and frequency offset, f. The signal is correlated coherently during T_{coh}, and N_I values are non-coherently accumulated. The possible delay/frequency pairs where a signal may be present correspond to those values of total correlation that surpass a certain threshold. It is not convenient to select the maximum of those values as the correct location of the signal because a further processing to combat the near-far effect is in order. Moreover, experiments have shown that a different threshold for each value of f has to be used. The reason is that the effect of external interference and cross-correlation with other GNSS signals is frequency dependent, which results in different post-correlation noise-plus-interference power at different frequencies. In a practical case, the duration of the coherent correlation is limited by the presence of bits and/or the accuracy of the clock+Doppler frequency estimation. It is possible to replace the conventional squared non-coherent correlation with the multiplication of two successive coherent values, after having conjugated one of them. This approach is called differential correlation. Although it offers a sensitivity gain of 1.5dB at moderate and large CNo values, it does not bring any gain at low CNo values.

It might be argued that it should still be possible to attain the required sensitivity by increasing N_I as much as necessary. This argument is flawed because of some real-world implementation aspects that are generally overlooked in analytical derivations. The key point is that the accuracy of estimation the frequency shift must be on the order of the reciprocal of total correlation time, and not on the order of the reciprocal of the coherent integration time as it is usually assumed in communication systems. Therefore, increasing N_I has also a negative effect on complexity since a finer frequency grid must be used for the search of the maximum of correlation peak.

Even if the price of a finer frequency search is to be paid, the total integration time cannot be arbitrarily large because the frequency shift, $f_{d,0}$, cannot be considered as constant during that time due to the receiver clock drift. A varying frequency shift cannot be estimated with a single value, f, with the required accuracy no matter how fine the search is. In this case, methods to estimate the clock dynamics would be needed, but this kind of solutions are not feasible in a handheld receiver. Current clock technology limits the integration period to less than ten seconds, and it is recognized that the development of more accurate and cost-effective clocks will be a key technological enabler of indoor GNSS solution with increased sensitivity [RD. 2].

There are other effects that limit the maximum value of the total integration time. The satellites and possibly the receiver are moving during the correlation time. However, the result of processing the signals during the integration time is only one value of τ for each satellite. Using these values of τ and the positions of the satellites at a given instant, the receiver provides one position fix. There is an inherent ambiguity because the position fix does not correspond to the position at any particular instant, but it is a kind of average of the positions along the correlation time. The same type of ambiguity is applicable to the choice of which instant should be taken to compute the satellite positions. Furthermore, the longer the total correlation time, the more energy per position fix is consumed by the receiver.

The next desirable step is to increase the coherent integration beyond the bit duration. There are data-aided and blind approaches to achieve this goal. In the data-aided one, the bits of the navigation message are sent by the terrestrial communication system as part of the assisting information. Thus, the receiver can easily compensate for the bit changes in the navigation signal. However, this approach is not the preferred solution since it has many implications at system level. The communications system (regardless it is a cellular system or WLAN, etc.) has to transmit continuously the navigation messages of all satellites in view and, what is more restrictive, the receiver needs to have access to the communications system whenever it wants to compute the position. Moreover, the transmissions have to be synchronized with the navigation messages as received from the satellites signals. In the normal operation of A-GNSS, the receiver can obtain the assisting information and use it later on to compute the position even if at that instant it has not access to the communications system.

The existence of pilot signals in Galileo should seemingly make the extension of the coherent integration easier because all the signal components are perfectly known at the receiver. However, this is not so straightforward in reality because the receiver needs to find out the timing of the secondary code

If correlation is computed using the FFT, the selection of the sampling frequency is a key aspect. The sampling frequency has to be incommensurate with the chip rate and, at the same time, provide a number of samples per code period close to a power of two.

The worst-case cross-correlation between GPS signals is 24dB if there is no bandwidth limitation, but this value decreases to 20dB or even less due to the small bandwidth of handheld receivers. The power differences found in the indoor environment may reach 30dB, so the inherent robustness of GPS signals is not enough to withstand the near-far (NF) effect indoors.

The result of coarse acquisition is a matrix of correlation values in a time-frequency grid. This matrix allows for a detailed analysis of the signal characteristics, and this analysis is not possible in the subsequent stages of the receiver, which only process a small part of the matrix. Therefore, near-far detection must be performed after coarse acquisition and its main goal is to discriminate the peaks that are due to near-far interference from the one (if it exists) that corresponds to the desired signal. If the near-far detector is not able to distinguish the correct peak, it is possible to apply a near-far mitigation technique, and coarse acquisition can be repeated again. From the user point of view, detection is much more important than mitigation. If the near-far interference on one signal turns out to be undetected, the error in the pseudorange and, hence, on the position will be extremely large (e.g. tens of kilometers). If the near-far interference is detected but not mitigated, the satellite will be declared unavailable.

Galileo employs longer PN codes and, as a consequence, it offers between 6dB and 30dB of increased NF protection. The range is so wide because it depends on which signal component is considered and on whether the coherent correlation extends to the complete secondary code or only to the primary one. It is anticipated for that reason that NF will be much less of a problem in Galileo, although this needs to be corroborated by experiments with real signals. Note, however, that this gain is obtained at the price of a more complex coarse acquisition

The measurement of the CNo is not only important if NF mitigation is applied, but it is an integral part of any receiver because it is used for signal quality monitoring. The quality of the signals is employed in the position computation, where each delay measurement is weighted by square root of the corresponding CNo to improve position accuracy. CNo estimators used in outdoor receivers fail in indoor receivers working in acquisition-only mode and need to be adapted.

Finally, it is worth mentioning that all the signal processing steps addressed above must be applied according to a state machine that takes into account the variety of situations found in a real scenario. The logic underlying this state machine is as important as the quality of each individual step.

2.2 Assistance Information

The DINGPOS platform includes assisted –GNSS capabilities, that are used in connection with Thales Alenia Space Location server providing the necessary assistance data.

These data are consistent with the 3GPP defined RRLP protocol, and are exchanged within OMA defined SUPL transactions. They consist of :

- ✓ Reference Time
- ✓ Reference Location
- ✓ DGPS corrections
- ✓ Navigation Model (Ephemeris data)
- ✓ Ionospheric Model
- ✓ UTC Model
- ✓ Almanac
- ✓ Acquisition Assistance data
- ✓ Real Time integrity

It must be noted that DGPS corrections are computed as Local Differential correction, or as EGNOS Differential corrections, depending on the distance of the User receiver to the Location Server reference GNSS receiver.

2.3 Wifi

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.

From a general point of view, the following figure shows the possible WLAN (thus including Wifi) location techniques.

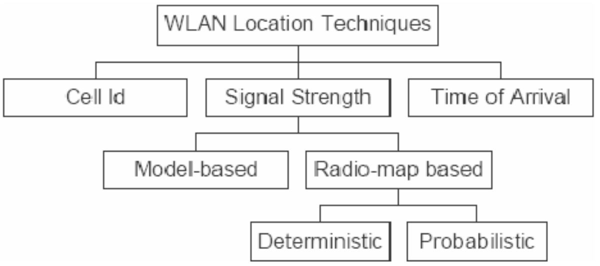

Figure 1 : Wifi location techniques summary.

In the Cell-Id method - also known as Closest Access Point method -, the network is divided into cells that corresponds to the radio coverage of a particular access point, which position is well-known. Hence, a mobile station associated with an access point is considered inside the cell. The Cell-Id approach is a fast and coarse location solution. The accuracy is directly related to the deployed network topology.

The Received Signal Strength (RSS) method basically relies on the correlation of a received signal strength with a particular location. Two techniques are mainly using this approach. The first technique known as model-based uses a mathematical propagation model to determine the distance between an access point and the mobile terminal to locate based on the measurements of the path loss. If the transmit signal level has been calibrated, measuring the received signal strength gives as estimation of the path attenuation which in turn provides a distance estimation. If several access points are in a visible range, the user's location can be determined. Most of the techniques based on that principle use on-site training data, which increases the accuracy of the positioning system. Claimed accuracy performances are within the range of 1.5m to 5m. The second technique relies on a map database of the received signal strength from all the visible access points. Two distinct approaches are used for position computation: either deterministic or probabilistic. In the former approach, the goal is to find the recorded sample having the smallest Euclidian distance to the observed sample. In the latter, the probability distributions of various access point are applied to the observed RSS pattern to find the most probable position. Radio-map based Wifi location techniques are usually separated in two phases: the offline phase, which gathers access point signal strength received from specific locations in a “radio-map”, and the online phase, which is the operational phase where the location system compares the measurements to the stored data in order to get the user position.

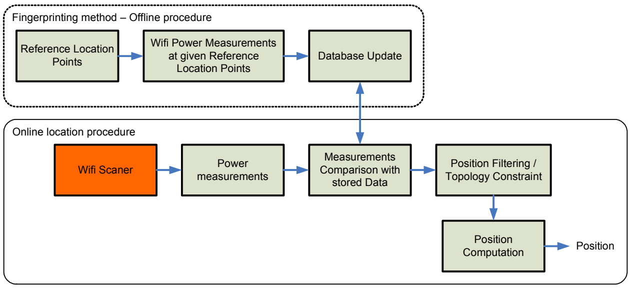

Figure 2: Wifi RSS-based Location Technique Principle.

The basic idea in Wifi TOA (and more generally in TOA) is to measure the propagation time of a signal and to convert it into a distance. It is computed based on the different between the transmission time and the reception time of a message. To be able to compute the propagation time, both transmitters and receivers shall be synchronized or time difference shall be accurately known. In TdoA location technique, the difference between the propagation time from the mobile terminal for a pair of base stations is measured and then processed to compute the location of the user.

TOA/TdoA are considered as the most accurate techniques as most of the multipath effects can be filtered out. However, as the current Wifi available standard is not providing the required tools, their implementation may seem quite complex.

2.4 DVB/UWB

The particular characteristics of ultra-wideband (UWB) signals make this technology an excellent candidate for precise positioning in harsh environments such as the indoor one. UWB systems are based on the unlicensed emission of a stream of low-power and subnanosecond pulses that typically have a spectral occupancy on the order of several GHz. Such a huge spectral occupancy provides positioning applications based on UWB technology an unprecedented advantage in precise time resolution with respect to conventional narrowband systems. Moreover, the impulsive nature of UWB signals has been shown to be optimal for radio transmissions under the low-SNR regime [RD. 3]. Therefore, successful operation can be undergone in indoor environments where significant attenuation is introduced because of the presence of blocking obstacles.

Except for this physical layer advantage, positioning algorithms for UWB signals do follow the same strategy as for conventional narrowband positioning systems. That is, the idea is to determine the time that a given signal (in this case, an UWB signal) takes to propagate from the transmitter to the receiver and then convert that measurement into a distance or pseudorange between these two devices [RD. 4]. This allows UWB measurements to be easily coupled and hybridized with other technologies such as Wifi, GNSS and sensors.

Current state-of-the-art on UWB positioning proposes the adoption of hybrid approaches where both signal-strength (SS) and time-of-arrival (TOA) measurements are combined to provide reliable position estimates. This hybrid solution has been shown to provide significant enhancements with respect to the case where only SS measurements or only TOA measurements are used. SS measurements are easily available at the receive terminals because this information is already required for detecting the presence of signal but also for handover purposes with the reference nodes. For instance, simple SS measurements can be obtained by summing the powers of all multipath components in the power-delay profile (PDP) at the receive terminal [RD. 6]. However, SS measurements by themselves cannot provide a very accurate ranging information because of the strong dependence with the time-varying propagation losses. Similarly, problems are also found when using only TOA measurements since closely spaced receive terminals can lead to unresolvable ranging singularities. The hybridization of SS and TOA is therefore a good strategy to improve positioning accuracy while suppressing singularities of TOA measurements [RD. 7] and is attracting attention for application to UWB technology.

2.5 Sensors

Over the last 10 years, the MEMS industry has spawned a wealth of applications. Several of these applications including the much-cited examples of automotive engine controls, airbag accelerometers, Anti-lock Braking System as well as camera motion control have moved to high-volume commercial production, thereby validating the basic MEMS technology, materials and processes used. The opportunities for MEMS are wide opened and the technology is established. Four types of low-cost MEMS sensors are of interest in the perspective of navigation namely accelerometers, gyroscopes, magnetometer and pressure sensors.

Using sensors as an augmentation to GNSS-based positioning systems is all the more interesting as their integration into consumer products is constantly increasing since a couple of years. Single-die sensors capable of providing measurements along three orthogonal axes can now be found in large volume (as for instance accelerometers [RD. 8], magnetometers [RD. 9]), whereas other sensors are likely to follow (currently two-axis gyroscope into one single-die [RD. 10]).

Sensor-based positioning methods have been widely studied. Given a set of sensors, traditional navigation algorithms may have very different performance in terms of accuracy and thus availability. As a comparison, IMU (Inertial Measurement Unit) of different grades are listed in below Table 1.

Inertial Measurement Unit	CIMU (Honeywell)	HG1700 (Honeywell)	Crista (Cloud Cap Technology)
Grade	Navigation	Tactical	Automotive
Accelerometers			
Turn-on bias (mg)	0.025	1	2,5
In-run bias (mg)	N/A	N/A	30 mg
Scale factor (PPM)	100	300	<10000
Gyroscopes			
Turn-on bias (°/hr)	0.0022	1	<1040
In-run bias (°/hr)	N/A	N/A	5400
Scale factor (PPM)	5	150	<10000
Cost	>$90000	>$20000	<$2000

Table 1: Typical IMU characteristics [RD. 11].

From that table, it can be seen that low-cost IMUs have characteristics far poorer than navigation or tactical grade IMUs, which consequently limit their use as standalone navigation means. It also makes mandatory the optimisation of the classical mechanization as depicted in the following figure.

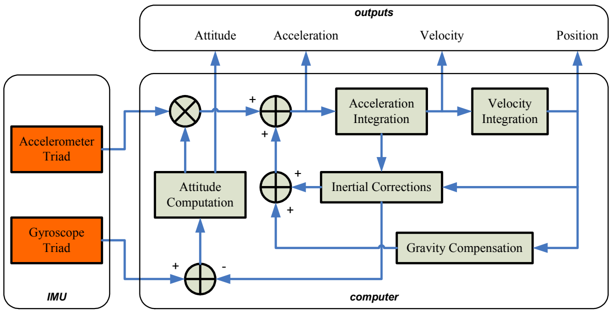

Figure 3: Inertial Navigation System Mechanization.

In order to reduce the impact of the sensors bias on the overall system performance and thus to increase the reliability of the navigation system, a different inertial mechanization dedicated to the particular case of the pedestrian navigation has been developed (see for instance [RD. 12] and [RD. 13] among others). Such mechanization, as illustrated in figure below, requires the sensors unit to be closely attached to the pedestrian. According to medical researches (see [RD. 14] and [RD. 15]), one can establish a relationship between the velocity or step length of a walking pedestrian and some parameters that characterise the acceleration experienced by this pedestrian

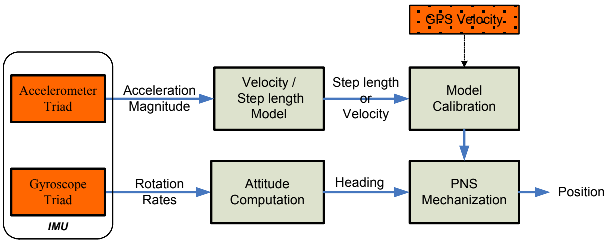

Figure 4: Pedestrian Navigation System Mechanization.

Figure 5 illustrates the theoretical and actual performance of the traditional Inertial Navigation System mechanization for a low-cost IMU (Xsens motion tracker unit). It clearly shows that such a mechanization does not allow standalone navigation for more than a couple of seconds. Opposite, Figure 6 shows the theoretical performance that can be achieved with the pedestrian mechanization, assuming a drifting heading source (blue plot) and a 5°-biased heading (red plot), and a constantly walking pedestrian. The availability of the navigation system is in that case tremendously increased.

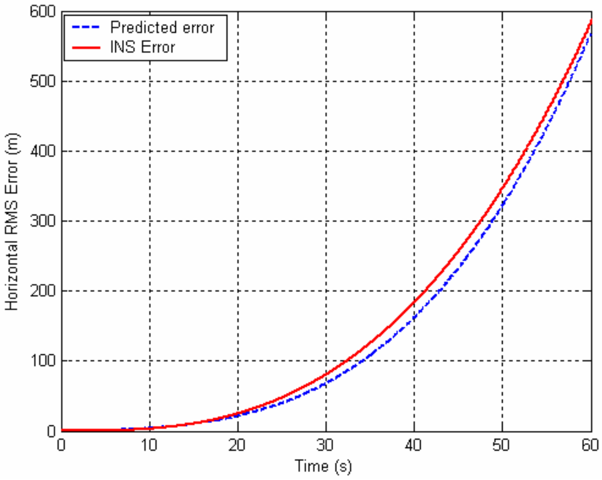

Figure 5: Predicted and Actual Inertial Navigation System Horizontal Error. Use case of a low-cost IMU (classical mechanization).

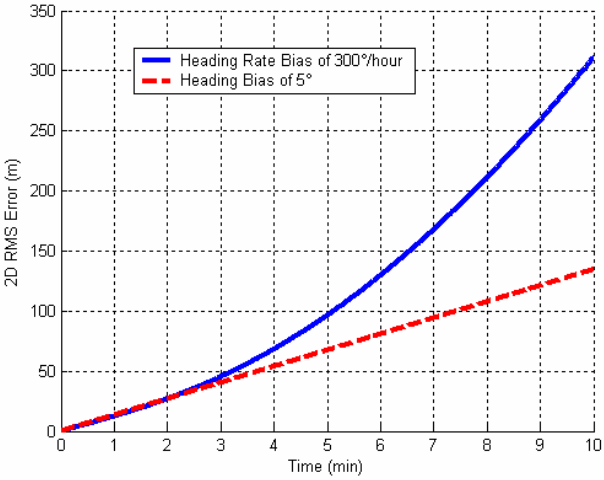

Figure 6: 2D Upper Bound Position Error given a Constant Velocity Bias of 2m/s and several heading errors (pedestrian mechanization).

2.6 Map-Matching

Map matching is a process that identifies the correct route of a user's navigation by associating the estimated positioning data of the user to the network map data. In many enhanced map matching algorithms, the user's location on the identified route can be determined. Mainly, the two essential components that impact the performance of a map matching algorithm are user's positioning and network data. Taking the example of vehicles localisation, their navigation solutions have some special attributes from the fact that vehicles are mostly travelling on roads. This property can be used to impose constraints on the position solution. The Map matching can also be defined as the process of imposing such constraints.

Most of the outdoor (land and car) navigation technologies were evolved from the marine and aviation navigation systems. For instance, DR processing is a classical navigation technique used in marine and aviation systems for route guidance, and has been integrated into the map matching process for car navigation. Alongside these developments, standards for digital road maps had evolved. For example, the Geographical Data File (GDF) provides a general data model for the definition and exchange of geographic information for Intelligent Transportation Systems (ITS) application [RD. 16]. Most of these works were limited to the road and its immediate surroundings, and would not meet the requirement for pedestrian's navigation or for indoor context. Nevertheless, map matching algorithms and its associated components (digital map and user positioning) still form the basic for pedestrian and indoor navigation developments.

Map matching techniques are often used to determine the accurate position of a vehicle on a road map. Most of the formulated algorithms utilise navigation data and the digital road network data. The MM problem probably does not have an ideal solution. All developed methods have their advantages and their disadvantages and are optimised for the applications they were designed for (see for instance [RD. 17] and [RD. 18]). The performance of conventional navigation systems seems to be sufficient for consumer applications; however, integrity demanding applications such as safety applications need a reliable MM process.

If both the digital map and the location provided by the navigation system were perfectly accurate, the MM would have been a straightforward task. All one has to do is to snap the location obtained from the navigation unit to the street network. However, the navigation system can have occasional errors and the digital map can suffer from both positional error and lack of information (e.g., missing corridor segments). The necessary sophistication of the MM algorithms depends on the nature of the application and the available data.

There are three complexity levels that a MM algorithm has to resolve:

- The most straightforward algorithm is needed when the user travels on a fixed network. The search domain for a street segment as a match candidate is very limited.
- A second level of MM algorithm complexity is needed when the user inputs a destination and the instrument determines a suggested travelling route. In this application, the algorithm assumes that the user follows the suggested route and matching is performed to that route. If the user deviates from the suggested route, the system detects a large discrepancy between the navigation system provided location and the matched location. Normally, in such cases, a new route and subsequently a new match are computed. The main drawback of using known route information is that it can result in an incorrect match if the user deviates only slightly from the known route.
- The third and most general MM algorithm does not assume any knowledge or any other information regarding the expected location of the user. It uses inputs from the navigation system under the form of coordinates in a defined frame and the relevant street / building network data to locate the user.

From a general point of view, MM algorithms can be grouped into two distinct families, the geometric based and the topological based. The first one uses geometric information of the network. The algorithms use geometric elements such as the shape of the segments of a route, and not the ways in which these are connected [RD. 19]. Generally, the geometric based approach can be categorized by point-to-point matching, point-to-curve matching and curve-to-curve matching. In point-to-point matching, an estimated location is matched to the nearest shape point (or node) of the network. A fundamental approach to determine the nearest distance between the estimated location and the shape point is through the Euclidean distance [RD. 19]. In point-to-curve matching, an estimated location is matched to the nearest arc in the network. The most common approach to identify the nearest arc is to use the minimum distance from the estimated location to the arc. As most of the arc can be modelled as piecewise linear curves, it is fairly simple to find the minimum distance from an estimated point to a curve [RD. 19]. The third approach, curve-to-curve matching, would be much better for non-straight routes as it consider several estimated positions simultaneously by matching the arc formed by these estimated positions to the closest curves of the network.

The performance of a geometric based map matching algorithm can be improved if geometric and topological information are used. Topological information refers to connectivity, proximity and contiguity of the network. Subsequently, when the geometry of the points/arcs as well as the connectivity, proximity and contiguity of the points/arcs within the network are considered, limitations present in geometric based algorithm can be compensated. Moreover, searches can be done in relation to the previously established matches and the context of the network, the result of the map matching is likely to be improved [RD. 19].

2.7 Cellular Techniques

These techniques refer to the localisation of a mobile device using the signals broadcast by communications networks established in a given local area. Traditionally, the infrastructure available depends on a series of transmitters established in each cell of the defined area.

For outdoor navigation the systems available are the standard (primarily digital) cellular networks UMTS (W-CDMA), GSM, CDMA, TDMA, etc., as well as other wireless networks established for the transmission of data between terminals such as Wifi or Wimax.

For indoor navigation specific infrastructure of this nature must be installed in order to have access to this series of data for indoor positioning, e.g., Ultra-Wide Band.

The techniques used to locate a terminal are usually one or a combination of the following and are identical for the signals used, although different systems/signal structures offer distinct advantages.

- ✓ Cell of Origin (COO)
- ✓ Enhanced Forward Link Trilateration
- ✓ Time Difference of Arrival
- ✓ Angle of Arrival
- ✓ Advanced Forward Link Trilateration
- ✓ Enhanced Observed Time Difference

As previously indicated combinations of these techniques can lead to improved solutions.

Obviously for indoor/deep-indoor navigation when signal penetration from GNSS or cellular networks is lost, indoor established systems will be fundamental. UWB in this case is an attractive option for various reasons, one being the high time resolution available with the UWB pulses, although it is subject to environmental and time varying effects which present interesting challenges for the user.

2.8. Filtering and hybridisation techniques

The position estimation combining measurements from different sensors can be made using snapshot Least Squares Estimation (LSE), where each epoch is independently estimated with the received measurements. However the accuracy can be highly improved considering in the estimation the past measurements and the user dynamics or state vector behaviour. When the dynamics is well known LSE is high efficiently used with measurements along a time arc. But when user dynamics is not well known or unpredictable recursive Kalman Filtering is the classical approach.

Kalman filter was initially designed for linear problems in the measurements and the state vector behaviour, so that a modification, the Extended Kalman Filter (EKF), is usually applied linearizing the measurements and 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.

There are different strategies to combine or hybridise the measurements with Kalman type filters:

- Loose coupling, where each sensor provide its own positioning estimation and a Kalman type Filter is devoted to perform cross consistency check, to complete the sensors calibration and to decide which is the source of the global positioning estimation. This approach is simple, robust, not more accurate than each sensor and has as major drawback the problem to use sensors when a single sensor has not enough observability of measurements
- Tight coupling, where each sensor provides its measurements to the filter, which includes measurement models as well as a user dynamics models so that the state vector comprises the positioning estimation and the sensors calibration. The redundancy of sensors allow to estimate positions in conditions of few measurements and the user model allows to have estimations by propagation of the state vector in short time spans with lack of measurements. However the conditions of use of the different measurements have to be carefully managed to avoid filter divergences
- Ultra-tight or deep coupling This is a tight coupling filter where the output state vector and covariance support the GNSS measurements obtention providing as feedback to the GNSS sensor an estimation of the expected next measurements

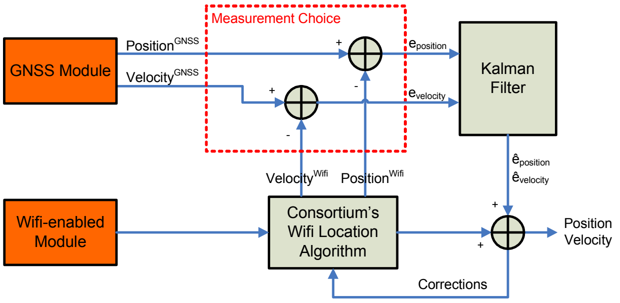

Figure 7: Wifi/GNSS loose coupling integration

Two implementations are possible regarding each integration strategy. The integrated navigation system can indeed operate in an open-loop or in a closed-loop mode. The open-loop involves the correction of the sensors errors (i.e. position, velocity and attitude) using GPS measurements, whatever their type. In such an implementation, the sensors operate independently without being aware of the existence of an error estimator. The Kalman filter estimates the errors that are used to correct the output of the sensors. Without feedback, the mechanisation error grows rapidly, and thus can introduce large errors into the integrated system.

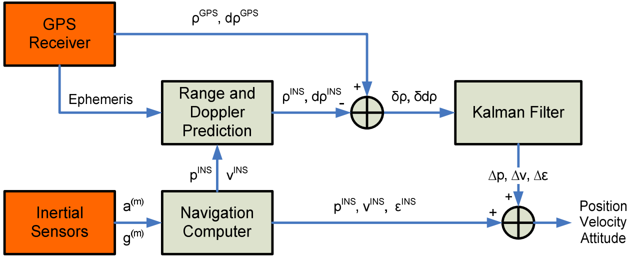

Figure 8: Tight coupling integration scheme. Open-loop architecture.

In a closed loop integration scheme, a feedback loop is used to correct the raw sensor output and other mechanisation parameters using the error estimates obtained from the Kalman filter. In this way, the mechanisation propagates small errors thus maintaining the small error assumptions used to get the sensors error model linear. The error states in that case must be reset to zero after every filter update. Additionally each GNSS measurement is combined independently with the sensors outputs. Outliers are more likely to be detected and removed using appropriate fault detection and exclusion algorithms based on the combination of the different navigation systems. There is furthermore no need to track at least four satellites to enable the correction of the sensors errors, what makes such a hybridisation strategy very attractive, especially in urban canyon or indoor environments.

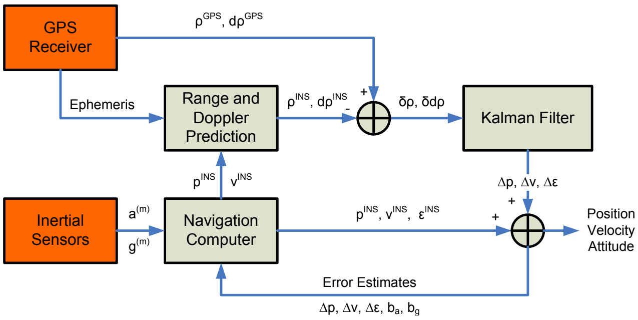

Figure 9: Tight coupling integration scheme. Closed-loop architecture.

2.8.1. Challenges to the hybrid filters for indoor navigation

The user positioning dynamics or User Model is one key element to consider in indoor applications. A usual approach is the Complementary Kalman Filter (several nested filters at different frequencies) where the user model is used for calibration purposes and to define the process noise, but the filter step for state vector prediction is replaced by the position directly derived from the measurements of the dead-reckoning sensors. In indoor applications these can be an IMU or a Pedestrian Navigation System combining IMU, heading and a bar altimeter sensors under a pedestrian motion model. The integration of a PNS based on inertial sensors with GNSS is often done through a loose coupling architecture.

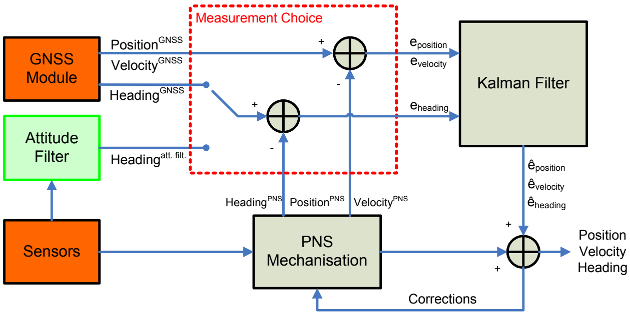

Figure 10: MEMS/GNSS Classical Integration Scheme for PNS.

On the other hand, the characterisation of the measurements quality and the observability provided by them on the final positioning will be also relevant to determine the weight in contributing the measurements from the different sensors to the hybrid estimation.

Another major problem in hybrid navigation is the management of the environment conditions. Levels, walls and doors impose constraints in the feasible positioning solutions and the affordable motion. The introduction of these domain considerations seems difficult to be introduced in a generic approach in the classical EKF. This is a critical aspect that has driven the search of alternative algorithms to the EKF. Several new alternatives have been recently introduced, such as unscented filters (UFs) (See [RD. 20] and [RD. 21] for instance), also known as sigma-point filters, and the particle filters (See [RD. 22] and [RD. 23]). which are being postulated recently for positioning estimation in indoor navigation (, e.g. Ref [RD. 24], [RD. 25]) thanks to its suitability to manage the environment conditions and constraints.

The particle filter, based on a set of random weighted samples (i.e., the particles), represents the density function of the mobile position. Each particle explores the environment according to the user dynamics model and map information. Their weights are updated each time a new measurement is received. The great strength of the method is that it is possible to forbid some movements like crossing the walls by forcing a zero weight for the particles having such behaviour.

3. DINGPOS PLATFORM ARCHITECTURE

The architecture selected for the DINGPOS platform is depicted in the figure below :

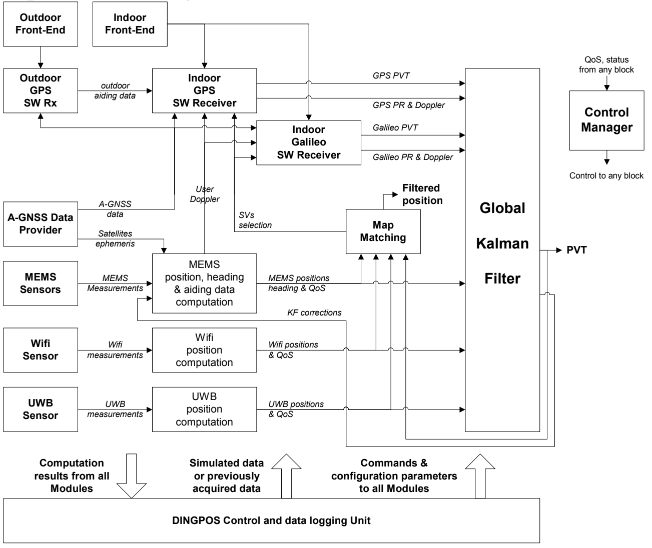

Figure 11 DINGPOS Architecture

The DINGPOS Platform comprises a PC with a number of USB interfaces to connect the different sensors: The two GNSS RF Front End, the MEMS, Wifi and UWB sensors,. The platform is connected to the Location server via an Ethernet interface and an IP router.

From a software point of view, the different algorithms are controlled via a Control and Data Logging Unit. Each sensor is associated to a dedicated algorithms block that provides the corresponding standalone PVT solution.

These PVT solutions also feed an extended Kalman filter in charge of elaboration the PVT for the different hybridization modes. Finally, a specific map matching algorithms enhances the performance of the different PVT computation modes.

The achievement of real-time operation is one major challenge for the indoor platform stem from both hardware and software design choices.

4. PRELIMINARY PERFORMANCES

4.1 HS acquisition of GNSS signals

Reliable code acquisition for HS-GNSS is one of the main problems to be faced within this project. Because of the presence of severe attenuation and phase/frequency uncertainties in the received signal, coherent integration during code acquisition must be restricted to just a limited time window. This significantly constraints the final performance and forces the receiver to adopt a non-coherent post-detection integration in order to extend the global observation interval beyond a bit duration. Two main approaches have been analyzed within the DINGPOS project to allow the extension of the correlation interval to cover several bits.

The first approach was based on the hybrid combination of differential correlation and non-coherent integration, similarly to the well-known concept of “dirty-template” synchronization commonly adopted in UWB systems [Yan04]. However, the traditional advantage of differential correlation when operating within a bit duration vanishes when extending the observation interval to cover several bits with unknown transitions. Moreover, operation under low C/N0 values is found to significantly degrade the final performance and thus, it suggests to discard dirty-template techniques as a potential candidate for HS acquisition of GNSS signals.

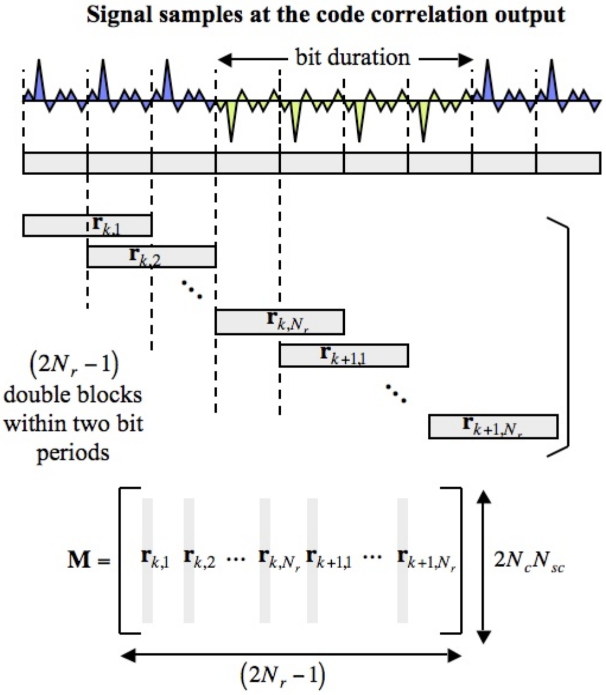

Figure 12: Data matrix for the double-FFT method.

The second approach, and the one finally adopted, consists on the implementation of the double-FFT acquisition method proposed in [Jim06]. This acquisition technique efficiently implements coherent integration of whole bit durations and leads to an overall receiver structure with superior performance to existing acquisition techniques in the literature. For the double-FFT acquisition method, blocks of samples of two code durations are stacked first into matrix form. Then, two FFT operations are then applied to this matrix for each one of the N_{f_C} coarse Doppler bins to be considered. The first FFT is used to correlate incoming signal samples (already pre-corrected with the corresponding coarse Doppler bin hypothesis) with the local code. To do so, the overlap-save method is adopted. The second FFT will allow us to obtain joint fine Doppler and fine code delay estimates.

In **Figure 12**, the number of repeated codes within a bit duration is N_r and the number of samples per chip N_{sc}. Once double data blocks have been stacked into matrix $\mathbf{M}$, FFT correlation is implemented so that the resulting samples can be stacked in matrix $\mathbf{M}_2$ according to $\mathbf{M}_2 = \mathbf{F}^H \left[(\mathbf{F} \cdot \mathbf{M}) \otimes (\mathbf{F} \cdot \mathbf{C}) \right]$, with $\mathbf{F}$ the discrete Fourier matrix, the local code matrix with replicant columns, $\otimes$ the Schur-Hadamard product and $\mathbf{F}^H$ the inverse discrete Fourier matrix. In practice, the efficient implementation of these operations involves the substitution of the DFT transform by the efficient FFT. Once signal despreading is obtained, a sliding submatrix selects some of the terms in matrix $\mathbf{M}_2$ as shown in Figure 13.

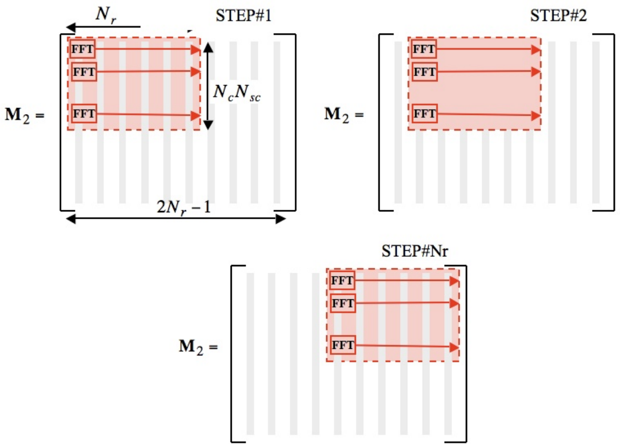

Figure 13 : Iterations for the code delay and fine Doppler search implemented by the double-FFT algorithm.

The results of these sliding FFT operations with the rows of the data matrix $\mathbf{M}_2$ are stored in an acquisition hypercube whose dimensions are equal to $(N_{FFT} \times N_{f_C} \times N_r N_{sc} \times N_r)$. With the aim of extending the integration time and avoid unknown symbol transitions, non-coherent integration is performed with the values contained within the hypercube. The final step after moving the sliding matrix up to N_r positions is to feed the hypercube to a threshold decision block and take the maximum peak value. The coordinates of this peak will correspond to the estimated fine and coarse Doppler, code delay and start of the bit transition, respectively.

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