Hybridization of MEMS and Assisted GPS for Pedestrian Navigation

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Exploration of hybrid inertial/GPS systems to provide continuous positioning through varying environments represents a growing field of interest to researchers. In particular, first responders and public safety professional would like to see robust systems that can operate indoors. This article describes work under way to develop a pedestrian navigation system based on inertial sensors and an assisted GNSS receiver. Special attention is paid to efforts being made in "gait analysis" to fine-tune the behavior of the inertial sensors as well as the stochastic models used in the system.

One of the primary uses of GNSS systems such as GPS is to help people navigate as they travel about the Earth. As with celestial navigation, GNSS enables us to find our position in unknown territories.

With suitable means of communications, GNSS functionality can also be extended to track people. Combining tracking techniques with geographical maps creates the possibility of providing guidance information to assist people in their movements, as is widely done for car navigation and safety-critical applications in support of aircraft, trains, and marine vessels.

In contrast to motorized vehicles, however, a large part of pedestrian movement takes place indoors or in light indoor environments. (These environments describe areas where the surrounding construction/vegetation block GNSS satellite signals to a greater or lesser extent. Urban canyons, sport stadiums, or a building entrance made of glass illustrate light indoors.)

For example, in the course of a single day a mobile maintenance worker receives new service requests and visits the associated area with his car. The worker spends the major part of his day repairing hardware inside buildings where he often needs navigation data in an unfamiliar environment. Moreover, he has an additional interest in any safety improvement that arises from his ability to navigate and be tracked on his work sites.

In the outdoors, where there is a clear line of sight to the satellites, GNSS technology is able to provide location with good accuracy and continuity of service. However, indoor and light indoor environments are quite challenging for satellite positioning and alternate navigation methods need to be sought that better suit these scenarios. The use of assisted-GPS (AGPS) and inertial navigation systems (INS) can be considered as two of these alternate methods.

AGPS techniques use data disseminated by a telecommunication channel to a GPS receiver in order to improve the receiver's sensitivity, reduce its time-to-fix, and minimize the complexity of its design. The techniques typically involve a mobile phone able to acquire GPS signals, a cellular network, and an assistance data server.

AGPS enlarges the working area of a stand-alone GPS receiver to urban canyons or even indoors, where large signal attenuation and degradation effects worsen receiver performance. However the recent success of AGPS must not hide its technical limitations. In these challenging environments, signal strength might be too low even for AGPS.

Even with sufficient signal strength, a high probability of acquiring only reflected (multipath) or cross-correlation signals introduces significant errors into the GPS measurements. Such situations highlight the need for complementary technology for reliable indoor navigation or tracking.. This article describes

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development of a pedestrian navigation system based on inertial sensors and an assisted GNSS receiver, using a loosely coupled scheme.

Inertial MEMS

Inertial sensors used in pedestrian navigation typically use micro-electromechanical system (MEMS) designs. MEMS result from the integration of mechanical elements on a common silicon substrate through micro-fabrication technology. They were not specifically developed for positioning, but they offer great possibilities for indoor and outdoor navigation in an autonomous and independent manner.

One of the first localization processes, largely based on step detection and identification algorithms, was developed at the Ecole Polytechnique Fédérale de Lausanne (EPFL). (See the article by Quentin Ladetto cited in the Additional Resources section at the end of this article.). Pedestrian navigation based on MEMS sensors is affected by large amounts of drift and noise, typical

of these sensors. These factors introduce errors into the estimation of displacement and azimuth.

We can reduce the effect of these errors by exploiting the biomechanical and physical characteristics of the human stride, but also by hybridizing MEMS information with absolute position information provided from other sources. The need for hybridization is also dictated by the fact that MEMS-based algorithms provide only relative data from the previous position solution to the current one. We need to use absolute positioning data, such as AGPS, to relocate or reinitialize the MEMS-based walking path in an absolute geographical reference frame.

The coupling of different navigation systems is an efficient way to improve positioning performances. The technique consists of combining measurements from complementary navigation devices to yield a hybridized system with increased accuracy, availability, and robustness. Pedestrian navigation based on MEMS and AGPS offer non-correlated complementary features that present themselves as good candidates for a hybridization scheme.

This coupling scheme has been studied mainly in transition phases from outdoors to indoors and the opposite. We can also consider it in a broader sense as a hybridization algorithm of MEMS-based positioning combined with data from any absolute positioning system.

The research presented in this article has been mainly carried out in the framework of the European project LIAISON (LocatIon bAsed servIceS for the enhancement of the wOrking environment) in which EPFL participates. The global objective of this research is to cope with the kind of positioning errors described previously and to improve pedestrian navigation solutions mainly for emergency interventions.

LIAISON intends to facilitate the work of isolated workers, such as firefighters or taxi drivers, by providing them a mobile location device. The results of LIAISON will help forward the entry of Europe in the regulations such as the E112 standard. The project, which
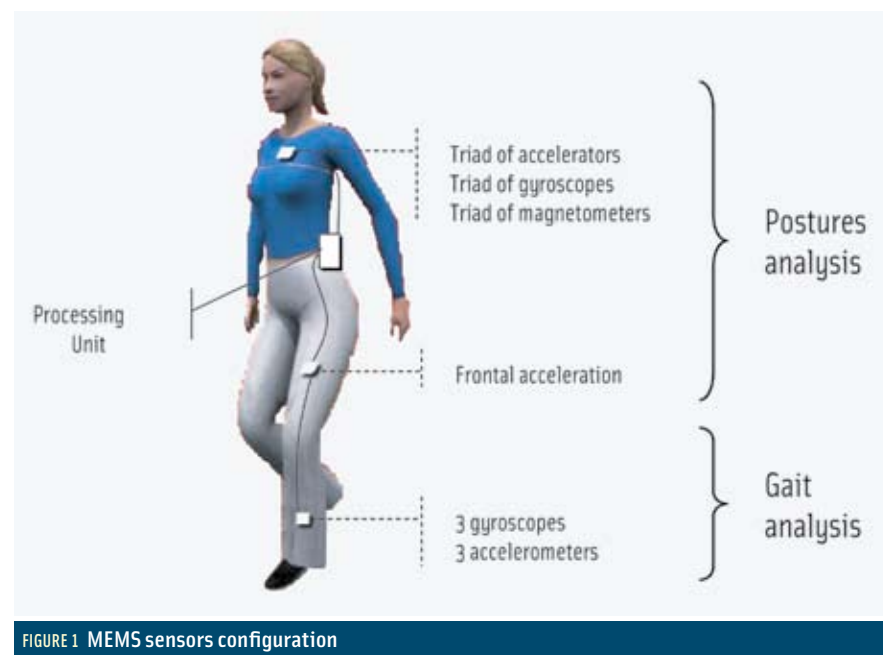

FIGURE 1 MEMS sensors configuration

is coordinated by Alcatel Alenia Space, officially began in September 2004 with a planned duration of 42 months.

MEMS–Based Algorithm

MEMS sensors, such as accelerometers, gyroscopes, magnetometers, and barometers, are regularly used to quantify the displacements of a subject using integration or pattern-recognition techniques.

Such techniques often rely on estimation models, for example, of step length or horizontal speed, which are primarily estimated in calibration phases. During calibration the person walks at a normal speed along a specific footpath with GPS fixed ambiguity position available to create an estimation model of a person's particular walking style.

The use of estimation models, however, limits our ability to follow the current stochastic behavior of a pedestrian. The calibration phase uses models that only estimate the displacement based on fixed values but don't measure and compute the real displacement. This poses a problem if the walking cadence changes, for example.

To cope with the complexity resulting from the entire freedom of movement of a subject, we developed a novel approach to pedestrian navigation. This included design of a MEMS-based algorithm to help characterize the human motion involved in walking.

Characterization of a worker's physical activity is a key element in the evaluation of his safety condition, particularly in the context of dangerous working scenarios. For that purpose, we employed a distributed architecture of the MEMS sensors, illustrated in **Figure 1**. This approach, described in the article by A. Paraschiv-Ionescu et al listed in Additional Resources, enables the analysis in real time of a worker's posture and movement.

Posture detection assesses basic activities such as sitting, standing, and lying. Detection of a possible emergency is accomplished by analyzing the posture and mobility of a person being monitored. For example, a worker in the same posture motionless for a duration of at least 90 seconds might indicate an emergency situation.

The inertial sensors, placed on the pedestrian's trunk and thigh, provide the data for posture analysis and orientation determination. The accelerometers and the gyroscopes placed on the shank are used in gait analysis.

At the end of each gait cycle, the distance travelled by a subject is calculated. The step length is computed from the angular rotation (α) of the shank fixed at a specific instant of the walking cycle using the following trigonometric relation:

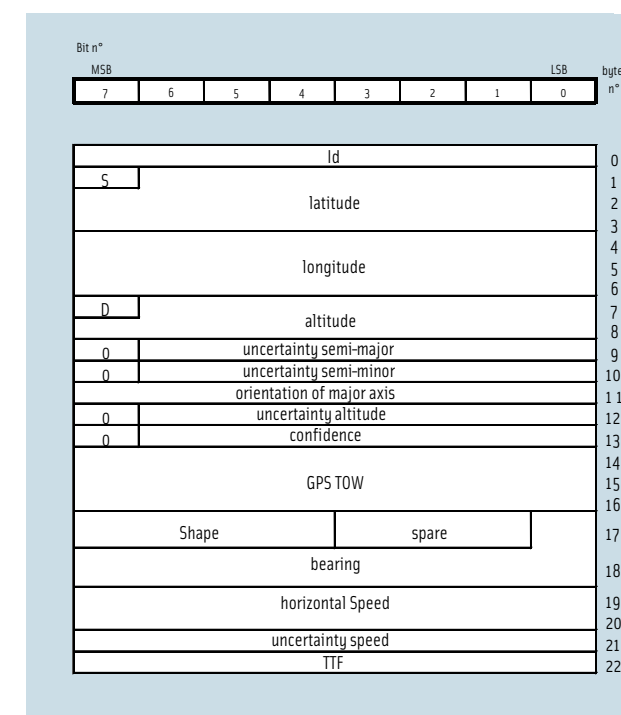$$s = L \times \sqrt{2 \times (1 - \cos(\alpha))}$$

FIGURE 2 Shape description of the 3GPP message based on the 3GPP Technical Specification 23.031

The MEMS-based algorithm estimates the length of the pedestrian's leg value L assuming that it relates to the height of a person multiplied by a scale factor resulting from physiological statistical figures. MEMS hybridization with AGPS enables a more accurate determination of the leg length. A walker's step length is described as the MEMS-based algorithm's output affected by a scale factor (λ) in the hybridization algorithm.

The MEMS-based algorithm provides the step length only at the end of a walking cycle that lasts between 1 and 2.5 seconds and occurs asynchronously. In this context, it is difficult to consider the step length directly in the hybridization algorithm. The MEMS-based algorithm can also generate an instantaneous velocity figure for the pedestrian. The step length (s) is function of the horizontal speed (v), the gait cycle duration (Δt) and the slope of the ground (γ).

$$s = v \times \Delta t \times \tan(\gamma)$$

Indoor and urban environments are generally constituted by flat ground. The slope of the ground can thus be ignored in the hybridization process and the

previous equation becomes:

$$s \approx v \times \Delta t$$

The introduction of the horizontal speed instead of the step length in the state vector of the hybridization process offer advantages. First, a pedestrian does not always walk at steady a pace. This is particularly true of public safety workers such as firefighters whose movements are irregular. Therefore, the estimation of instantaneous values like the walking speed in meters per second offers more realistic and current tracking of a worker. Moreover, the AGPS receiver provides the horizontal speed and not the incremental distance travelled from the previous position. It can thus be used as a more accurate direct observation.

The MEMS-based positioning algorithm estimates the pedestrian's changes in altitude. The gait analysis algorithm detects whether a walker is climbing or descending stairs and outputs the amount, n, of upward or downward stairs. The height variation results in the product of this number by a fixed stair height equal to 0.20 m.

$$h_{k+1} = h_k \pm n \times 0.2$$

AGPS measurements

In order to implement a standardized AGPS format, we selected the 3GPP Universal Geographical Area Description (UGAD) outlined in the publication by European Telecommunications Standards Institute (ETSI) cited in the Additional Resources. Launched in 1998, the 3rd Generation Partnership Project (3GPP) is a collaboration agreement designed to establish a globally applicable third-generation mobile phone (GSM, UMTS) system specification and thus to define standards in telecommunication formats.

This 3GPP UGAD technical specification describes the content of the geographical area, including the type and encoding process of data. Although the use of this format offers the advantage of working with a common standard, it introduces some constraints when dealing with hybrid systems such as ours.

Figure 2 depicts the coding of the format and information elements of the 3GPP location message used for the AGPS data and contains the following elements:

- the position in WGS84 geographical coordinates with a corresponding position uncertainty ellipse
- the horizontal speed with the associated uncertainty
- the bearing
- the GPS time of week
- the time to fix (TTF) position

The typical encoding resolution of the geographical position is lower than two meters in the east direction and lower than one meter in the northing. This limitation in AGPS position accuracy is in the range of that for low-cost GNSS receivers commonly used for AGPS. Consequently, no major effect is expected on the AGPS/MEMS integration scheme. However, the use of the 3GPP format for other indoor positioning techniques, such as WiFi or Bluetooth, can induce a loss of the positioning accuracy. The accuracy of these indoor techniques is often better than what the encoding format can provide.

Velocity. The format provides the horizontal speed and the bearing in terms of the direction of the horizontal velocity component taken clockwise from north.

The AGPS horizontal velocity is derived from the Doppler frequency shift of the GPS carrier wave. As long as the satellite velocity is precisely known, the Doppler effect enables computation with a high accuracy of the ground velocity of the pedestrian. The satellite velocity predicted by the broadcast ephemeris in the navigation message is sufficiently accurate to achieve accuracies in the order of several centimeters per second. (For more discussion, see the article by L. Serrano et al in Additional

Resources.) Furthermore, the noise level of Doppler-derived velocity is far less compared with the noise level of position-derived velocity.

Common Time. Time synchronization is one of the major issues in the development of an inertial/AGPS coupling scheme. The AGPS location data includes the GPS Time Of Week (TOW) in seconds received from the GPS satellite broadcasts. A MEMS unit has its own clock. Therefore, a common time marker has to be defined between the MEMS and the AGPS observations. For the tests presented later, we used the dynamics of the pedestrian to synchronize the navigation data generated by the two technologies. Each trial starts with a period of standing motionless before walking.

AGPS position determination also provides the needed time to fix (TTF) the position. The AGPS computation can focus either on time to first fix (TTFF) performance or sensitivity. Because in urban and indoor environments the amount of available satellites in direct line of sight might be critical, sensitivity performances are important. On the other hand, decreasing the TTF ensures the provision of GPS positions in a short time span and allows hybridization with MEMS observations. TTF might be used to reject old AGPS positions in a real-time hybridization process.

Hybridization Process
Figure 3 shows the extended Kalman filter (EKF) designed for the hybridization of MEMS and AGPS information. Being continuous and independent of the environment configuration, the measurements provided by the inertial module are used for the mechanization part of the filter and the AGPS measurements for the update of the filter.

The state vector of the EKF contains the following parameters: the North N and East E components of the pedestrian position, the horizontal velocity v, a scale factor λ affecting the MEMS-based velocity output and the MEMS-based heading perturbations δH.

The vertical component can be treated either as a state vector component computed simultaneously in the coupled
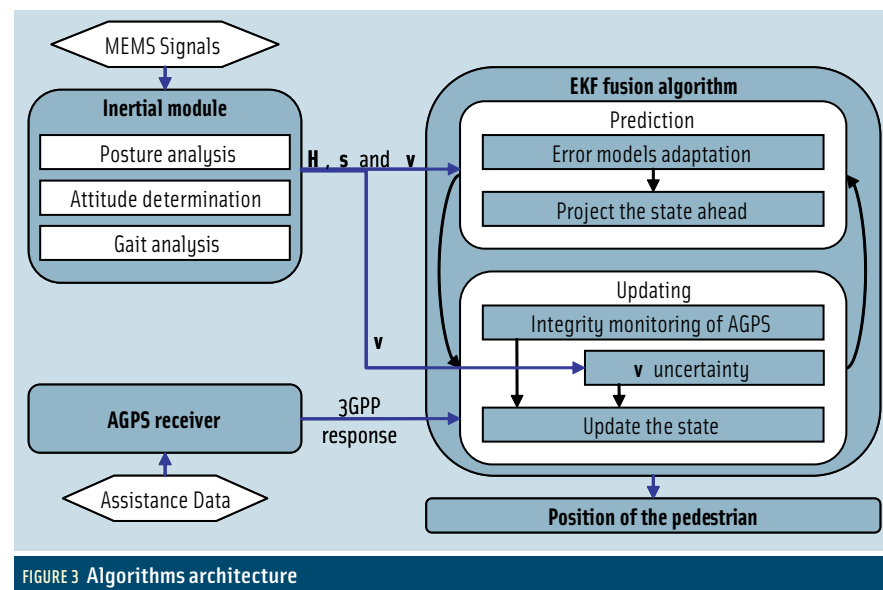

FIGURE 3 Algorithms architecture

scheme or in a separate process. As discussed previously, pedestrian altitude is not directly related to MEMS sensor observations integration but rather to the gait analysis. Therefore, the utilization of height as a variable in the state vector is of less interest. A separate coupling architecture processes the height component using the AGPS height observation as the true height.

The case of a person changing floors using an elevator supports the approach of treating the height in a separate process. In such a situation, MEMS observations cannot reflect the altitude change. Using the AGPS positions as measurements in the filter would deteriorate the output and affect the MEMS-based error estimations. The risk arises from interpretation of the change in the altitude as an error in the gait analysis, whereas the person was just standing in the lift.

The pedestrian trajectory is described by the following classical mechanism:

$$\dot{E} = \lambda \times v \times \sin(H + \delta H)$$

$$\dot{N} = \lambda \times v \times \cos(H + \delta H)$$

This system of equations is non-linear with respect to the system variables, which is why the EKF is used.

AGPS Integrity Monitoring
Signal attenuation indoors due to walls reduces the availability of AGPS positions, making it important to exploit all available AGPS measurements in

the coupling scheme. However, GNSS receiver operation indoors is also strongly affected by multipath, which decreases positioning accuracy.

In order to constrain this problem and reject measurements in which the uncertainty of the positioning accuracy is too large, the modelling of the measurement error covariance matrix in the Kalman filter uses the incoming position uncertainty from AGPS measurements.

However, the reliability of the positioning accuracy uncertainty provided by the AGPS receiver is also a concern. To assess this aspect, we consider the physical constraints of the pedestrian walk, the predictive capability of the MEMS-based algorithm, and study the innovation of the Kalman filter.

The specifics of human movements in walking can assist the adaptive manner of addressing the integrity monitoring of AGPS measurements, which enables the system to reject bad measurements. MEMS sensors record the changes in the cadence of walking that induce physical effects. The AGPS variations in time should be in line with the smooth continuous changes recorded by the inertial sensors.

The positioning accuracy of the MEMS system decreases as a function of the travelled distance. A five percent average drift over the distance one walks has been observed. Experimental results

estimate the velocity of a pedestrian at between 0.8 and 1.2 meter per second. A dynamic threshold (τ), resulting from previous data and the time span between two AGPS updates, can be computed to test the innovation sequence.

$$(\Delta z_k - H \times X_k) \leq \tau$$
$$\tau = v \times (t_{AGPS,k+i} - t_{AGPS,k}) \times 5\%$$

where $t_{AGPS,k+i}$ is the AGPS position update associated with time (k+i), $t_{AGPS,k}$ is the previous AGPS position update associated with time k, and v is the MEMS-based estimation of the pedestrian horizontal walking speed.

Adaptive Measurement Covariance Matrix
Indoors and in light indoor environments, AGPS positioning accuracy may vary from several meters up to several thousands of meters. A well-modelled measurement error covariance matrix is important to ensure good performances from the Kalman filter.

Creating this matrix is a critical part of the hybridization scheme. Each new AGPS position provided is associated with a position uncertainty, which can be used in an adaptive manner in the filter. The semi-major axis uncertainty,

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the semi-minor axis uncertainty, the semi-major axis orientation, and the confidence level are used to compute variances associated with easting and northing coordinates.

Horizontal speed uncertainty. We have developed an additional enhancement to the adaptive treatment of the measurement covariance matrix based on the uncertainty of the AGPS horizontal velocity. The AGPS horizontal velocity varies with the quality of the AGPS mea-

surement, which in turn relates directly to the surrounding obstacles and the signal to noise ratio for each tracked GNSS satellite.

Considering the fact that in our case the AGPS horizontal velocity results directly from the Doppler shift of the GPS carrier wave, the reliability of the horizontal velocity estimate is expected to be better than the one provided by the position coordinates themselves. This also depends on any prefiltering that might be done to the AGPS results before being available in the 3GPP format for the coupling scheme.

Because we expect a higher level of confidence in the size of the uncertainty in the AGPS horizontal velocity, the
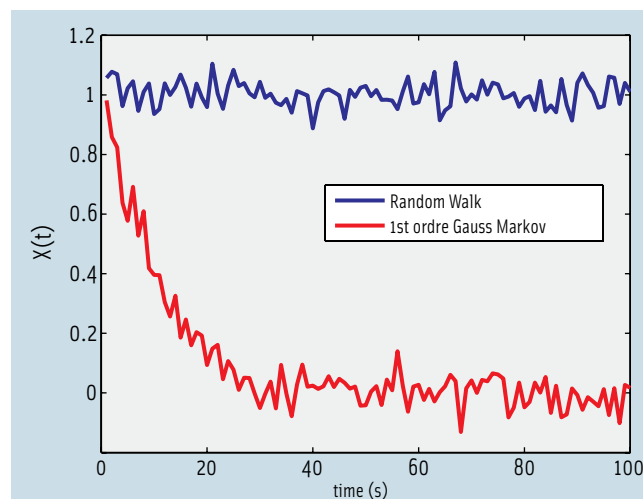
FIGURE 4 Comparison of stochastic error models

observation of the behavior of this data over time allows the adaptation of the measurement covariance matrix. This is done to adjust overly optimistic uncertainties of the accuracy of the AGPS geographical coordinates. A function — for example, an exponential function — decreasing the weight of the measurement covariance matrix associated with the AGPS measurement is applied to cope with the weakness of the uncertainty integrity.

This scheme has been developed to cope with the specific behavior observed in the GPS receiver used in our pedestrian navigation system. This low-cost receiver was used for testing purposes in the EPFL. This solution cannot easily be applied to any AGPS module.

Stochastic error models in outdoors and indoors. The horizontal velocity can be statistically modelled in different manners. We will discuss two stochastic models considered for the prediction equation and the error modelling: the random walk and the first-order Gauss Markov.

The random walk model yields a constant number for all times, but the values are given by a random variable. If the discrete random walk process is used to model the horizontal walking speed, it can be described as the average speed a navigation system user has walked from a starting point with the addition of a random horizontal velocity component at every step.

In a first-order Gauss-Markov pro-

cess, the current value is correlated with the previous epoch value at some extent specified by a degree of freedom with added Gaussian noise. In fact, a first-order order Gauss-Markov model is obtained by passing white noise through a low pass filter. The initial condition is chosen to make the process stationary. The autocorrelation function of the Gauss-Markov process is an exponential decreasing function. This means that the values of the Gauss Markov sequence are less correlated the further apart in time they are.

Stochastic Models

The coupling of AGPS with MEMS enables correction of the errors that affect the inertial sensors over time. However, another expected enhancement of interest from this hybridization is to get more reliable and accurate pedestrian navigation data in transition phases from outdoors to indoors or vice versa. In these transitions, the hybridization filter tries to identify AGPS outliers to reject them.

The integrity monitoring presented earlier accomplishes this task when the changes in successive AGPS positions are large and occur in the short term. But when changes in successive AGPS positions are small and happen over a long period, the integrity monitoring process will have difficulty identifying and rejecting bad measurements.

This phenomenon can be expressed as a low drift or a small deviation from the true trajectory. In that case, the behavior expected from the Kalman filter is to run in prediction mode. This situation occurs when not enough satellites can be tracked or if the multipath effect is strong.

In the prediction phase, the mathematical discrete equations that prop-

agate the scale factor affecting the MEMS-based horizontal velocity can be written, with $W(t_k)$ a Gaussian white noise, as:

- $X(t_{k+1}) = X(t_k) + W(t_k)$ for the random walk
- $X(t_{k+1}) = (1-\beta \times \Delta t) \times X(t_k) + W(t_k)$ for the first-order Gauss-Markov process, with $1/\beta$ the constant time

In the prediction phase, with the use of a first-order Gauss Markov process model for the horizontal velocity scale factor, the value of the latter decreases towards zero during a short time. Consequently, the horizontal velocity also converges to zero. The physical interpretation of that convergence is that the pedestrian is stationary, but in reality the pedestrian is still moving. In this case, the filter is just running in the prediction phase only and is showing the position as being at the same place.

If the horizontal velocity scale factor is modelled with a random walk, its value remains constant. This stationary behavior is interpreted as a pedestrian walking with a constant speed. Therefore, the use of a random walk process in the transition phases or indoors is more appropriate for the INS/AGPS coupling scheme. **Figure 4** illustrates the behaviors of both stochastic processes.

On the contrary, when good AGPS measurements are available, the use of a Gauss Markov process performs better. The stochastic process reflects well the physiological parameters of the walk. A pedestrian usually walks at a smooth pace. Even when he desires route guidance, he will first examine his surroundings to find an indication and then slow down. Using a stochastic process that implies a correlation between successive times remains meaningful.

Field Trials of AGPS/MEMS

The pedestrian navigation system, comprised of the MEMS and AGPS parts, has been tested on the EPFL campus in two different scenarios. For the first scenario, we chose an open-sky environment outdoors. This test shows the full functionality of the filtering.

The second scenario corresponds to the typical route that a visitor is fol-

FIGURE 5 Cap mounting system

lowing while arriving at the EPFL and entering into the building. This scenario is associated with what was previously described as the transition between outdoors and indoors and vice versa. The second scenario allows a more realistic assessment of the positioning technique performances.

A person walking at steady pace was equipped with the following hardware carried in a backpack:

- Three inertial "boxes" distributed on the body as depicted in Figure 1. Each box is composed of a triad of orthogonal accelerometers, a triad of orthogonal magnetometers and a triad of orthogonal gyroscopes.
- A 16-channel, single-frequency receiver and antenna. This receiver is a low-cost, mass-market receiver whose function can be extended to AGPS applications.
- A geodetic-quality, 20-channel dual-frequency receiver connected to a separate antenna used to determine precisely the true walk of the pedestrian. This trajectory is used as the reference trajectory for the results discussed later.
- Both antennas mounted on the user's head minimizing the offset between the reference trajectory and the hybridized footpath. (See **Figure 5**).
- An electronic notebook to record the data from the MEMS module and the GPS receiver. Data acquisition

software, developed by the authors, prepared the recorded GPS data in the 3GPP format described earlier.

Performance assessment

The reference trajectory was postprocessed using differential GPS with fixed ambiguities. The average horizontal accuracy of the reference trajectory is one centimeter. For the parts of the trajectory where an ambiguities-fixed solution was unavailable, the geographical map of the campus was used. Orthophotos of the campus with a 15-centimeter resolution have been georeferenced and used as reference for the indoor and light indoor environments.

The MEMS and the AGPS modules are synchronized, but there is no time synchronization between the reference and the hybrid trajectories. Therefore, we used a time-independent technique that rebuilds the reference trajectory as a spline with curvilinear abscissa to assess the accuracy of the hybrid trajectories. The final accuracy results from the minimum distances that separate
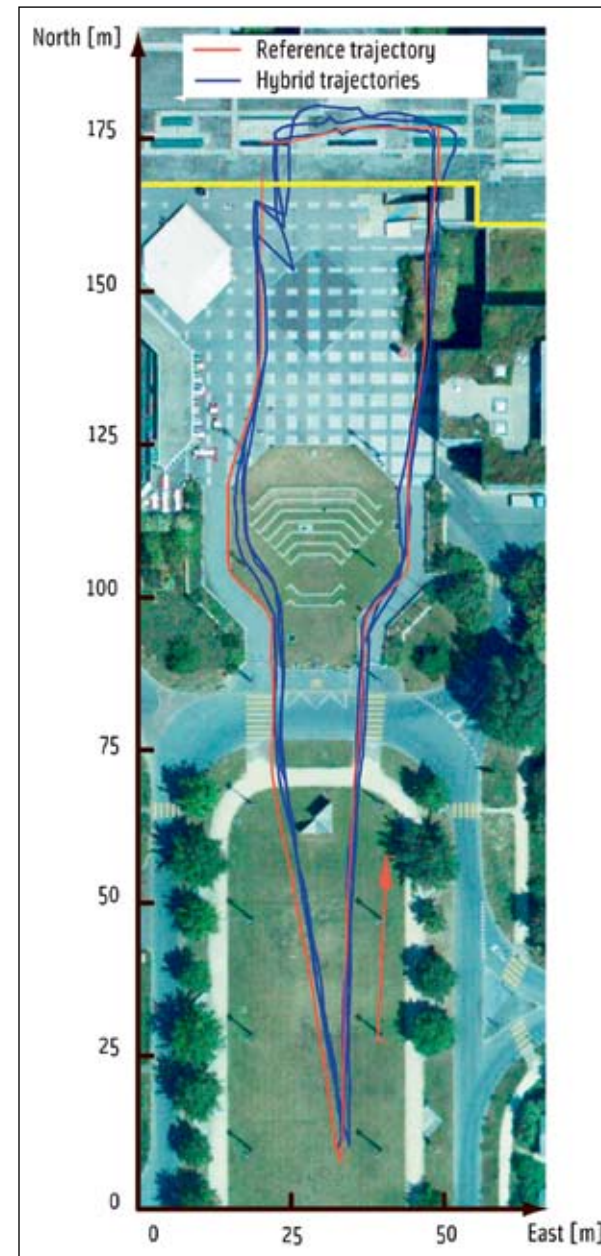

FIGURE 6 Outdoors Indoors scenario

the filtered trajectories from the constructed spline.

The outdoors scenario was performed six times. The average accuracy was 0.84 meters with a standard deviation of 51 centimeters.

Figure 6 depicts the second scenario, a 370-meter course that was walked three times. The average duration to walk along the footpath is 5.5 minutes with 1 minute indoors. The starting point is located in the south at the bottom of the figure image with the northerly walking direction is indicated by an arrow. The
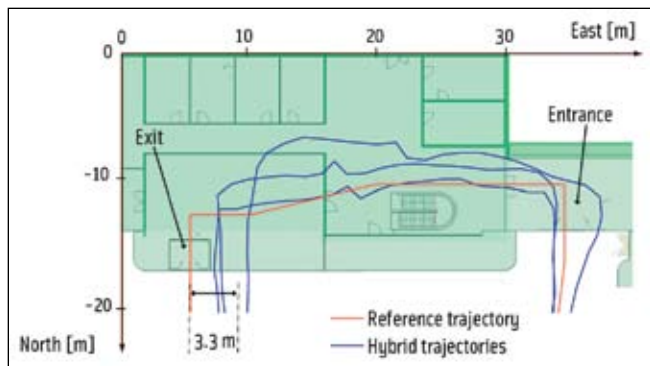
FIGURE 7 Indoors path

As expected, in the test accuracy decreases inside the building. When a person walks indoors, the filter relies only on the MEMS sensors that are affected by large drift and noise. The longer this period lasts, the larger is the deviation from the true trajectory.

indoor portion lies to the north of the yellow line.

The three hybrid trajectories match with a good confidence level the true walked path drawn in red, at times overlapping one another so closely as to be indistinguishable in the figure. The average accuracy for this outdoor scenario is 0.93 meters associated with a standard deviation of 0.99 meters.

The EKF operates well as the pedestrian moves from outdoors to light indoors. It handles the transition in a smooth manner that preserves the accuracy.

As expected, accuracy decreases inside the building. When a person walks indoors, the filter relies only on the MEMS sensors that are affected by large drift and noise. The longer this period lasts, the larger is the deviation from the true trajectory.

When the person exits the building and the AGPS measurement integrity is assessed, the filter is able to correct the accumulated deviation and converges back to the true footpath. This deviation is illustrated on **Figure 7**.

Conclusions

The extended Kalman filter and the enhancements presented earlier show interesting improvements for outdoors/indoors transition scenarios, compared to existing loosely coupled schemes. The main achievements result in an improved accuracy and reliability. Thanks to the distributed MEMS sensors configuration, the tracking of the movements of a person is also more precise. The filter is able to output accurate quasi-instan-

taneous data that are useful for safety applications.

Being able to identify the time a person is entering a zone where AGPS data are not reliable remains a difficult task. The deterioration of AGPS is often correlated with surrounding obstacles. The provision of additional data that indicated if the pedestrian is still outdoors or has just gone indoors could improve the" filter performances.

Without thinking about more complex techniques, such as match-mapping, for example, it certainly would be interesting to try to improve the hybridization process by incorporating data on the number of satellites tracked and their signal-to-noise ratio in addition to the existing 3GPP location format.

Acknowledgements

Manufacturers

The hybrid navigation system described in this article used an Antaris GPS chipset from **u-blox AG**, Thalwil, Switzerland, and the Mtx 3DOF orientation tracker from **Xsens Technologies B.V.**, Enschede, The Netherlands. A Legacy receiver from **Javad Navigation Systems**, Santa Clara, California USA, and Moscow, Russia, connected to an XS1 GPS antenna from **Antcom Corporation**, Torrance, California, was used to determine precisely the true walking motion of the pedestrian.

Additional Resources

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