Utilizing pulsed pseudolites and high-sensitivity GNSS for ubiquitous outdoor/indoor satellite navigation

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Abstract— **Pseudolites provide a means for bridging the gap between outdoors and indoors when GNSS (Global Navigation Satellite System) positioning is concerned. This paper presents a ubiquitous outdoor/indoor GNSS navigation platform that utilizes GPS (Global Positioning System), GLONASS, and pulsed pseudolite (PL) signals for seamless positioning. When a pseudolite signal is pulsed to efficiently transmit the GNSS-like signal only at particular time instants, interference problems between the terrestrial pseudo-satellite signals and the space-based satellite signals are significantly reduced. Pulsed pseudolites are strategically placed indoors at known locations at the ends of building corridors to assist high-sensitivity GPS and GLONASS positioning. A particle filtering solution is implemented to combine the high-sensitivity GNSS and the pseudolite proximity information in order to provide a seamless outdoor/indoor positioning platform. As demonstrated with real-life experiments, pseudolites provide a convenient navigation aid indoors for a GNSS receiver without the need for using additional hardware.**

Keywords- Indoor navigation, pulsed pseudolites, particle filter, proximity sensing, high-sensitivity GPS, GLONASS, GNSS

I. INTRODUCTION

Pseudolites (PL), i.e. pseudo-satellites transmitting GNSS-like (Global Navigation Satellite System) signals, provide a means for bridging the gap between outdoors and indoors when GNSS positioning is concerned. The same receiver technology can be utilized both for acquiring live GNSS signals as well as the PL signals. However, if not properly designed with respect to timing, identification, and signal power, PL signals can introduce severe interference without improving the positioning availability.

In October 2011, a recommendation was comprised by the Electronic Communications Committee (ECC) of the European Conference of Postal and Telecommunications Administrations (CEPT) describing a regulatory framework for authorisation regime of indoor GNSS pseudolites in the band 1559-1610 MHz [1]. The recommendation states, among others, that the GNSS PL equivalent isotropically radiated power should be limited to -50 dBm in general cases; that the operation of indoor GNSS pseudolites should be limited to the band 1559-1610 MHz; and the indoor GNSS pseudolites should use dedicated codes only as reserved by the corresponding GNSS operators. The recommendation opens up new possibilities for the technology development and implementation of indoor pseudolite-based positioning.

A pulsing scheme of the pseudolite signal successfully reduces interference problems: the pseudolite signal is efficiently transmitted only at particular time instants. In this paper, with the ECC recommendation in mind, pulsed pseudolites are strategically placed indoors at known locations in office building corridors to assist high-sensitivity GNSS positioning. A particle filter is implemented to fuse the proximity information of the pseudolites at known locations and the high-sensitivity satellite-navigation positioning result. The implemented scenario resembles the Indoor MEssaging System (IMES) [2, 3] in which location information is transmitted to suitable GNSS receivers, since here proximity sensing and known PL location are utilized. In addition to the positions derived from pseudolite proximity and GNSS, floormap-information is integrated to the result to further improve the obtainable accuracy. The location obtained from GNSS is restricted to the corridor location, based on sensing the proximity of the pseudolite.

In the preliminary analysis conducted herein, accuracy of below 8 meters is achieved in a typical glass, concrete, and steel office building with pseudolite-proximity (6 pseudolites are installed in a 3-storey building, 3 per floor accessed) and high-sensitivity indoor GNSS signals fused together. Integrating floormap information enhances the accuracy even further to below 7 meters. Pseudolites provide a convenient navigation aid indoors for a GNSS receiver without the need for using additional hardware. The pulsing scheme and utilization of non-visible satellite identification numbers reduces the risk for interference for any non-participating receiver.

In this paper, section II discusses briefly pseudolites and high-sensitivity GNSS. Section III presents the general concept of particle filtering. Section IV discusses the applied filtering

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scheme with its state vector, measurements, applied particle filtering, and floormap restriction approach described. Section V presents the conducted experimental setups and the obtained results. Section VI concludes the paper.

II. PSEUDOLITES AND HIGH-SENSITIVITY GNSS

A. *Pseudo-satellites*

A pseudo-satellite, or pseudolite, is a ground-based transmitter of GNSS-like signals [4, 5]. These ground-based transmitters have been used to complement the satellites since the earliest days of the GPS concept [6]. Pseudolites can augment traditional GPS navigation techniques via various ways: Cobb [6] categorizes the concepts into direct ranging pseudolites, mobile pseudolites, digital datalink pseudolites, carrier-phase differential GPS ambiguity resolution with pseudolites, and synchronized pseudolites.

An additional, important concept within pseudolites is the proposition of the RTCM-104 committee that pseudolite signals are transmitted in frequent, short, strong pulses [7]. The pulses would be strong enough to be easily tracked, despite having a duty cycle of only about 10% but the interval between the pulses would allow a receiver to track real satellite signals without interference [6]. The pseudolites utilized in this study were manufactured by Space Systems Finland [8] and one is shown in Fig. 1. In this indoor pseudolite implementation, 3 pseudolites were place on the 1st floor of an office building and 3 on the 3rd floor, in which the experimental testing was conducted. Pseudolites transmitted pulsed GPS L1 C/A signals with -35 dBm power (pulses were only 87 µs in length). The GPS pseudo-random noise (PRN) codes were utilized of satellites that were on the other side of the Earth at the time of testing and thus whose space based signals were not available to avoid interference. In many PL applications, the close range between the receivers and the PLs results in non-linearity, but in our setup the non-linearity is not a concern because the PLs are used as beacons only.

Figure 1. Pseudolite by Space Systems Finland Ltd with an antenna

B. *High-sensitivity GNSS*

The performance of a high-sensitivity assisted GNSS receiver is nowadays fairly good also in indoors, typically providing a level of accuracy within tens of meters, e.g. [9-11], excluding underground garages and windowless constructions. In outdoor environments, GNSS typically offers a level of accuracy within a couple of meters. The high-sensitivity receivers utilized in this study were the Fastrax IT500 GPS receiver [12] and the Fastrax IT600 GPS/GLONASS receiver [13]. The receivers are shown in Fig. 2 in their miniature evaluation kits.

Figure 2. Fastrax IT500 and IT600 receivers in their mini-evaluation kits with antennas

III. BASICS OF PARTICLE-FILTERING

Particle filters (PF), also known as Sequential Monte Carlo (SMC) methods, recursively represent the required posterior density function of a state by a set of random samples with associated weights. Considering a system with a state-space representation given by

$$\begin{aligned} \mathbf{x}_k &= f_k(\mathbf{x}_{k-1}, \mathbf{u}_k) \\ \mathbf{y}_k &= g_k(\mathbf{x}_k, \mathbf{v}_k) \end{aligned} \quad (1\text{-}2)$$

where $\mathbf{y}_k$ is the measurement vector, $\mathbf{x}_k$ the unknown state vector to be estimated, g_k is a measurement function, f_k is a system transition function, $\mathbf{u}_k$ and $\mathbf{v}_k$ are noise vectors, and the subscript *k* denotes the time index at time t_k, the aim with particle filtering is to estimate the sequence of hidden parameters $\mathbf{x}_k$ based only on the observed data $\mathbf{y}_k$ for $k = 0,1,2,3,\ldots$ From the Bayesian estimation perspective, this is equivalent to computing the posterior distribution $p(\mathbf{x}_k|\mathbf{y}_{1:k})$, where $\mathbf{y}_{1:k} = [\mathbf{y}_1, \mathbf{y}_2, \ldots, \mathbf{y}_k]$.

In a PF, the posterior distributions $p(\mathbf{x}_k|\mathbf{y}_{1:k})$ are approximated by discrete random measures defined by particles and weights assigned to the particles [13]. The basic steps of a generic PF are:

- suppose a set of *N* weighted samples $\{w_{k-1}^{(j)}, \mathbf{x}_{k-1}^{(j)}\}_{j=1}^{N}$ is used to approximate the posterior $p(\mathbf{x}_{k-1}|\mathbf{y}_{1:k-1})$ at time

t_{k-1} with the following point distribution $p(\mathbf{x}_{k-1}|\mathbf{y}_{1:k-1}) \approx \sum_{j=1}^{N} w_{k-1}^{(j)} \delta\left(\mathbf{x}_{k-1} - \mathbf{x}_{k-1}^{(j)}\right)$

where $\delta(\ )$ denotes the Dirac-delta function.

- new samples are generated from a suitably designed proposal distribution, which may depend on the old state and the new measurements: $q\left(\mathbf{x}_k \middle| \mathbf{x}_{k-1}^{(j)}, \mathbf{y}_k\right)$. The new importance weights are set to $w_k^{(j)} \propto w_{k-1}^{(j)} \frac{p\left(\mathbf{y}_k \middle| \mathbf{x}_k^{(j)}\right) p\left(\mathbf{x}_k^{(j)} \middle| \mathbf{x}_{k-1}^{(j)}\right)}{q\left(\mathbf{x}_k \middle| \mathbf{x}_{k-1}^{(j)}, \mathbf{y}_k\right)}$

Thus, a new set of samples $\left\{w_k^{(j)}, \mathbf{x}_k^{(j)}\right\}_{j=1}^{N}$ is approximated to be distributed according to $p(\mathbf{x}_k|\mathbf{y}_{1:k})$ at time t_k. Before proceeding to the generation of the particles for the next time instance, the effective particle size is estimated. If the effective particle size measuring the degeneracy of the particles is below a predefined threshold, resampling takes place; otherwise new particle generation and weight computation is performed, as described in e.g. [13]. Resampling eliminates particles with small weights and replicates particles with large weights.

More details about PF can be found from, for example, [14-21].

IV. PARTICLE FILTERING FOR POSITION ESTIMATION

A pedestrian is assumed here to move on a two-dimensional Cartesian plane. Pedestrian positioning equations utilizing a constant speed model are thus applied here in a horizontal plane for the position estimation.

A. State model

The state vector at time instant k is defined as

$$\mathbf{x}_k = \left[X_k \ Y_k \ \dot{X}_k \ \dot{Y}_k\right]^T \tag{3}$$

where k denotes the current epoch, X_k is the coordinate in East direction, Y_k is the coordinate in North direction, $\dot{X}_k$ is the speed in East direction (in m/s) and $\dot{Y}_k$ is the speed in North direction (in m/s). $(X,Y)_k$ is the 2-Dimensional (2D) position of the user at a discrete time k and $(\dot{X},\dot{Y})_k$ is its time derivative, i.e., the velocity vector in 2D. The applied state model is defined as

$$\mathbf{x}_k = \mathbf{F}\mathbf{x}_{k-1} + \mathbf{w}_k$$

where the state transition matrix $\mathbf{F}$ is defined as

$$\mathbf{F} = \begin{bmatrix} 1 & 0 & \Delta t & 0 \\ 0 & 1 & 0 & \Delta t \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{4}$$

where Δt is the sampling period. The random process $\mathbf{w}_k$ is the process noise with known statistics, here assumed zero mean Gaussian noise, $\mathbf{w}_k \sim N(0,\mathbf{Q}_k)$, where $\mathbf{Q}_k$ is the process covariance matrix as

$$\mathbf{Q}_k = \begin{bmatrix} \frac{\Delta t^4}{4}\Omega & \frac{\Delta t^3}{2}\Omega \\ \frac{\Delta t^3}{2}\Omega & \Delta t^2\Omega \end{bmatrix} \tag{5}$$

where

$$\Omega = \begin{bmatrix} \sigma_X^2 & 0 \\ 0 & \sigma_Y^2 \end{bmatrix} \tag{6}$$

B. Measurement model

Position, speed and heading are obtained from the GNSS receiver and the pseudolite positions are obtained as measurements based on the proximity of the pseudolite i.e. when the pseudolite signal is in track.

1) Position measurement

The measurement model for positions can be defined as

$$\mathbf{y}_k = \mathbf{H}\mathbf{x}_k + \mathbf{I}_2 v_p \tag{7}$$

where the design matrix is defined as

$$\mathbf{H} = [\mathbf{I}_2 \ \mathbf{0}] \tag{8}$$

where $\mathbf{I}_2$ is the 2x2 identity matrix and v_p refers to the measurement noise of the position measurements.

The measurements include observations from the high-sensitivity GNSS receiver and the location from the pseudolite in track

$$\begin{aligned} X_{GNSS,k} &= X_k + v_{GNSS} \\ Y_{GNSS,k} &= Y_k + v_{GNSS} \\ X_{PL,k} &= X_k + v_{PL} \\ Y_{PL,k} &= Y_k + v_{PL} \end{aligned} \tag{9-12}$$

A pseudolite location measurement is available every time the pseudolite with known coordinates is tracked with a software receiver with at least a 30-dBHz carrier-to-noise density ratio (C/N_0). This threshold value was chosen based on empirical assessment.

2) Speed measurement

Speed obtained from the GNSS is defined as

$$S_k = \sqrt{\dot{X}_k^2 + \dot{Y}_k^2} + v_S \tag{13}$$

3) Heading measurement

The heading measurement from the GNSS is defined as

$$\phi_k = \arctan(\frac{Y_k}{X_k}) + v_\phi \tag{14}$$

The v_{GNSS}, v_{PL}, v_S, and the v_ϕ are the measurement noise with known statistics, here assumed to follow an independent Gaussian distribution, i.e. $v_{GNSS} \sim N(0, R_{GNSS})$, $v_{PL} \sim N(0, R_{PL})$, $v_S \sim N(0, R_S)$, and $v_\phi \sim N(0, R_\phi)$, where R_{GNSS}, R_{PL}, R_S, and the R_ϕ are the measurement variances. The speed and especially the heading measurement from the GNSS are indoors not of high quality and this is taken into account when setting the variance values, as also discussed for multi-sensor pedestrian positioning in [22].

The problem of tracking the pedestrian indoors is to infer the mobile state $\mathbf{x}_k$ from these sequential measurements. Since the measurement equations for the speed and the heading are nonlinear, a particle filter is used for the state estimation.

C. Description of applied particle filter

The particles in the position estimation are generated according to the prior distribution of $\mathbf{x}_k$, i.e.,

$$\mathbf{x}_k^{(j)} = \mathbf{F}\mathbf{x}_{k-1}^{(j)} + \mathbf{w}_k^{(j)} \tag{15}$$

where j refers to the particle number. The corresponding weight $w_k^{(j)}$ of each particle is updated as

$$w_k^{(j)} = l_{\mathbf{y}_k,GNSS}^{(j)} * l_{\mathbf{y}_k,PL}^{(j)} * l_{S_k}^{(j)} * l_{\phi_k}^{(j)} \tag{16}$$

where

$$l_{\mathbf{y}_k,GNSS}^{(j)} = N(\mathbf{y}_k; \mathbf{H}\mathbf{x}_k^{(j)}, R_{GNSS})$$

$$l_{\mathbf{y}_k,PL}^{(j)} = N(\mathbf{y}_k; \mathbf{H}\mathbf{x}_k^{(j)}, R_{PL})$$

$$l_{S_k}^{(j)} = N(S_k; \sqrt{(\dot{X}_k^{(j)})^2 + (Y_k^{(j)})^2}, R_S) \tag{17-20}$$

$$l_{\phi_k}^{(j)} = N(\phi_k; \arctan(\frac{Y_k}{X_k}), R_\phi)$$

where $N(\cdot)$ refers to the normal probability density function. Based on the weights in Eq. (16), deterministic resampling is used to eliminate particles with small weights and replicate ones with large weights. At the end of every time step k the state estimation is the weighted mean of the particles $\mathbf{x}_k^{(j)}$, i.e.,

$$\hat{\mathbf{x}}_k = \sum_{j=1}^{N} l_k^{(j)} \mathbf{x}_k^{(j)} \tag{21}$$

D. Floormap aided position restriction based on pseudolite proximity

The aiding provided by floormap information is performed by utilizing the building layout. A simple approach is adopted here to extract the building layout information on office building corridors, and then to utilize it in the fusion model in an efficient way: 1) the headings of the corridors with respect to the origin East and counter-clockwise positive are extracted and their related slopes, 2) the GNSS locations (i.e. the position measurements) are forced to lie on the corridor slopes when the pseudolites in these corridors are being tracked. This improves thus the position measurement quality derived from the GNSS receiver when the GNSS positions are forcefully transferred to the corridor locations.

V. RESULTS

The utilization of high-sensitivity GNSS and indoor pseudolites for a seamless outdoor/indoor positioning solution was tested and analyzed in an office building environment. A particle filter was applied in the fusion of GNSS location, speed, heading, and pseudolite proximity information with a number of particles N=1000. This amount was chosen based on empirical assessment and is a good compromise between computational resources and accuracy provided.

A. Test setup description

Experiments were conducted in the 1st and the 3rd floor corridors of the Finnish Geodetic Institute in July 2012 for about 6 minutes in each floor. The pedestrian tests started outdoors, then the pedestrian tester went indoors to perform a loop, and the tests ended outdoors with GNSS availability, respectively for both floors. NovAtel's SPAN GPS/INS high-accuracy positioning system [23] providing centimeter-level accuracy was used as a reference. The SPAN reference system is shown in Fig. 3. Fig. 4 shows the radio for the software GNSS receiver by Fastrax Ltd. which is used to track the pulsed pseudolite signals. Fig. 5 presents the floor map of the 1st floor test area as well as pictures describing the environment. Fig. 6 presents the floor map of the 3rd floor corridors as well as pictures describing the environment.

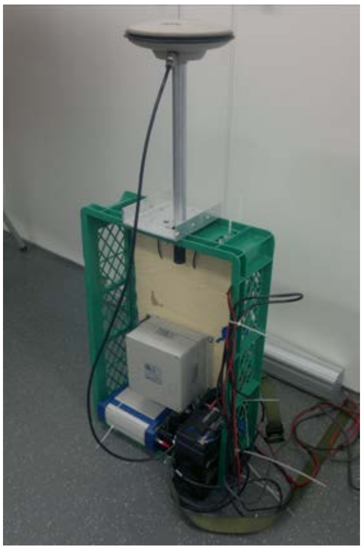

Figure 3. SPAN reference system

Figure 4. Radio front-end of the Fastrax software GNSS receiver used for pseudolite signal tracking

Figure 5. Test area 1: floor-map of 1st floor and the environment

Figure 6. Test area 2: floor-map of 3rd floor and the environment

B. *Navigation results*

The applied positioning technique combining pulsed pseudolites and high-sensitivity GNSS does not cause interference with outdoor GNSS reception. The interference of PLs on non-participating receivers is widely assessed in [24-25]. Indoors, the pulsing mitigates in addition the near-far problem very effectively, even without receiver modifications. The pulsing does not address the indoor multipath problem though, but since the PLs are used as beacons in this setup, multipath on the pseudolite signals are not of concern.

Navigation results for the 1st floor are presented first. Position solutions of the Fastrax IT600 GPS/GLONASS receiver are compared to the particle filtering solutions fusing the GNSS and the pseudolite proximity. In Fig. 7, the SPAN reference (ground truth) is presented as well as the locations of the 3 pseudolites in addition to the IT600 GPS/GLONASS result and the particle filtering solution. Fig. 8 presents the horizontal errors of the results on the 1st floor: the GNSS solution provides an average error of 15.8 meters in this experiment whereas the particle filtering solution provides an average horizontal error of 7.6 meters.

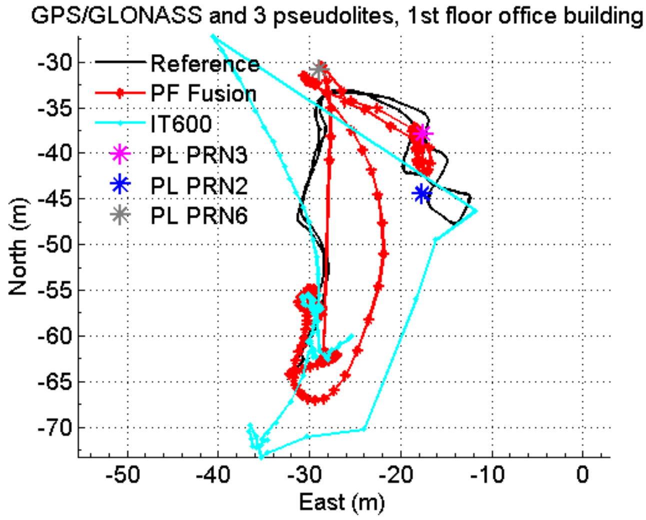

Figure 7. Results in an East-North coordinate frame with GPS/GLONASS Fastrax IT600 receiver (cyan) and the particle filter results with 3 GPS L1 pseudolites used for proximity sensing (red)

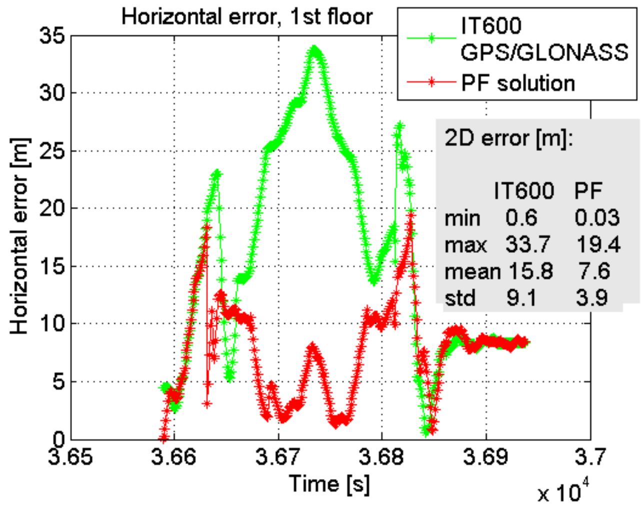

Figure 8. Horizontal errors of the solutions in the 1st floor experiment including GNSS (green) and particle filtering with pseudolites and GNSS (red)

In the following, results are presented for the 3rd floor experiment with the high-sensitivity Fastrax IT500 GPS receiver and 3 pseudolites combined in the described particle filter. In Fig. 9, the SPAN reference (ground truth) is presented as well as the locations of the 3 pseudolites in addition to the IT500 GPS result and the particle filtering solution.

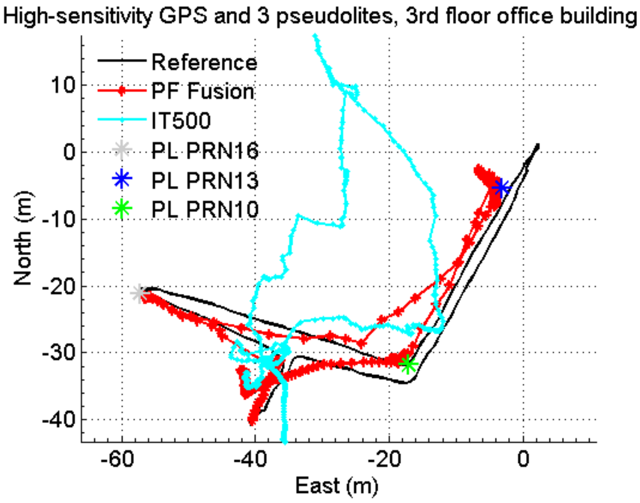

Figure 9. Results on the 3rd floor with the Fastrax IT500 GPS receiver (cyan) and the particle filter result with 3 GPS L1 pseudolites used for proximity sensing (red)

When applying the floormap for corridor restriction of the GNSS position based on the pseudolite proximity, the results are improved even further as Fig. 10 illustrates. In Fig. 10, the SPAN reference (ground truth) is presented together with the locations of the 3 pseudolites in addition to the IT500 GPS result and the particle filtering solution utilizing the building layout/floormap assistance.

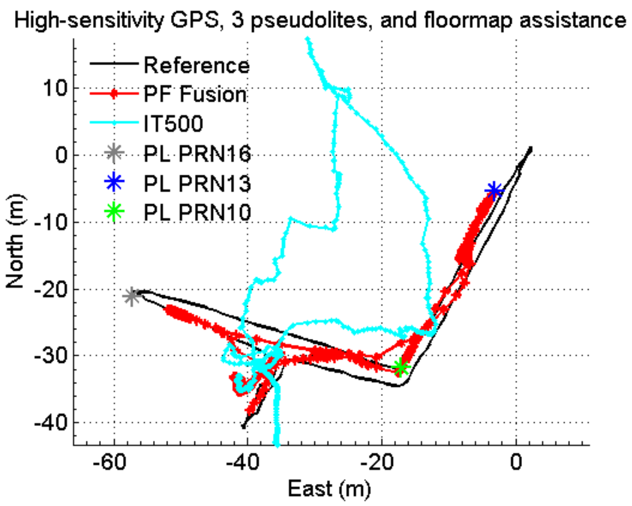

Figure 10. Results with the Fastrax IT500 GPS receiver (cyan) and the particle filter result with 3 GPS L1 pseudolites used for proximity sensing as well as floormap assistance (red)

Fig. 11 presents the horizontal errors of the achieved results for the 3rd floor: the GPS solution provides an average error of 11.7 meters whereas the particle filtering solution with pseudolite proximity information utilization provides an average horizontal error of 7.7 meters and the floormap building layout restriction provides an average error of 6.6 meters. As can be seen from both Figures 8 and 11, the error grows when the receiver is far apart from the pseudolites.

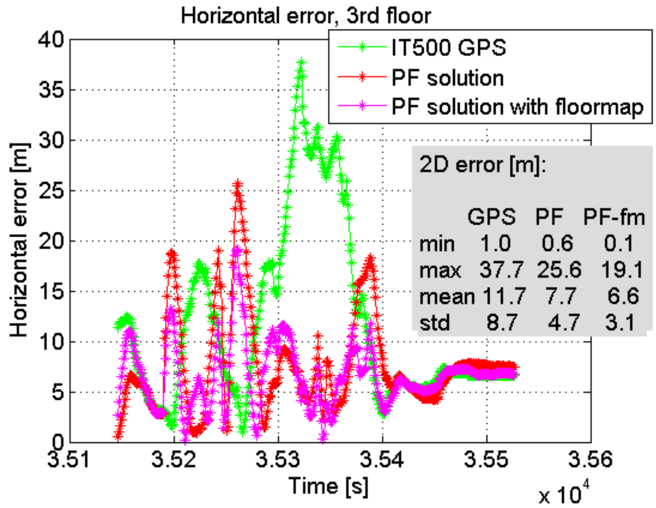

Figure 11. Horizontal errors of the solutions in the 3rd floor experiment including GPS (green), particle filtering with pseudolite proximity information in addition to GPS (red), as well as the addidtional floormap assistance by building layout restriction (magenta)

Table 1 summarizes the horizontal position errors and shows the usefulness of indoor pseudolite tracking with a GNSS receiver for proximity sensing for performance improvement. Building layout assistance provides even better positioning accuracy for indoor positioning.

TABLE I. POSITION RESULTS SUMMARIZED

Solution	Horizontal error statistics [m]			
	min	***max***	***mean***	***std***
1st floor				
IT600	**0.6**	**33.7**	**15.8**	**9.1**
GNSS+PLs in PF	**0.3**	**19.4**	**7.6**	**3.9**
3rd floor				
IT500	**1.0**	**37.7**	**11.7**	**8.7**
GPS+PLs in PF	**0.6**	**25.6**	**7.7**	**4.7**
3rd floor with building layout assistance				
IT500	**1.0**	**37.7**	**11.7**	**8.7**
GPS+PLs+ floormap in PF	**0.1**	**19.1**	**6.6**	**3.1**

VI. CONCLUSIONS

This paper demonstrated the benefits of utilizing pulsed pseudolites indoors for assisting high-sensitivity GNSS positioning with simple proximity sensing when the pseudolite signals are in track. A simple particle filtering approach was implemented for the space-based GNSS and pseudolite fusion in addition to integrating building layout corridor location restriction through floormap assistance to the particle filter solution. Pseudolites present a suitable navigation aid indoors for a satellite navigation receiver without the requirement for needing any additional hardware than the GNSS radio. Future work includes additional optimization of the implemented particle filter as well as experiments with a denser pseudolite infrastructure for enhanced positioning accuracy.

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