Asynchronous Pseudolites and GNSS Hybrid Positioning

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***Abstract*—Pseudolites have the potential to extend Global Navigation Satellite System (GNSS) usage to environments where GNSS navigation is usually precluded. This also applies to asynchronous pseudolite systems, i.e. systems where the different pseudolites operate in an independent way and have the potential to enable metre level navigation. Asynchronous pseudolite systems require however dedicated strategies in order to integrate GNSS and pseudolite information.**

In this paper, a hybrid asynchronous pseudolite/GNSS system is developed and an extended navigation solution integrating both pseudolite and GNSS observations is obtained. Loosely- and tightly-coupled integrations are considered along with two different pseudolite positioning approaches: proximity and Receiver Signal Strength (RSS)-based location. The performance of the approaches proposed has been tested in different scenarios including static and kinematic conditions. The methods developed are effective techniques for integrating heterogeneous measurements from different sources such as asynchronous pseudolites and GNSS and suitable for different contexts.

***Keywords*—Asynchronous system, GNSS, GPS, Loosely coupled, Pseudolite, Tightly coupled**

I. INTRODUCTION

The usage of Global Navigation Satellite System (GNSS) signals in difficult environments such as open-pit mines, urban canyons and indoors is hindered by signal attenuation and blockage. Moreover when signals are available, measurements are usually affected by multipath and fading effects. In such conditions, the lack of signals of good quality makes GNSS-based navigation unreliable, if not unfeasible. For this reason, several complementary technologies have been developed to bring location services in such environments. Among the proposed solutions, pseudolites or pseudo-satellites have the potential to extend GNSS usage to environments where GNSS navigation was previously precluded. Pseudolites are ground based transmitters which are able to provide GNSS-like signals in environments characterized by poor satellite visibility and bad reception conditions. Pseudolites have been traditionally used in a synchronous configuration where all the pseudolites are synchronized against a common time scale, thus the same principle adopted by GNSS positioning is used to compute the user position. Despite the potential of synchronous pseudolites, alternative solutions have been recently considered where each pseudolite operates independently without requiring complex synchronization mechanisms. This has led to the development of asynchronous pseudolite technologies characterized by a simplified system design and reduced costs.

The lack of synchronization between the different pseudolites does not allow the extraction of travel time information and different techniques have to be adopted to determine the user position. In this respect, two approaches have been considered in the literature: the proximity principle and the usage of Receiver Signal Strength (RSS) measurements. The proximity principle has been adopted by the Indoor Messaging System (IMES) developed by the Japanese Aerospace eXploration Agency (JAXA) as part of the Quasi-Zenith Satellite System (QZSS). In this case, the user determines its position as that of the closest IMES transmitter. When RSS measurements are used, the received pseudolite power is converted into distances using an empirical model whose parameters can be transmitted as part of the pseudolite navigation message.

The potentiality of asynchronous pseudolites was considered by [1] where indoor navigation was demonstrated with a metre level accuracy. Although both proximity and RSS information were considered, in [1] the authors did not investigate potential synergies between GNSS and asynchronous pseudolites. Indoor location was achieved using measurements extracted only from pseudolite signals.

In this paper, a hybrid asynchronous pseudolite/GNSS system is developed where pseudolite observations are converted into measurements compatible with the GNSS navigation solution. An extended navigation solution integrating both pseudolites and GNSS observations is thus obtained.

Two different integration strategies are considered:

- *loosely coupled* integration, where the position computed using the pseudolite system is integrated within the GNSS measurement model
- *tightly coupled* integration, where the distances obtained using RSS positioning are used together with GNSS pseudoranges.

When the first type of integration is implemented, the position obtained using a pseudolite system alone is determined with either the proximity or the RSS-based approach. The position solution is then integrated in the GNSS positioning block. In this case the Weighted Least Squares (WLS) cost function to be minimized for determining the final user position is made of two terms. The first one is determined by the pseudoranges obtained using a High Sensitivity (HS) GNSS receiver, while the second keeps into account the proximity information.

In the tightly coupled approach, only RSS observations are considered and the Carrier-to-Noise density power ratio (C/N_0) measurements of the pseudolite signals are at first converted into distances using an empirical model as detailed in [1]. The distances obtained exploiting C/N_0 measurements are then used together with the pseudoranges generated by a

HS receiver. Also in this case, the user position is obtained by solving a mixed WLS problem defined by the GNSS pseudorange measurements and the pseudolite distances.

The techniques developed have been thoroughly analyzed from an experimental point of view showing the advantages of the approaches proposed. The algorithms developed were tested in difficult environments including the meeting room of an office building made of concrete. Two pseudolite systems were adopted: the asynchronous pseudolite system developed in [1] and implemented on a Universal Software Radio Platforms (USRPs) and the Commercial Off-the-Shelf (COTS) pseudolite system developed by Space System Finland (SSF) [2].

From the testing, it emerges that the information provided by an asynchronous pseudolite system allows the user to compensate for the limited satellite signal availability. A single GNSS measurement allows the user to recover timing information whereas additional observations improve the accuracy of the overall navigation solution.

The methods developed are effective techniques for integrating heterogeneous measurements from different sources such as asynchronous pseudolites and GNSS. Moreover, the possibility of weighting the measurements according to their quality and type makes the algorithms flexible and suitable for different contexts. The usage of asynchronous pseudolites significantly reduces system costs and alleviates the requirement of having transmitters operating in the same frequency bands as that adopted by GNSS.

The remainder of this paper is organized as follows: in Section II, asynchronous pseudolite positioning is reviewed and the concept of pseudo-measurement is introduced. The integration strategies considered are also detailed. The experimental setup adopted for the analysis is detailed in Section III and the results obtained are described in Section IV. Finally conclusions are provided in Section V.

II. PSEUDOLITE POSITIONING AND INTEGRATION STRATEGIES

In this section, different positioning techniques which can be used along with asynchronous pseudolites are briefly summarized. The concept of pseudo-measurements is introduced and the integration strategies adopted in this work are detailed. For asynchronous pseudolite positioning, it is assumed that N pseudolites are in view and that their position

$$P_{pl,i} = (x_i, y_i, z_i) \tag{1}$$

is known. The index i is used to denote quantities pertaining the ith pseudolite. Moreover, the receiver is able to extract C/N_0 measurements which can be used for proximity and RSS positioning.

A. Proximity positioning

When a single pseudolite is in view, the receiver can determine its position as that of the pseudolite which is assumed to be close to it. This is the most simple form of location based on proximity. When several pseudolites are in view, proximity positioning can be extended in different ways for example considering the position of the pseudolite associated to the strongest received signal. Another approach is to compute the user position as a linear combination of the pseudolite positions:

$$P_u = (x_u, y_u, z_u) = \frac{\sum_{i=1}^{N} w_i P_{pl,i}}{\sum_{i=1}^{N} w_i} \tag{2}$$

where w_i is the weight assigned to the ith pseudolite and is a function of the pseudolite signal C/N_0. In this work, the following relationship is adopted:

$$w_i = 10^{(C/N_0)_i/20} \tag{3}$$

where C/N_0 measurements are assumed to be provided in dB-Hz. Eq. (2) defines the Weighted Centroid Localization (WCL) approach. Note that w_i has been selected in order to reflect the fact that the quality of distances, as provided by a GNSS/pseudolite receiver, are proportional to the square root of the inverse of the C/N_0 expressed in linear units. The C/N_0 is implicitly used here as an indication of proximity.

B. RSS positioning

RSS is defined as the voltage measured by a receiver's Receiver Signal Strength Indicator (RSSI) circuit and corresponds to the power measured on a logarithmic scale. It is usually modeled as [3], [4]:

$$P(d) = P_0 - 10\alpha \log_{10} \frac{d}{d_0} \tag{4}$$

where $P(d)$ is the RSS measured at the distance d from the emitter. α is the path-loss exponent and P_0 is the power received at a short reference distance, d_0.

The C/N_0 is a function of the received power and hence (4) can be rewritten in terms of C/N_0 measurements:

$$\left(\frac{C}{N_0}\right)_i = K_i - \alpha 10 \log_{10}(d_i) \tag{5}$$

where K_i is a constant accounting for the power of the ith transmitted signal and for the reference distance d_0.

When the constants K_i and α are known, a direct relationship between the measured C/N_0 and transmitter-receiver distance can be established. Transmitter-receiver distances can be expressed as a function of the user position:

$$d_i = \sqrt{(x_u - x_i)^2 + (y_u - y_i)^2 + (z_u - z_i)^2}. \tag{6}$$

Finally, the user position can be determined by minimizing the cost function [1]:

$$J(x, y, z) = \sum_{i=0}^{N-1} \left(\frac{C}{N_0}\right)_i E_i^2 \tag{7}$$

where

$$\begin{aligned} E_i = {} & \left(\frac{C}{N_0}\right)_i - K_i \\ & + \frac{1}{2}\alpha 10 \log_{10}\left[(x - x_i)^2 + (y - y_i)^2 + (z - z_i)^2\right]. \end{aligned} \tag{8}$$

C. Pseudo-measurements and loosely coupled integration

One of the methods used to include additional information in the computation of the user position is the conditional Least Squares (LS) adjustment where *a priori* conditions are included in the measurement model [5]. The conditions are known with certain *a priori* accuracies which are used as weights in the WLS algorithm. The constraints are converted into conditions which can be interpreted as measurements or pseudo-measurements.

An example can be found in [6] which adopted pseudo-measurements modeling the behavior of the inter-system bias between GPS and GLONASS. The improvements provided by the inclusion of a priori conditions on the altitude were evaluated in [7], [8]. Finally, [9] assessed the benefits of pseudo-measurements for Receiver Autonomous Integrity Monitoring (RAIM) algorithms in urban scenarios. In this paper, three constraints are introduced exploiting the information provided by the asynchronous pseudolite system.

Consider the case where a first estimate of the user position, $P_u = (x_u, y_u, z_u)$, is available. This position is obtained using the approaches detailed in Section II-A and Section II-B and is expressed in the frame local to the pseudolites. This position can be converted in to the East North Up (ENU) frame

$$P_u = (x_u, y_u, z_u) \rightarrow (E_{u,pl}, N_{u,pl}, U_{u,pl}) \tag{9}$$

and used to add the following equations in the LS iteration adopted by a GNSS receiver to solve for the user position:

$$\begin{bmatrix} E_{u,pl} - E_0 \\ N_{u,pl} - N_0 \\ U_{u,pl} - U_0 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} \Delta E \\ \Delta N \\ \Delta U \\ \Delta(cdt) \end{bmatrix} \tag{10}$$

where:

- E_0, N_0 and U_0 are the position estimates in the previous epoch. The algorithm is initialized by selecting E_0, N_0 and U_0 as the mean of the pseudolite positions.
- ΔE, ΔN, ΔU and $\Delta(cdt)$ are the errors to add to the nominal states in order to obtain the updated solution
- cdt is the receiver clock bias.

The impact of the constraints in (10) are weighted relatively to the level of confidence provided to the pseudolite solution. These conditions can be included in the measurement model, allowing solution with only one visible satellite which is used to estimate the clock bias. If no satellite is available the solution of the hybrid system is coincident to that provided by the pseudolite system alone.

This approach can be considered as a form of loosely coupled integration since the position derived from the asynchronous pseudolite system is used to improve the GNSS solution.

D. GNSS/Pseudolite tightly coupled integration

A second integration approach exploits the RSS positioning algorithms described in Section II-B where distances are estimated from each pseudolite. Pseudolite distances can be used directly in the GNSS measurement model. In this case, the vector containing the differences between the actual and estimated measurements is given by

$$\delta\rho = \begin{bmatrix} \delta\rho_1 \\ \delta\rho_2 \\ \vdots \\ \delta\rho_j \\ \delta d_1 \\ \vdots \\ \delta d_N \end{bmatrix} \tag{11}$$

where ρ_j is the jth pseudorange obtained using a HS GNSS receiver. $\Delta\rho$ is used in the iterative computation of the WLS navigation solution and the design matrix of the hybrid system is made of two blocks: the first is related to GNSS pseudoranges and the second to the pseudolite distances. The design matrix of the hybrid system is expressed by the following formula:

$$H_{Hyb} = \begin{bmatrix} a_{GNSS_1} & b_{GNSS_1} & c_{GNSS_1} & 1 \\ a_{GNSS_2} & b_{GNSS_2} & c_{GNSS_2} & 1 \\ \vdots & \vdots & \vdots & \vdots \\ a_{GNSS_j} & b_{GNSS_j} & c_{GNSS_j} & 1 \\ a_{PL_1} & b_{PL_1} & c_{PL_1} & 0 \\ \vdots & \vdots & \vdots & \vdots \\ a_{PL_N} & b_{PL_N} & c_{PL_N} & 0 \end{bmatrix} \tag{12}$$

where a, b, c are the cosine directors of the vector from the receiver position to the device that broadcast the signal, either satellite or pseudolite. The solution is obtained using a WLS estimation technique where the weights of the pseudolite distances were empirically determined.

Since the integration is performed at the measurement level, it can be considered as a form of tightly coupled integration.

III. EXPERIMENTAL SET-UP

Several data collections were conducted in different scenarios in static and kinematic conditions. The first data collection was performed in static conditions and the receiver was placed on a balcony at the entrance of the first floor of an office building. In this scenario, GNSS signals are blocked by the building and by the nearby trees. GNSS measurements were also affected by gross errors due to multipath and fading. Only one pseudolite was used and only loosely coupling using proximity information has been considered. The receiver used for the test is a LEA-6T u-blox receiver with a patch antenna; the receiver was connected to an Andorid mobile phone to collect and store the data. The pseudolite used was the one described in [1] and implemented on a USRP. A pre-survey was performed using a geodetic technique to determine the coordinates of the reference point where the receiver antenna was placed. Hence the position solution was evaluated in terms of horizontal and vertical errors.

Several data collections were also performed in a large meeting room (about 10×7 m) of an office building. In this case, four COTS pseudolites [2] were used and placed in the corners of the room. Initially, the receiver was static in a known position, thus the navigation solution accuracy was evaluated in terms of horizontal errors. Moreover, repeatability tests were performed. During these tests, the user carried out several loops around a large table placed in the middle of the meeting room trying to

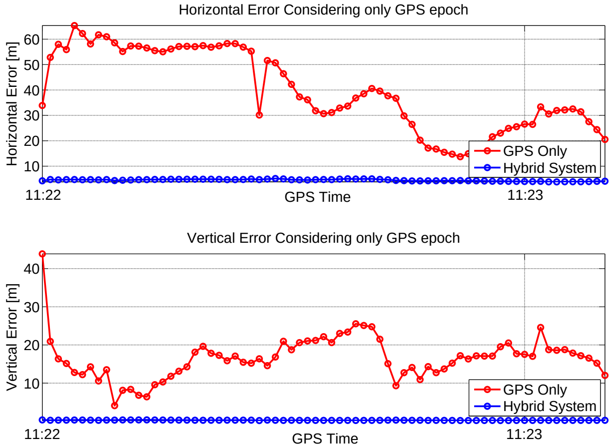

Fig. 1. Horizontal and vertical errors for the partially obstructed scenario as a function of time. Comparison between GPS-only solution and hybrid solution with proximity information.

repeat always the same trajectory. The quality of the navigation solution was assessed by comparing the different trajectories estimated for the different loops. A high consistency level of the navigation solution indicates the good performance of the system.

IV. Experimental Results

In this section, results obtained using pseudolite/GNSS hybrid systems are presented.

The errors evaluated for the partially obstructed scenario are plotted as a function of time in Fig. 1. From the figure, the benefits of the inclusion of pseudolite measurements clearly emerge: proximity information significantly reduces both horizontal and vertical errors. Note that the pseudolite was placed inside the building at about 5 meters from the reference point. Despite this distance, loosely coupling significantly reduces the positioning error. The GNSS horizontal error varies from 15 to 60 meters whereas for the hybrid system, the maximum error is 5.5 meters. Note that the maximum error does not only depend on the distance of the pseudolite from the user position, but also on the relative weight between pseudolite and GNSS measurements. Overweighting the pseudolite contribution would limit the maximum error to the distance between rover receiver and pseudolite. In the proximity case, GNSS measurements would not be used and a constant position would be found even if the user is moving. For these reasons the weight were empirically selected as a compromise between bounding the maximum error and system reactivity to position changes. This explains why the maximum error is slightly greater than the distance between the user and pseudolite position. The horizontal and vertical errors of the hybrid solution are better shown in Fig. 2: proximity information bound the horizontal error to 5 meters and provides sub-metric accuracy in the vertical component. This can be explained by the fact that the pseudolite and the reference point had approximately the same height.

Results obtained for the meeting room tests are discussed herein. The case where the receiver was static in a known position is considered in Fig. 3 and Fig. 4 which show the East and North components of the different position solutions. The three proposed configurations provide similar performance

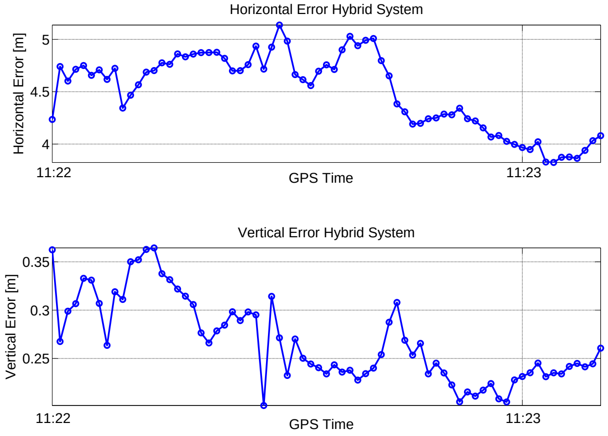

Fig. 2. Horizontal and vertical errors of the hybrid solution with proximity information for the partially obstructed scenario.

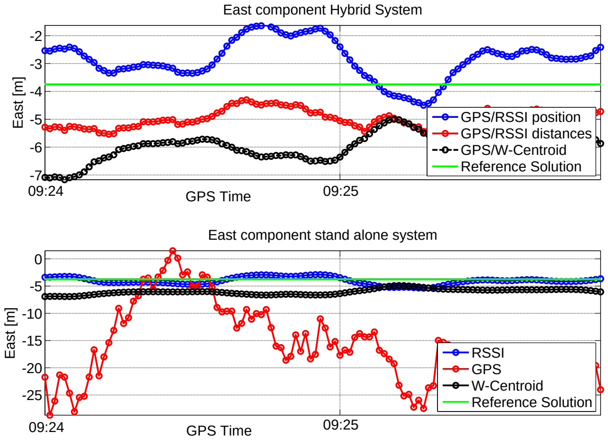

Fig. 3. East component estimated for the static case in a deep indoor environment. Different hybrid systems.

with a metric order accuracy. In the lower box of Fig. 3, the East coordinate estimated using standalone systems is plotted as a function of time: pseudolite solutions are characterized by meter level accuracy whereas the GPS solution is affected by gross errors. Similar conclusions can be made for the North component shown in Fig. 4.

The horizontal positionning results are shown in a local frame in Fig. 5. The spread of the clouds provides an immediate representation of the magnitude of the error and allows a simple comparison between the considered configurations. Loose integration between GPS and RSS seems to be characterized by the biggest error whereas tightly coupling provides the best performance. The right part of Fig. 5 shows the horizontal solutions computed using standalone systems: the benefits of system integration clearly emerges.

Results obtained for the repeatability tests are shown in Figs. 6 and 7. East coordinates estimated using the hybrid systems are plotted as a function of time in Fig. 6: a periodic pattern can be clearly identified showing the different laps performed by the user. Only sub-meter differences were found between the three configurations considered. In the lower box of Fig. 6, the East coordinates estimated using standalone systems are also provided. From the figure, it can be noted that, even if less accurate, also the GPS solution is characterized

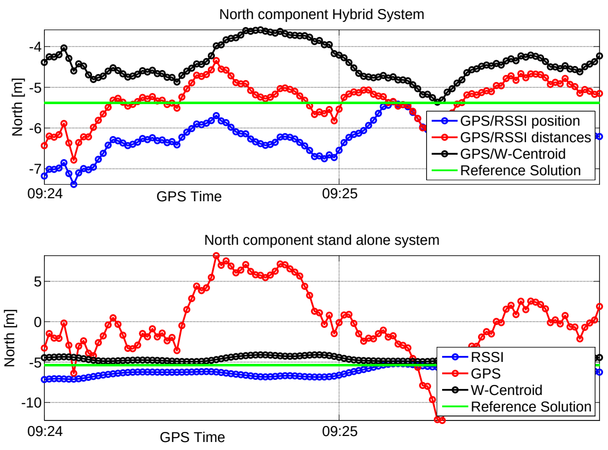

Fig. 4. North component estimated for the static case in a deep indoor environment. Standalone systems.

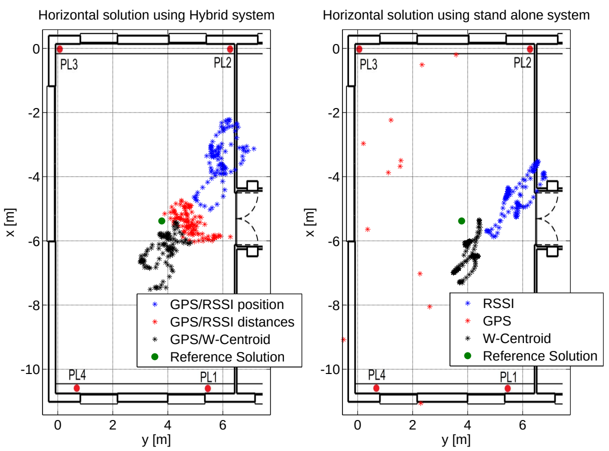

Fig. 5. Horizontal solutions in a local frame, static test in a deep indoor scenario (meeting room).

by a periodic behavior. This result is probably due to the presence of windows on the two opposite sides of the room along the East-West direction. In this way, the receiver was able to obtain sufficiently good geometry conditions and to discriminate the user motion along the East direction. The North coordinates estimated using the different approaches are shown in Fig. 7 as a function of time. Conclusions similar to that obtained for the East component can be drawn when considering hybrid navigation systems. Only the standalone GPS solution is significantly degraded and biased. This is due to the geometry of the room which does not have windows on the North and South sides.

The horizontal solutions for a single lap are shown in Fig. 8 for the different configurations. Only in the GPS standalone and in the tight integration case, it is not possible to identify the lap performed by the user. When GPS is used in a standalone way, the user is placed outside the room and a bias

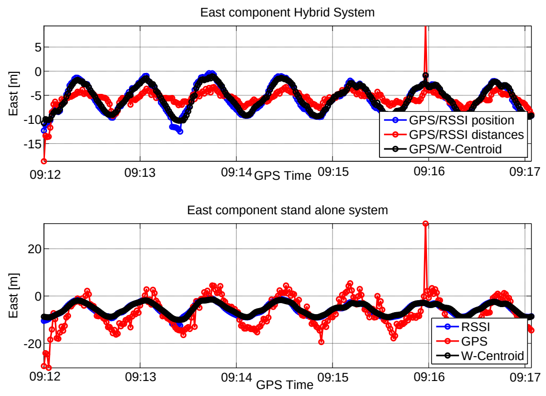

Fig. 6. East component estimated for the repeatability test performed in a large meeting room.

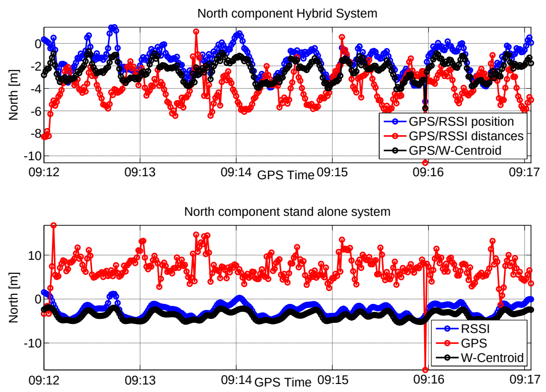

Fig. 7. North component estimated for the repeatability test performed in a large meeting room.

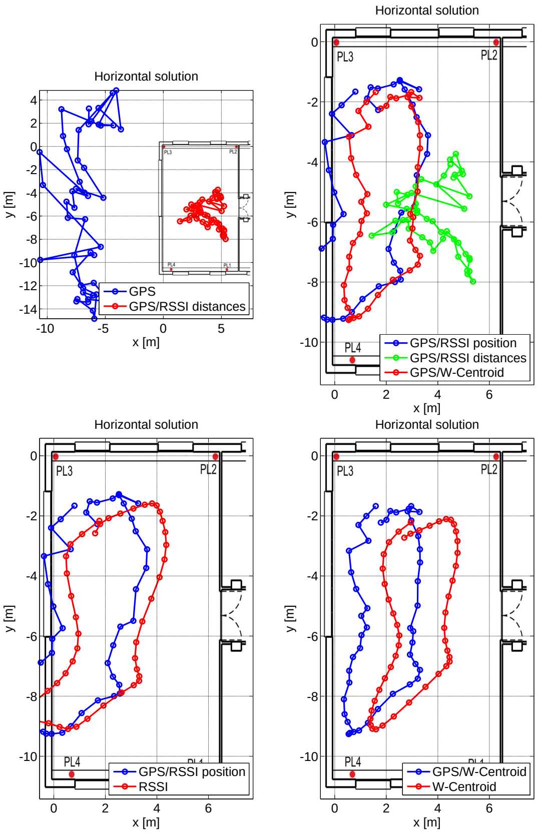

Fig. 8. Horizontal solution estimated for the repeatability test performed in a large the meeting room. A single lap is provided for improving the clarity of the representation.

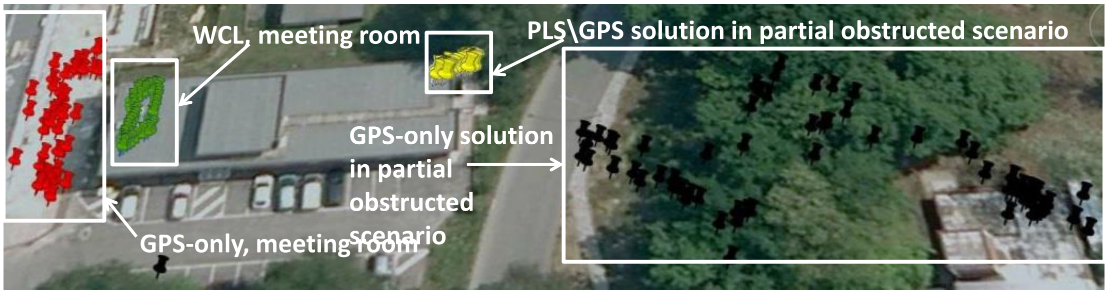

Fig. 9. Different position solutions obtained for the partially obstructed and meeting room scenarios. GPS standalone for the meeting room scenario (red), GPS and proximity for the meeting room scenario (green), GPS standalone for the partially obstructed scenario (black) and GPS and proximity for the partially obstructed scenario (yellow).

of more than 10 meters is observed. In the tight integration case, although the user is placed inside the room, it is not possible to identify his trajectory. This fact can be explained by the poor quality of the pseudoranges provided by the HS receiver. In dynamic conditions integration strategies used to improve the measurement qualities are less effective and large biases can be present. The results obtained with the tight integration strategy indicate that more weight should be given to pseudolite measurements. This aspect will be better investigated in future work.

Finally, the results of the different tests are summarized in Fig. 9 where GPS standalone (red and black markers) and GPS loosely-coupled with proximity information (green and yellow markers) are compared. The advantages of using an hybrid positioning system clearly appear.

V. CONCLUSIONS

In this paper, the potentiality of a hybrid asynchronous pseudolite/GNSS system was investigated. Three different configurations were considered including two forms of loosely coupled integration and a tightly coupled integration strategy. The approaches proposed have been tested in static and kinematic conditions in different environments.

From the analysis it emerged that the use of the hybrid system significantly reduces the horizontal and vertical position errors with respect to standalone GNSS-based positioning. For example, in a partially obstructed environment the maximum positioning error is reduced by a factor ten when integration is performed.

Indoor tests showed that standalone GNSS-based navigation is unfeasible indoors. The integrated pseudolite/GNSS system was enable to provide metre level accuracy in a large meeting room of about 70 square meters. The strategy proposed for the integration seems to have a limited impact and only sub-meter differences were generally observed among the configurations considered. The tests also showed that HS receivers are less effective in kinematic conditions and that careful measurement weighting has to be implemented when performing tightly coupled integration.

The results obtained using pseudolite/GNSS hybrid systems demonstrate that the synergy between GNSS and pseudolites has the potential to enable seamless navigation.

These results are particularly encouraging, since they were obtained without exploiting map constraints and prior knowledge of the user position. Other sources of proximity information can be used, for example to further constrain the navigation solution.

ACKNOWLEDGMENT

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The tests conducted for this work were performed in the GPS L1 frequency band solely in order to reduce the development time and to exploit GNSS receivers available on the market. Other frequencies can be adopted for this type of operation.

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