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Radio-Asissted Inertial Navigation System by Tightly Coupled Sensor Data Fusion: Experimental Results

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*Abstract***— Experimental results from data fusion of an inertial sensors based navigation system aided by a pedestrian step length estimations and an ultra-wideband system (UWB) are presented in this paper. One part of the presented experimental setup is a torso mounted inertial system with IMU, barometer and electronic compass with additional step length updates. The other part is the UWB system: The receiver is mounted on a backpack and measures the signal time of flight differences to several indoor base stations. In the paper the hardware setup, UWB implementation, step length updates as well as the data fusion filter are discussed. Finally results are presented, that show the advantage of a tightly coupled navigation filter, where range measurements are processed directly in the navigation filter.**

Keywords: INS, Pedestrian Navigation, UWB, Tightly Coupled, Integrity Monitoring

I. INTRODUCTION

In indoor scenarios radio-based localization systems can achieve centimeter accuracy (e.g. with UWB) with the solution being stable over time. This technology has however a severe drawback: the number of access points (APs), that is required for a sufficient radio coverage, is high. On the other hand, pure “inertial” navigation, based on an Inertial Measurement Unit (IMU), magnetic compass and a barometric sensor with additional step length updates (SLU) are subject to drift with time. The integration of these complementary systems can combine their advantages. For this kind of systems often a loosely coupled integration is selected: From Time Difference of Arrival (TDoA) measurements a 3D position is estimated and used as a position update in the fusion filter. This eases data fusion a lot. However if less than 3 TDoA measurements are available, no 3D position update can be calculated.

Becasuse of this reason a tightly integration is preferred. In [1] the use of a foot mounted IMU and UWB for Indoor tracking of a person is proposed. A tightly coupled navigation filter benefits of both, IMU and UWB time of arrival measurements. Furthermore, zero velocity updates during the stance phases of the foot mounted sensor increase the accuracy. Experimental results are presented, when the inertial system is bridging the phases without UWB reception. To overcome the problems of correlated TDoA measurements, the authors propose to treat the receiver clock as an unknown, so they solve for position and time. This can be a problem for erratic drifting receiver clocks, so we propose to use a decorrelation method which is well known from GPS/INS integration and is presented in [2]. Furthermore the authors propose the use of a foot mounted IMU, however this often is not welcome depending on the application.

In [3] also a tightly coupled approach is presented, but in this case for a torso mounted system. The authors propose the use of TDoA as well as angle of arrival measurements (AoA). The results are promising: the authors conclude that further investigation has to be done in the field of outlier detection. In comparison to [3], we will present another processing of step length updates together with IMU and UWB measurements, based on the stochastic cloning technique. This makes it possible to use the step updates as well as the raw MEMS IMU measurements for state prediction in a complete navigation filter (position, velocity, attitude, biases).

In the present paper, we propose a torso mounted approach, where only TDoA measurements are combined with the inertial system. Not using AoA measurements reduces the complexity of the UWB base stations which were developed in this work. The TDoA measurements and IMU measurements are processed in a Kalman filter. To calculate the actual position, step length estimation combined with a magnetic compass and a barometer is used to bridge UWB outage periods. This is also known as dead reckoning.

After an introduction to our algorithms, the experimental results of the synchronized UWB and INS system will be presented. The inertial data is recorded with a torso-mounted Integrated Pedestrian Navigation System (IPNS). The synchronous TDoA measurements are obtained with a UWB system, using one mobile receiver (integrated with the IPNS platform) and several APs.

From several indoor scenarios, positioning results are presented and analyzed regarding integrity and accuracy and visualizing the benefit of the tightly coupled integration. The number of active UWB-APs is varied; even one valid TDoA (two APs) gives a significant positioning improvement compared to the loosely coupled approach.

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II. Subsystems

A. *Integrated Pedestrian Navigation System (IPNS)*

For torso mounted pedestrian navigation systems, [4] proposes the use of a dead reckoning approach with a step length estimator. For heading information the use of a magnetic compass and a barometric height sensor for height estimation is proposed. For robustness in the present approach, the heading angle is estimated not only with the compass readings but IMU measurements are used for leveling and integrity monitoring.

We have developed a multi sensor pedestrian navigation system containing IMU, barometer, magnetic compass, and additional sensors like laser ranger and monocular camera. The system is presented in Fig. 1.

Fig. 1: Multi sensor pedestrian navigation system with IMU, Barometer, and Magnetometer with additional sensors (laser ranger, camera).

In a dead reckoning system, first, steps are detected regarding down and forward acceleration, based on thresholds which have been obtained for an optimal step detection for multiple users. Especially the observation of the forward acceleration helps to detect non walk movement like jumping or walking back. With each detected step from the torso IMU signal, a new step with a defined step length and heading is computed. The result is a polygon of 2D points (or 3D points if the barometric height sensor is in use).

To define a step length, there exist two possibilities: Either a fixed step length can be assumed or the step length is estimated based on the acceleration energy and step frequency of the current step [4]. The basic formula is

$$\mathrm{SL} = \alpha \cdot \mathrm{f_{step}} + \beta \cdot \mathrm{var}(\vec{a}_{3D}) + \gamma, \qquad (1)$$

where SL is the estimated step length, $\mathrm{f_{step}}$ is the step frequency and $\mathrm{var}(\vec{a}_{3D})$ is the acceleration energy of a step. To estimate the parameters α, β and γ, a number of calibration walks, covering slow strolling as well as quicker walks with longer step lengths have to be performed. With a Least Squares Estimator, finally the step length parameters for one particular person can be computed.

In this first approach of UWB INS integration with real data, a constant step length has been used for simplification. In the future, the variable step length approach will be used, which is already implemented in the version of the system not using the UWB support..Of course, for practical usage it is absolutely essential that this calibration is computed automatically with a given ground truth. In our non UWB system it is already possible to calibrate this torso system with both: a very accurate foot mounted system (indoor) or with GPS (outdoor). Therefore the user has to walk with several velocities to ensure the observability of the step length parameters. This will be adopted also to the UWB INS system soon.

Finally, a resulting 2D vector is estimated by combining the step length with an estimated yaw angle based on a magnetometer and an IMU for leveling and integrity monitoring. The resulting 2D vector is used as a Step Length Update (SLU) in the navigation filter. To have a correct estimation of the uncertainty in the navigation filter, we propose to use stochastic cloning [5]. A stochastic cloning filter can be used where a measurement refers to a relative change of a state in a certain time interval. This concept for processing step length estimation is used to implement step length estimation in the UWB/INS system. If this technique is not used and the new position is updated with a constant uncertainty for a position update in the navigation filter, then any absolute positioning update, like e.g. UWB, would barely improve the solution.

Stochastic cloning is performed for the two absolute states of the Kalman filter states of horizontal position x and y. After every step length update (SLU) these states are cloned. To include the correlations between the actual and cloned states the state vector of the Kalman is extended with the two cloning states.

To preserve the correlation between the cloned states, the system covariance matrix is extended for the covariance matrix of the cloned states and their cross-correlation covariance and the state is also extended with an additional system model with transition matrix Φ and process noise matrix G:

$$\begin{pmatrix} x_{k+1} \\ x_{k+1}^c \end{pmatrix} = \begin{pmatrix} \Phi & 0 \\ 0 & I \end{pmatrix} \begin{pmatrix} x_k \\ x_k^c \end{pmatrix} + \begin{pmatrix} G_k \\ 0 \end{pmatrix} w_k. \qquad (2)$$

It is obvious that the cloned state is not propagated (stationary state). Only the original states are propagated as before (evolving states). The measurement step of the stochastic cloning Kalman filter for a step length update refers to the actual and the cloned state. The standard Kalman filter equations can be used with the extended measurement matrix for the cloned states:

$$H_k = \begin{pmatrix} 1\,0 & \ldots & \ldots & | -1 & 0 \\ 0\,1 & \ldots & \ldots & | \,0 & -1 \end{pmatrix}. \qquad (3)$$

Then the cloned states are corrected by the remaining cross correlations. For more details, see [5]. Fig. 2 shows the position uncertainty of a stochastic cloning based SLU/INS integration. The uncertainty is growing with time, as the step length update is only a relative measurement, it does not provide any absolute position information. So if an absolute position update is obtained, it can support the filter immediately with position information.

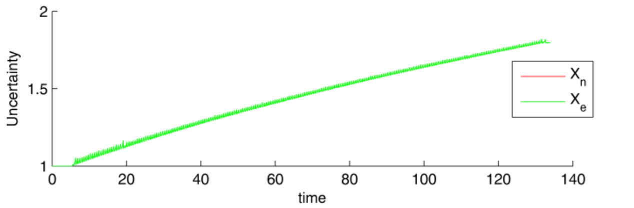

Fig. 2: Position uncertainty (in m) of the inertial system, only updated with step length updates after every foot step. The uncertainties are rising (time in s) constantly due to the stochastic cloning technique for both directions: north and east, as long as not other update is processed.

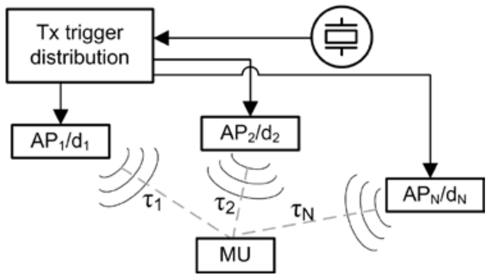

Fig. 3: UWB system configuration for TDoA measurements with marked signal propagation delays: d_N in cables and τ_N in air.

B. UWB TDoA system

UWB is a technology, which allows using low power wideband signals without a license. The UWB transmitter generates Gaussian-shaped pulses of approx. 250 ps width, which occupy around 7 GHz bandwidth (-10 dB BW) at a center frequency of 6.8 GHz. The pulse propagates through a channel and reaches the receiver, where an energy detection and 1-bit A/D conversion is performed. The operational range for this kind of transmission is above 20 m, what is more than enough for most indoor applications [6].

The working principle of the UWB TDoA system, based on the above-described hardware, is depicted in Fig. 3. The stationary part of the UWB system consists of *N* nodes, distributed in the scenario, called access points (APs). The position of the APs with regard to the used coordinate system needs to be known. The broadband electromagnetic impulses are sent from APs, triggered from a clock source. They are radiated in a sequential manner, whereby their initial mutual delays d_N have to be precisely known (one calibration measurement at the beginning). The mobile unit (MU) is equipped with a radio receiver, being capable of receiving and demodulating UWB pulses. During the measurements the trigger signal of 1 MHz (1 µs repetition rate) was used (simple pulse train, without information modulation). The time delays between pulses, within one transmission period, were set in the range from 20 to 250 ns. The APs were equipped with directive antennas (Vivaldi-type) and at the MU an omni-directional broadband radiator (Monocone) was employed.

The AP trigger clock runs unsynchronized with the MU and the full TDoA information can be obtained from a single measurement (one T_X clock cycle). The differences are calculated with respect to the first incoming pulse ($\tau_1 = 0$) according to (4).

$$\Delta\tau_{12} = (d_2 + \tau_2) - (d_1 + \tau_1) \tag{4}$$

Other time differences can be calculated using the same procedure. For precise delay measurements between received pulses, the Time-to-Digital Converter (TDC) from acam®, model GPX, was used. This device is capable of measuring the time differences down to 27 ps quantization steps. This resolution would theoretically allow range measurement precision of less than 1 cm. This can be considered as an upper limit of the positioning accuracy, which however in practice additionally depends on the geometrical orientation of APs and MU. This relation is described by the DOP values [7], [8].

For a full 3D UWB-stand-alone positioning solution at least 4 APs (3 TDoAs) are required; for 2D solution one AP less can be used. Nevertheless in order to navigate through the multi-room indoor scenarios the required number of APs would be irrationally high. Because of this drawback in the section IV the approach of tightly coupled data fusion, between an UWB and IPNS system is introduced.

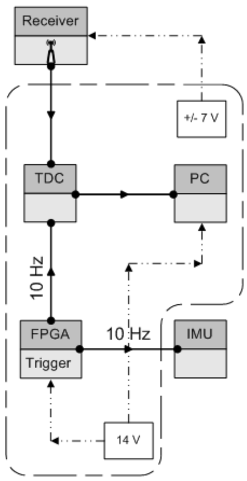

Fig. 4: Interconnection scheme of the subsystems integrated on one platform with synchronization by trigger signals.

C. Synchronous IPNS-UWB measurements and integration

Fig. 4 shows the interconnection scheme of both subsystems, as described above in this section, within the Backpack Navigator (BN).

The acquired IPNS data is transferred to the PC. The UWB frontend receives the radio signals, detects them and forwards to the TDC unit (PCI card, mounted in the PC). In order to fully profit from the sensor fusion, the collected IPNS and UWB data needs to be fully synchronous. The *event clock* (implemented in the Xilinx Virtex 5 FPGA) sets the flags in both systems at a rate of 10 Hz, what allows a frequent data mapping. At the same time it determines the update rate of the localization/navigation solution of the overall system.

Within each 100 ms period of the event clock 100 TDoA measurements are performed and averaged. This allows for reduction of the normally-distributed time quantization error of the TDC and increases the accuracy of the UWB system

[9]. The PC can then calculate the navigation solution, based on the synchronous IMU and UWB data.

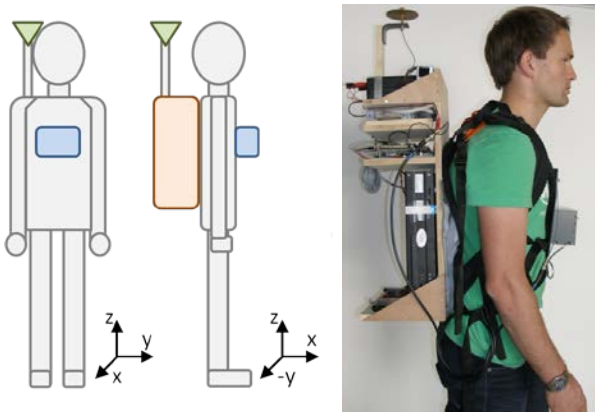

Fig. 5: Mounting and orientation of the Backpack Navigator. The mounting of the IPNS is marked in blue, UWB antenna position in green and data fusion unit in orange (left) and person wearing the backpack-system during the measurements (right).

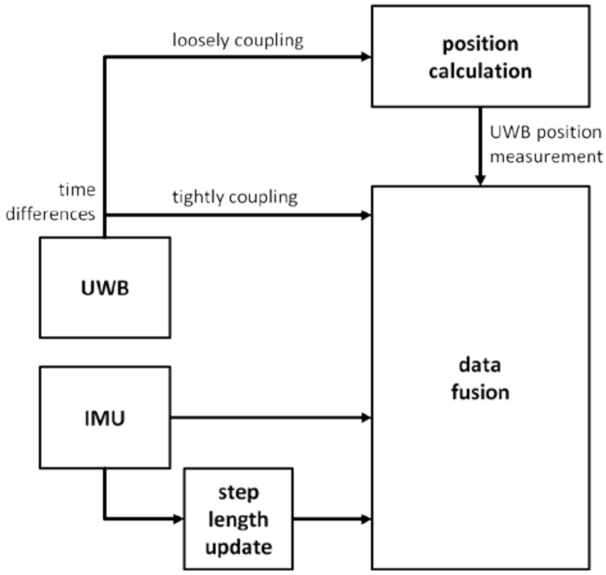

Fig. 6: Block diagram of the UWB/INS integration. The datafusion block is a strap down algorithm and a error state Kalman filter correcting the strap down by SLU and UWB (closed loop correction). Loosely and tightly coupling are possible, in this paper, thightly coupling is proposed.

The mounting of the BN is depicted in the Fig. 5. It is currently running on batteries, allowing for autonomous operation of approx. 1 h. The power consumption of the entire system is 42 VA, whereby the IPNS together with UWB receiver requires less than 5 % of this amount. The substitution of the commercial FPGA development board and PC by a dedicated solution would greatly improve the performance in this regard. At the same time the total weight of the BN (presently 9.5 kg) could be significantly reduced.

III. UWB/INS INTEGRATION

At first both systems, INS and UWB, were developed and considered separately however to improve the positioning solution, the output data should be merged. In general there are two ways to do this, as depicted in Fig. 6: First, a *loosely-coupled-integration* can be implemented, where the time differences (TDOA) will be used to calculate a UWB positioning solution and are used as an position update in a Kalman filter. However in order to calculate a stand-alone position solution from ranges, a minimum number of 4 APs is required.

Another method is the *tightly-coupled-integration*, where time difference measurements are directly processed by a Kalman filter in the measurement. In this case already 2 range measurements can improve the solution.

Both navigation filters were implemented as 15 state Error State Kalman Filters. The filter states are position, velocity, attitude and sensor biases of gyroscope and acceleration sensor. A strap down algorithm is used to propagate the IMU measurements and the Kalman filter estimates the errors based on UWB and SLU (closed loop strap down correction). The IMU measurements are treated as known inputs so the IMU noise parameters are treated as system noise in the Kalman filter. We are using a TDoA implementation, so TDoA measurements are calculated as the difference measurements between an actual range and the range measurement to one defined base transmitter.

Due to the Time Difference of Arrival approach a decorrelated Kalman filter measurement update is implemented as all TDoA measurements are correlated with the master transmitter. If this is not done, the estimation of uncertainty can become too optimistic. In GPS processing, this is a common technique and was adapted to the problem here.

To overcome the non linear nature of the local triangulation, several filter methods can be used but as the problem is not a multi modal one (no maps are used), we have decided to use not a particle filter but an iterative Kalman filter is implemented; up to 4 iterations are done to find a good linearization point. This is different to GPS where the linearization is not a problem at all due to long distances between user and transmitter. The schematic representation of both tightly and loosely coupling is shown in Fig. 6. Finally to catch outliers an innovation based integrity monitoring can be switched on. Based on the prediction of the navigation filter TDoA ranges are discarded, if the residual between measurement and prediction exceeds the confidence interval, see [2] for more details.

IV. RESULTS

In this section, the qualitative results of the UWB/INS integration are presented, based on a Matlab evaluation. Measurement data is recorded in an empty room with 3 UWB transmitters marked as red dots in the map and a corridor which is not equipped with UWB APs. As only 3 antennas are used, only a 2D position is estimated, the height of the person is assumed to be known and until now, the positioning is limited to only one floor. The master transmitter for the TDoA measurements is antenna 1 on a window at the bottom right, antenna 2 is mounted on the top right and antenna 3 is mounted on the wall on the left side. The pure UWB measurements are plotted as crosses in the map. The ground truth of the trajectory is provided by 10 measurement points. The actual measurement points which are used in the present case are interconnected by lines (magenta). Keep in mind that the person walks not on the magenta path but only on the markers. The color of the trajectory and of the pure UWB measurements is changing over time as indicated in the legend.

The UWB/INS integration is as follows: Step length updates are used to support the inertial navigation filter solution with delta position measurements. For a correct handling of the uncertainty in the navigation filter, the stochastic cloning technique is used. As soon as UWB range measurements are available, the drift of the solution can be eliminated due to an absolute position measurement. We found that without step length updates the pure inertial solution is drifting too much during UWB outages so this solution was not considered at all.

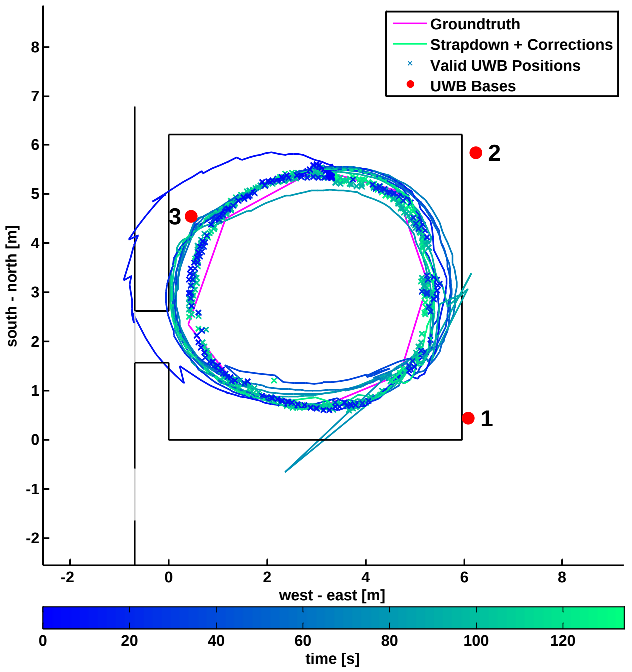

Fig. 7: Tightly Coupled integration, AP 2 outage: 30..90s.

In Fig. 7 and Fig. 8 a comparison of tightly and loosely coupling will be presented: At the beginning all 3 active APs are transmitting and the TDoA measurements are calculated relative to antenna number 1. The Tightly Coupled navigation algorithm provides a similar navigation solution like the Loosely Coupled implementation beside the fact that it shows a longer transient phase at the beginning. In case of an extended AP-blackout, Tightly Coupled can show its advantages: AP 2 (on the right top) was shut down between second 30 and 90. Only two antennas were active during that time and a calculation of the position wasn't possible with the pure UWB measurements. As a result of that, the loosely coupled update in the navigation filter cannot be evaluated and the trajectory drifts towards north. After 60 seconds, it is corrected immediately, as soon as a new position fix is gathered. This fast correction is possible due to a correct estimation of the uncertainty by the presented stochastic cloning technique: the uncertainty after 60s outage is several meters, so a position update in the navigation filter will improve the position immediately. In contrast, the tightly coupled approach benefits from every measurement, even if only one TDoA measurement is available. In the present case during the phase where AP 2 is not reachable, only the TDoA measurement between AP 1 and 3 is used for a correction vertical to the time difference hyperbola. And as the person is moving on a circle, the direction of the corrections is changing over time, so a 2D correction is done and the solution does not drift away, although the result is not quite as good as with three antennas.

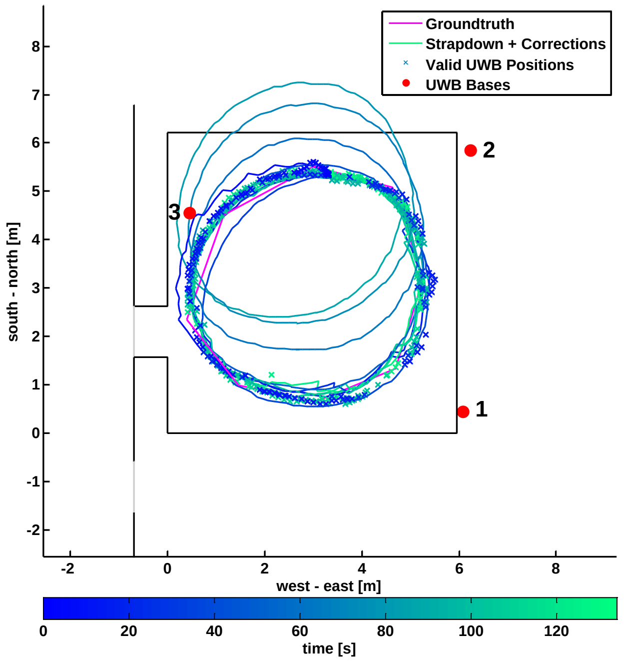

Fig. 8: Loosely Coupled integration, AP 2 outage: 30..90s.

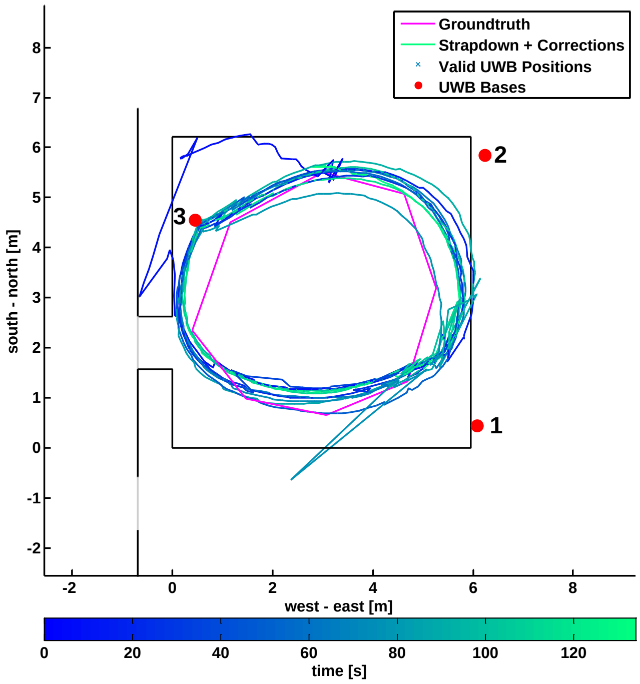

Fig. 9: Tightly Coupled integration, AP 2 outage: entire time.

If AP 2 is missing the entire time, (Fig. 9 and Fig. 10) this effect is even more obvious: The Loosely Coupled solution is actually a pure strapdown + SLU solution, which slowly drifts away. The tightly coupled approach still benefits even from only one TDoA measurement.

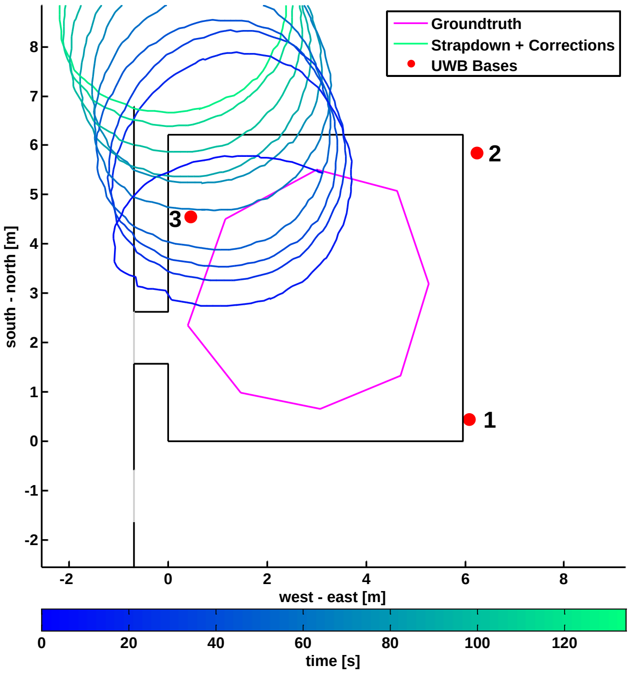

Fig. 10: Loosely Coupled integration, AP 2 outage: entire time.

In Fig. 11, another scenario is presented where the user walks along 4 points in the room. After the transient phase (one round), the tightly coupled approach shows a similar accuracy as the UWB position fixes (crosses).

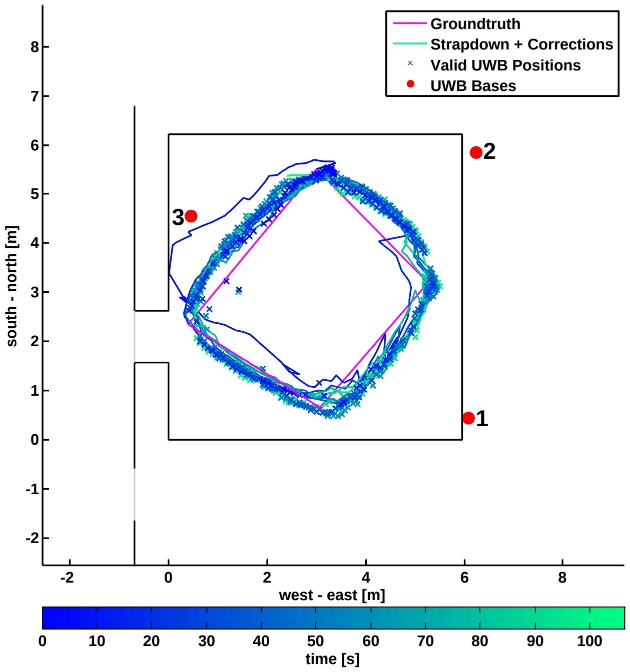

Fig. 11: Tightly Coupled, transient phase during first round.

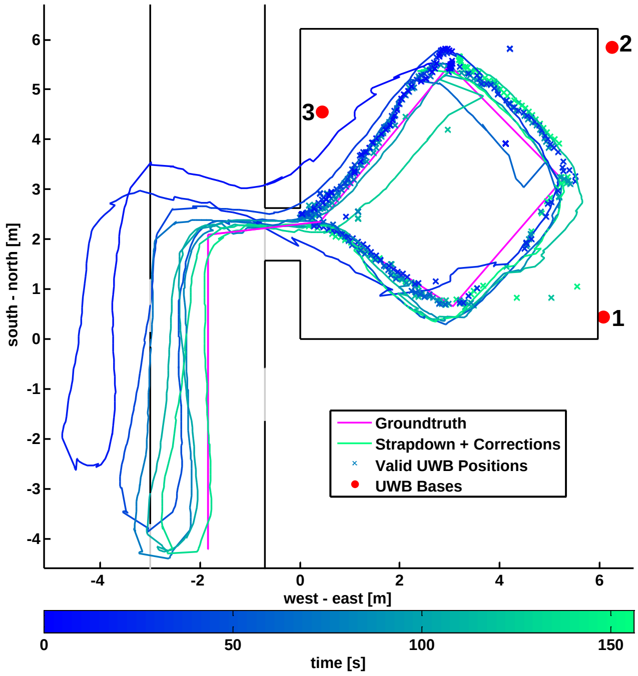

Fig. 12: Tightly Coupled, after transient time, the performance is better than loosely because of measurements in the door area available.

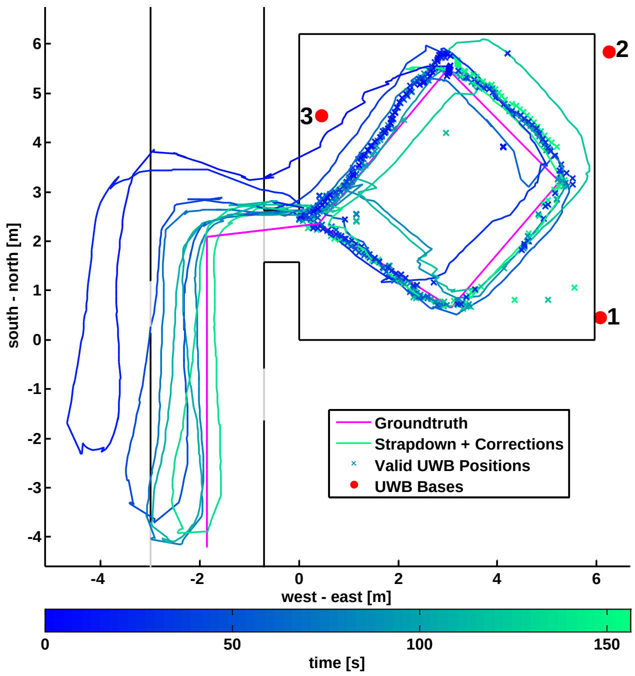

Fig. 13: Loosely Coupled, no measurements outside the room, door area slightly drifting as no UWB position updates are available, transient phase at the first round of the trajectory.

Fig. 12 and Fig. 13 the results of a longer path are presented, where the user is leaving the UWB equipped region. The results are similar beside the transient region, where only one TDoA measurement can be estimated because the left antenna (number 3) is mitigated. Like this no fix position can be calculated and the loosely coupled solution shows a wrong position solution when passing the door. No fix position can be calculated because no UWB update is available. As a result the loosely coupled solution is displaced to north when passing the door. In the corridor, the accuracy of the navigation solution is based on the SLU implementation, so both solutions are very similar, as no UWB measurements are valid.

Fig. 14 presents the horizontal dilution of precision (HDOP) in the map. It is obvious that outside of the room, even if measurements were available, the TDoA measurements won't help much due to the fact that outside, a change in position doesn't yield a similar change in the TDoA measurement. When equipping buildings with ranging systems, this surely must be taken into account.

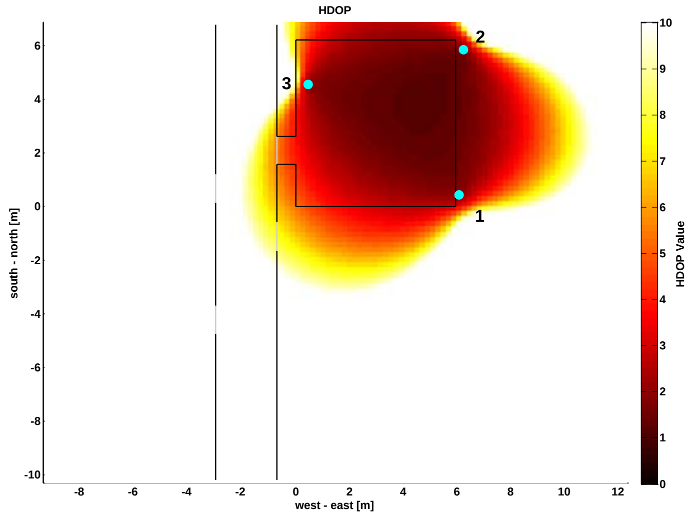

Fig. 14: Horizontal dilution of precision (HDOP) for the area.

V. Conclusions

The presented UWB/INS integration gives a comparison of a loosely and tightly coupled integration of a radio-assisted inertial navigation system.

With a mobile UWB/INS system, synchronous data is recorded and processed in a loosely and a tightly coupled navigation filter. Step length updates are used to reduce the drift of the INS and to bridge UWB outages successfully. The paper shows the hardware setup of the inertial system as well as the developed UWB backpack and base stations. Two data fusion techniques (loosely and tightly) are presented, which can both be supported by step length updates. A correct processing of these delta measurements is presented by using the stochastic cloning technique.

Finally the results of both integration techniques are presented and compared. After a transient phase, the tightly coupled approach shows better performance especially if not enough ranges are available for position estimation, since every single range measurement is processed in a tightly coupled implementation. The results are very similar to the simulations which we have evaluated in a previous work; the accuracy of the integrated system is in the lower decimeter range.

Future work will include the quantitative evaluation and the implementation on a vehicle with odometry. Furthermore a larger area will be equipped with radio transmitters to gather more scenarios and to refine or adapt the integration technique if necessary.

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