Integrity Monitoring for UWB/INS Tightly Coupled Pedestrian Indoor Scenarios

Christian Ascher*, Lukasz Zwirello**, Thomas Zwick** and Gert Trommer*

* Institut für Theoretische Elektrotechnik und Systemoptimierung (ITE)

** Institut für Hochfrequenztechnik und Elektronik (IHE)

Karlsruher Institut für Technologie (KIT), Kaiserstr. 12, 76131 Karlsruhe, Germany

Email: christian.ascher@kit.edu, lukasz.zwirello@kit.edu

***Abstract*— In this paper a tightly coupled UWB/INS system for pedestrian indoor applications is presented. In indoor environments wireless signal outage and severe multipath propagation very often lead to ranging errors and make pure UWB-based localization barely possible. On the other hand inertial sensor based systems (INS) are known for their drift with time. The integration of those two systems will allow to profit from their advantages. For the sensor data fusion the tightly coupled approach and integrity monitoring are crucial factors for a robust implementation. One possibility is the Time of Arrival (ToA) approach where the user clock bias and drift are modeled and estimated in the navigation filter. The other possibility is the Time Difference of Arrival (TDoA) approach, where the range measurements are differenced totally eliminating the clock error. If user/transmitter clocks do not follow the clock drift model very well, it is better to apply the TDoA approach. For time of arrival applications, innovation based integrity monitoring is standard. However for the use of Time Difference of Arrival measurements (TDoA) in this paper an Innovation Based Integrity Monitoring (IBIM) method is presented. This is done to determine and omit all TDoA measurement combinations including the incorrect UWB receivers. This novel approach is verified in a simulation environment. A user trajectory and inertial data are provided by a custom developed pedestrian walk generator, based on real measurement data. The UWB data is generated by a wave propagation simulator for the given indoor trajectory.**

***Keywords*—Impulse Radio UWB, TDoA Positioning, Tightly Coupled, Integrity Monitoring, Pedestrian Indoor Navi**

I. INTRODUCTION

Since many years, numberless research groups worldwide attempt to model and build pedestrian navigation systems. There are numerous possible fields of application for this technology in the private and military sector. Inertial sensor based Pedestrian Navigation System developed in the last years show a very good short term performance however the drift of the navigation solution with time is still a problem. The implemented additional sensors, such as barometer or magnetometer and algorithms like adaptive Step Length Updates (SLU) improve the stability; however the method of sensor data fusion is still curtailed. In order to achieve long term stability that could be accepted by the market and potential users, other technologies will have to be used for support. They should exhibit very good long term stability, whereby the short term one is rather of minor importance. One of such technologies, offering decimeter range positioning accuracy in indoor scenarios, but suffering from poor short term stability is the impulse-radio ultra-wideband (UWB).

In this work a model of an indoor UWB localization system and its tight coupling with an inertial navigation system for pedestrian indoor tracking applications is presented. It includes the wave propagation simulation in a real building, the positioning algorithms, simulation of the INS and the integration Kalman filter of both systems. The main scope of this work is to identify and highlight the possibilities and the shortcomings of different system configurations as well as to establish a firm basis for the planned hardware integration.

In [1] the algorithms as well as first integration results of a Tightly Coupled UWB/INS system are presented. They treat the UWB measurements as Time of Arrival measurements so the clock error and clock drift of the user system must be estimated in the navigation filter. The time of arrival approach has the advantage that the correlation due to the differencing does not need to be considered. Furthermore simple integrity monitoring (IM) can be used which the editors also have implemented as it was a crucial factor.

However in this GPS/INS research it was found that if user receiver/transmitter clocks do not follow the implemented clock drift model very well, it is better to implement time difference of arrival (TDoA) measurements. In this case, the clock errors are totally eliminated and the tuning of the estimation filter for clock states is obsolete. Even if the clock does not follow a given model at all, the filter will not be affected. Based on this, the use of a tightly coupled UWB/INS integration based on time difference of arrival measurements is advisable. The resulting set of hyperbolic equations can then be solved with the Taylor series equations, given e.g. in [2].

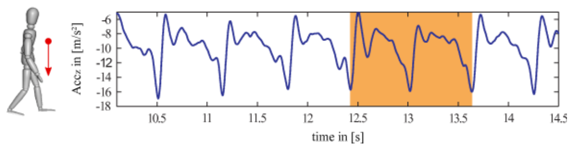

Fig. 1: Acceleration Signal in z-direction.
The sample is marked in orange

The paper discusses this navigation filter which is implemented as an error state Kalman filter as well as the

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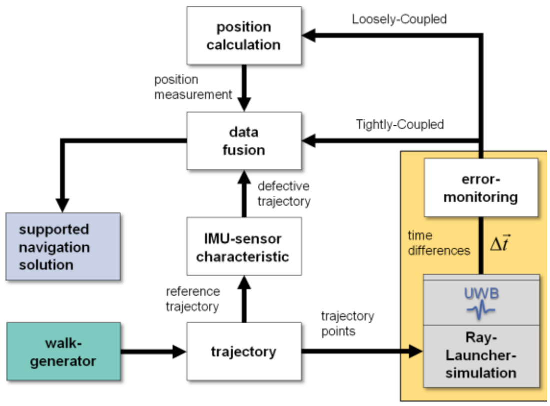

Figure 2: Integration scheme of an INS and UWB system – the alternatives: Loosely and Tightly Coupled Approach in the same scheme

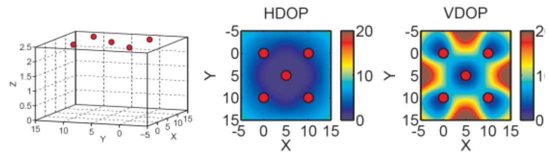

Fig. 3: Dilution of Precision for receivers all in one plane

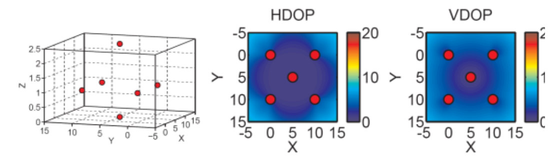

Fig. 4: Dilution of Precision for a 3D distributed case, the vertical dilution is much better than before

impact of an Iterative Kalman Filter during initialization. In this work the measurement decorrelation due to the differencing is also taken into account and discussed.

For rough error detection, a velocity filter approach for the detection of incorrect range measurements is presented.

The main scope of this paper addresses the influence of integrity monitoring algorithms, where an innovation based monitoring method especially for time difference of arrival measurements to obtain a robust integrated system has been developed.

II. Simulation Environment

A. Walkgenerator

The generation of IMU signals is based on a real step sample recorded by a MEMS grade IMU that is mounted on the torso of a test person, see also Fig. 1. Different maneuvers are possible like forward run, curve and standing as well as variable velocities. It is also possible to create a corridor based walk and the walk generator will approximate the walk with human steps. The ground truth is derived by calculating the strap down of the ideal IMU data.

The output of the walk generator is the ideal IMU data and the trajectory ground truth. To simulate a real IMU, the walk-generator output is modified with error statistics, see Fig. 2, of MEM Sensors available on the market: ADIS16355-IMU from Analog Devices and NavChip-IMU ISNC01 from Intersense. In our pedestrian navigation system setup we can use each of the sensors. For sensor errors, we are modeling the Angle Random Walk (ARW) and Velocity Random Walk (VRW) as white Gaussian noise processes with statistics given in the data sheet. Furthermore the in-run bias stability was modeled as Gauss-Markov-Process of the 1st order. The generation of the magnetometer data is performed by superposition of the current yaw angle (walk generator) with a white Gaussian noise (WGN) with a standard deviation of 4°. The barometer data is created from a known height superimposed with a WGN with a standard deviation of 0.5m. More details on the functionally of the walk generator can be found for example in [3].

The resulting inertial sensor data shows the characteristics of a quite realistic walk. As known from experiments a pure inertial system will always have rather poor long term stability. In the next sections, two methods to improve the long term stability are presented, Ultra Wide Band (UWB) and step length updates (SLU).

B. UWB and Ray-Launcher simulation

In order to improve the long term stability of the INS an additional system is introduced. Considered scenario is a UWB system, which consist of a mobile client (coupled with IMU) and access points (AP) distributed in the building.

The APs belong to the infrastructure, and as such are interconnected and know their own position. A mobile UWB sensor is capable of measuring the relative distances between itself and AP (similar to pseudo-ranges). What makes the UWB the perfect candidate for this task is the large bandwidth which depending on the regulation can reach up to 7.5GHz, and fine time and spatial resolution.

Due to the fact that there is no synchronization between mobile unit and AP’s only pseudoranges can be measured which are captured by the mobile clock error. For a UWB stand-alone solution a minimum of four AP have to be available (three relative time differences). In the presented work an optimal placement of UWB base stations, based on DOP-values (dilution of precision), was performed which shows, that the distribution of all

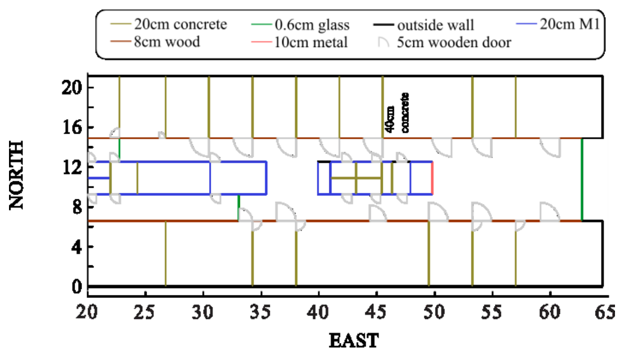

Fig. 5: Building with structure information

base stations in one plane yields a high vertical dilution of precision, see Fig. 3 and 4.

In order to achieve information about distortion of the UWB signals in a real environment one floor of our office building has been digitized. An exact 3D model with all the information regarding the electrical parameters of the objects has been used as a base for wave propagation simulations, see Fig. 5. The UWB-transmission in a realistic channel model has been simulated with Ray-Launcher (RL).

The RL is a wave propagation simulation tool developed at our institute. It is capable of calculating the transmission between two points in a predefined scenario (complex geometry with given electrical properties) including such effects as multiple reflection, transmission and diffraction. The transmit antenna is modeled as a point source radiating in all directions. The radiation pattern can also be included. The radiated power is represented by rays that are launched in certain directions. The rays are equally distributed over the sphere with the point source located in the center of the sphere. The results of the simulations were confirmed by measurements numerous times and due to this, RL is a perfect candidate to simulate indoor UWB transmission.

The TDoA-based localization algorithms, along with NLOS detection schemes, were implemented as well. Methods for the detection of inconsistent measurements are presented in section IV.

The major disadvantage of the UWB-based positioning system is the requirement of the number of continuously available base stations. And this number increases even more if one takes into account shading effects caused by objects. In the real environment it would lead to an unrealistic high number of AP's. This is a starting point for an idea of combining the UWB measurements with inertial systems. Even simple range information can correct the long time drift of the IMU system. The detailed information regarding sensor fusion is presented in chapter III.

C. Step-Length-Update

To improve the inertial long term stability for torso mounted pedestrian navigation systems, a Step Length Update (SLU) can be included in the navigation filter. This filter support uses step identification based on accelerometer data of the IMU, observing the event of a step and estimating the user step length. The step length was calculated based on the known reference trajectory and the known step moments. Those ideal step lengths were then superposed with a normally distributed noise with a standard deviation of 20cm. The combination of step length and the latest heading angle is a dead reckoning path and can be used in the UWB/INS integration filter which will be described in the next section.

III. INS/UWB Integration

In this work loosely and tightly-coupled UWB/INS integration is presented. The schematic representation of the UWB/INS integration process is shown, see Fig. 2 again where both, loosely and tightly coupled methods are presented.

A. Loosely and Tightly Coupled integration

The easiest integration technique for range measurements, as known from GPS integration algorithms, is the loosely coupled approach. Here the range measurements first go through the position calculation (cp. Fig. 2) and the result is combined with the inertial sensor data in an error state Kalman filter. This works only if more than 3 range measurements are available. This is why we propose the use of a tightly coupled approach instead; this alternative is also shown in Fig. 2 where time difference measurements from UWB are directly processed in the navigation filter. Already two ranges at one single epoch can be processed in the filter. Furthermore SLUs prevent the inertial system from short time drift as described above. Finally the magnetic field sensor for yaw angle measurements and a barometer for height updates are used.

The navigation filter is an Error State Space, closed loop filter, based on [1] and [4], where the inertial data is used to estimate position, velocity and attitude with a strapdown mechanization. As the inertial data of MEMS based sensors and the position and orientation estimation is only accurate for short time, these are typically combined with stabilizing sensors, such as GPS or in this case UWB, in a Kalman filter; so the sensor errors can be estimated improving the estimations. As the UWB measurements are differenced, there is no need to estimate the UWB transmitter clock error and drift in the navigation filter. Hence the errors of the following states are estimated in the Kalman filter: position, velocity, orientation and the biases of accelerometer and gyro:

$$\Delta\hat{\vec{x}}_k = (\Delta\vec{r}, \Delta\vec{v}, \Delta\vec{\Psi}, \Delta\vec{\mathrm{b}}_{\mathrm{acc}}, \Delta\vec{\mathrm{b}}_{\mathrm{gyro}}) \qquad \mathbf{1}$$

The Kalman filter prediction step is similar to the loosely coupled approach and will not be carried out here. Also the measurement equations for barometer and compass updates do not need to be given here.

To present the innovation based integrity monitoring, the Kalman filter equations for UWB measurements will be derived in the following: The innovation Δy_{1j} in the Kalman filter for time difference of arrival measurements

$$\vec{\boldsymbol{\rho}} = \begin{pmatrix} \vec{\boldsymbol{\rho}}_{\mathbf{12}} \\ \vdots \\ \vec{\boldsymbol{\rho}}_{\mathbf{1N}} \end{pmatrix} \qquad \mathbf{2}$$

can be calculated from the measured time differences ρ_{1j} and the estimated time differences from the estimated positions of transmitter $\hat{\vec{r}}_T$ (which is the user) and the known positions of the receivers $\vec{r}_{Rj}$. Then the innovation can be written as:

$$\Delta y_{1j} = \rho_{1j} - h(\hat{\vec{x}}) \qquad \mathbf{3}$$

$$\Delta y_{1j} = \rho_{1j} - \left\|\hat{\vec{r}}_T - \vec{r}_{R1}\right\| - \left\|\hat{\vec{r}}_T - \vec{r}_{Rj}\right\| \qquad \mathbf{4}$$

From the nonlinear function h(x) following the Taylor series, the measurement matrix **H** can be calculated as:

$$\mathbf{H}(t_k) = \frac{\partial h}{\partial x}\bigg|_{tk} = \begin{pmatrix} [\vec{\mathbf{e}}_{TR_j}^T - \vec{\mathbf{e}}_{TR1}^T] \; 0_{1x12} \\ \vdots \\ [\vec{\mathbf{e}}_{TR_N}^T - \vec{\mathbf{e}}_{TR1}^T] \; 0_{1x12} \end{pmatrix} \quad 5$$

with the unit vector

$$\vec{\mathbf{e}}_{TRj} = \frac{\left(\hat{\vec{r}}_T(t_k) - \vec{r}_{Rj}\right)}{\left\|\hat{\vec{r}}_T(t_k) - \vec{r}_{Rj}\right\|} \quad 6$$

Finally the Kalman filter measurement is processed with the Kalman gain matrix

$$\mathbf{K}_k = \mathbf{P}_k^- \mathbf{H}_k^T \cdot \left(\mathbf{H}_k \mathbf{P}_k^- \mathbf{H}_k^T + \mathbf{R}_k\right)^{-1} \quad 7$$

with measurement covariance $\mathbf{R_k}$ and the filter a priori covariance $\mathbf{P_k^-}$. Notice that by differencing the measurements between base receiver and the other available measurements the measurement covariance matrix **C** of the measurements $\vec{\rho}$ would have entries not only in the main diagonal but also others. This can be found when calculating the expectation value

$$\mathbf{C} = cov\{\vec{\rho}\} = \begin{pmatrix} 2\sigma^2 & \sigma^2 & \dots \\ \sigma^2 & 2\sigma^2 & \dots \\ \vdots & \vdots & \ddots \end{pmatrix} \quad 8$$

Now either this covariance matrix is taken into account in the measurement update $\mathbf{R_k}$ but this increases the calculation burden. The better possibility is to decorrelate the covariance and the measurements: a diagonal matrix **D** can be calculated from the Cholesky decomposition $\mathbf{C} = \mathbf{LDL^T}$ and is used as the covariance $\mathbf{R_k}$ in the Kalman filter step. Furthermore the measurements need to be decorrelated:

$$\hat{\vec{\rho}}\,' = L^{-1} \cdot \hat{\vec{\rho}} \quad 9$$

As the measurements do not have identical variances after this transformation, the estimation would be unbiased but not efficient [5]. Efficiency can be ensured by weighting the measurements by

$$\vec{w} = 1/\mathrm{diag}\{\mathbf{D}\} \quad 10$$

B. *Iterative Kalman filter approach*

In local networks like UWB, for a moving person the directions to the receiver constellation is rapidly changing due to short distances between receiver and transmitter in contrast for example to GNSS signals. This makes the linearization of the measurement equation $h(\vec{x})$ valid only around a small area around $\vec{r}_T$. But for initialization and reinitialization the approximation with the linear model often is not valid. In this case we propose the use of an iterative Kalman filter (IKF). With this, the nonlinear measurement function $h(\hat{\vec{x}})$ is approximated multiple times resulting in an enhanced position estimate until the improvement is marginal [6]. Be aware that the filter covariance is not updated multiple times but only after the last estimation step with the actual measurement matrix and Kalman gain matrix.

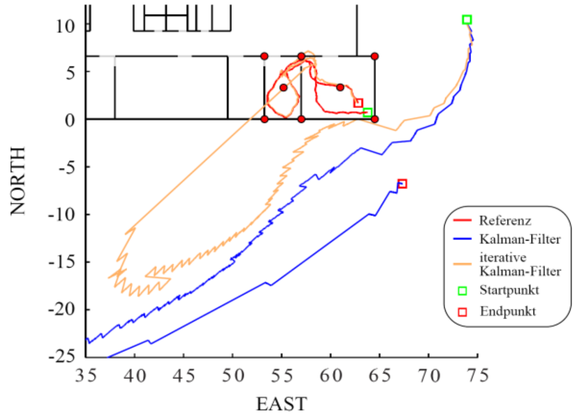

Figure 6: Improvement by the use of Iterative Kalman filters

In Fig. 6, the initialization of a trajectory is given where the initialization point is more than 5m away from the real position. The standard KF does never converge but with the iterative KF, the solution converges after some time. So the IKF can be a powerful tool during initialization and reinitialization.

IV. VELOCITY MONITORING

A simple but effective way to monitor new UWB measurements before using them in a filter is to monitor the velocity which is calculated from time differences of UWB position estimates. Especially in a strong multi path environment the calculated velocity can be used to omit faulty measurements. This is demonstrated in Fig. 7 at t=[7s..12s , 45..51s]. This monitoring is used for rough fault detection before the navigation filter when more than 3 receivers are available, with 2 different thresholds for vertical and horizontal velocities.

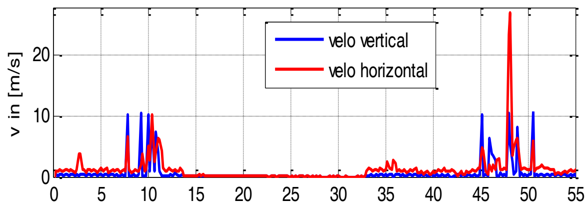

Figure 7: Velocity from position differences

V. INNOVATION BASED INTEGRITY MONITORING

The UWB/INS Navigation Kalman filter as described above works fine for range measurements with white noise distribution. This holds not for realistic UWB range measurements in deep indoor environments due to multipath, non-line of sight errors and shading effects. To detect faulty measurements, we propose a new method for integrity monitoring.

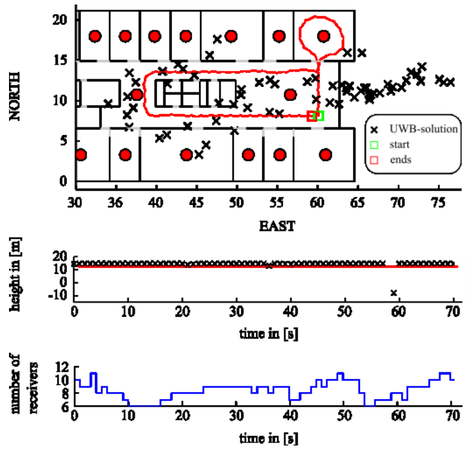

Figure 8: simple positioning results for UWB without any integrity monitoring, reference is plottet in red

There are several integrity monitoring methods which are receiver autonomous (RAIM), e.g. the range comparison method or the Parity Space method but these do not use inertial data to improve their position by a prediction.
When using inertial data combined with UWB time of arrival (ToA) measurements, integrity monitoring can be based on the innovation of the range measurement, this is also used in [1].
But for time difference of arrival measurements (TDoA), a novel method called Innovation Based Integrity Monitoring (IBIM) has been developed. It is used to solve a slightly different problem: As the measurement innovations are correlated with each other due to differencing, multiple measurements need to be rejected if only one range measurement is faulty, especially if the main measurement ρ_1 is not correct.
In TDoA applications range measurements between transmitter (user) and receivers (infrastructure) are differenced and then are used in the navigation filter.
For INS aided systems, the navigation solution yields a good inertial prediction until the next user position measurement. So the innovation or residual for each measurement can be calculated as a difference between prediction and measurement.
As presented in [1] the innovation for undifferenced measurements are tested using hypothesis testing on the residuals/innovations of the Kalman filter, when the errors are higher than those estimated from the confidence interval. In the case of differenced measurements (TDoA) a similar approach is used to detect errors: The TDoA innovations (derived above), can be combined to a residual vector:

$$\Delta\vec{Y} = \left(\Delta y_{12}, \Delta y_{13}, \ldots \Delta y_{23}, \Delta y_{24}, \ldots \Delta y_{N-1,N}\right) \tag{11}$$

Now as a rejection criterion we use the difference between the residual vector $\Delta\vec{Y}$ and the lowest residual $\min(\Delta\vec{Y})$:

$$\Delta\tilde{\vec{Y}} = \Delta\vec{Y} - \min(\Delta\vec{Y}) \tag{12}$$

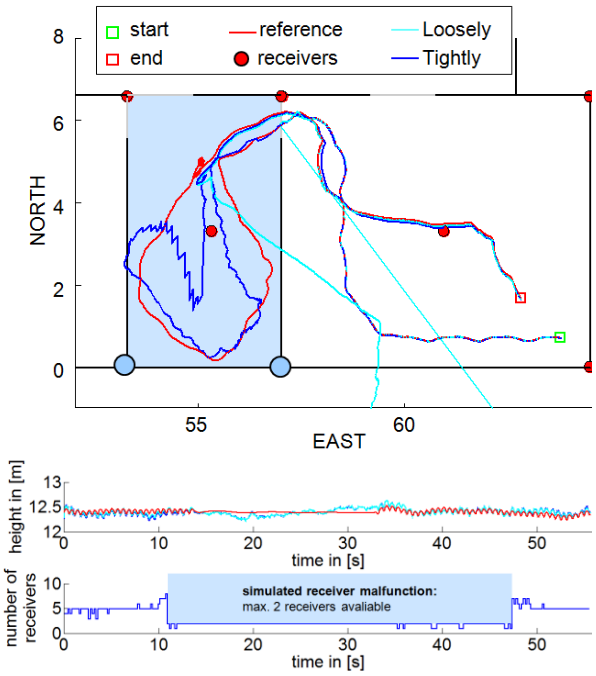

Figure 9: Loosely vs. tightly coupling, simulated receiver malfunction in left room, 2 available, IMU: ADIS16355, no SLU

This modified residual vector now is divided into logical LARGE and SMALL by a threshold based on the confidence interval of the actual estimate and measurement noise:

$$\vec{\epsilon}_k \sim N\left(0, \mathbf{H}_k \mathbf{P}_k^{-} \mathbf{H}_k^{T} + \mathbf{R}_k\right) \tag{13}$$

As one faulty receiver range influences all combinations with this receiver, we use a counter for each receiver which is increased for each of the used receivers, if their residual is LARGE. Otherwise the counter is decreased. Finally the receivers with high counters are identified and all TDoA range combinations with these receivers are omitted. With this, the incorrect TDoA measurements can be observed and rejected if they are higher than the confidence interval.

VI. Results

In this section the results for a deep indoor scenario will be presented. 15 receivers are distributed in the hallway and in the rooms. Fig. 8 shows the results of a simple positioning without inertial data. The pure UWB solution shows high errors when no integrity monitoring is used.
Fig. 9 shows a comparison between loosely and tightly coupling. The trajectory runs through two rooms, where in the first one (right) the perfect UWB reception is present and in the second one (on the left) only two UWB receivers are available (marked in blue). During the run in the second room a 20 second long pause was introduced, in which no movement is performed. In the loosely-coupled integration the positioning solution starts drifting away as soon as less than 4 receivers are visible and the calculated solution lies outside the room after a few seconds. When the moving person enters the first room again the Ultra-Wideband measurements pull the

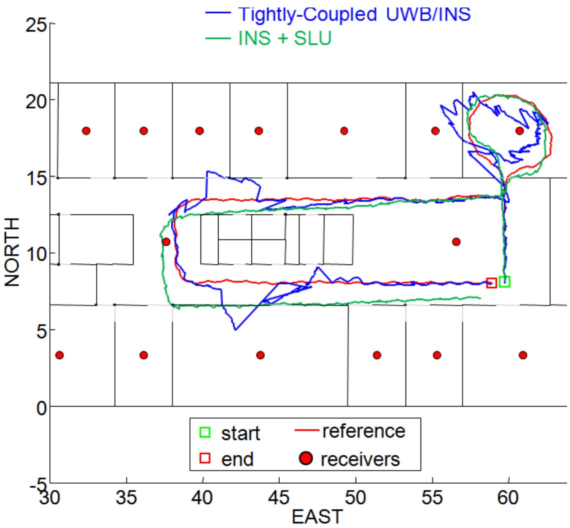

Figure 10: Tightly coupled integration from UWB and INS and the results of pure inertial navigation with step length updates (SLU)

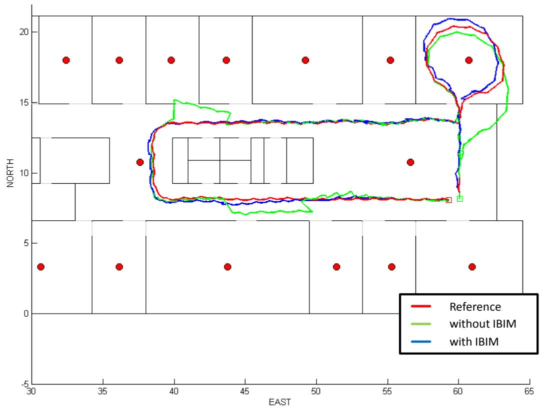

Figure 11: First results with IBIM: tightly coupled vs. tightly coupled with IBIM

positioning solution back to the correct area. On the other hand the tightly coupled approach allows much better navigation. During the steady phase the solution drifts to the south as no north-south aiding is available from the two receivers. However it still remains within the room and as soon as the movement appears the solution improves due to the changing geometrics.

Fig. 10 shows the results of the tightly coupled UWB/INS integration in another scenario. In the hallway and in the room on the top right, when only few line of sight receivers are visible, range errors occur. The pure inertial estimation which is based on step length updates (SLU) is also shown in this plot with a obvious drift due to the MEMS grade inertial sensors.

When combining all information to an Tightly Coupled UWB/INS/SLU integration, the results are better because when only few UWB updates are available, the step length updates pretend the solution to drift too much, this can be seen in Fig. 11. Only, if faulty measurements are available due to multipath and non line of sight situations, errors still occur. However with the presented Innovation Based Integrity Monitoring (IBIM) decision algorithm for TDoA cases we found promising results and robustness.

VII. Summary and Conclusion

In this paper a complex study on UWB/INS integration techniques for pedestrian indoor navigation systems has been performed. The special emphasis was put on advantages investigation of Tight Coupling. A special simulation environment for UWB and IMU has been developed, where various filter supports and different methods of data fusion can be evaluated. Furthermore a novel IBIM method for rejection of the incorrect TDoA measurements has been introduced. The simulation results are very close to reality and they show the advantage of the tightly coupled approach. Combined with the integrity method a robust integration has been implemented. Based on these results it is planned to test the filters and the implemented integrity monitoring with real UWB and inertial data.

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