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# Integrity Monitoring for UWB/INS Tightly Coupled Pedestrian Indoor Scenarios

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***Abstract*— In this paper a tightly coupled UWB/INS system for pedestrian indoor applications is presented. In indoor environments the wireless signal outage and severe multipath propagation very often lead to ranging errors and make a pure UWB-based localization barley 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. For Time of Arrival (ToA) applications, innovation based integrity monitoring is standard. But for the use of Time Difference of Arrival measurements (TDoA) in this paper an Innovation Based Integrity Monitoring (IBIM) method is presented 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 walkgenerator, 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**

## I. INTRODUCTION

Since many years, or even decades, 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. The Integrated Pedestrian Navigation System (IPNS) developed in the last years at the ITE [1] shows 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 this paper also the impact of an Iterative Kalman Filter during initialization and re-initialization is discussed. A velocity filter approach for a detection of incorrect range measurements is used for rough error detection. Furthermore the influence of Integrity Monitoring algorithms is evaluated and we have developed an innovation based monitoring method especially for Time Difference of Arrival measurements to obtain a robust integrated system

## 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. Different maneuvers are possible like forward run, curve and stand as well as variable velocities. A trajectory can be defined which is approximated by the walk generator 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 of MEMS sensors available on the market. More details on the functionally of the walkgenerator can be found in [4].

### B. UWB and Ray-Launcher simulation

In order to improve the long term stability of the INS an additional system is introduced. Our scenario is a UWB system, which consist of a mobile client (coupled with IMU) and base stations (BS) distributed in the building. The BSs 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 BS (similar to pseudoranges). What makes the UWB the perfect candidate for this task is the large signal bandwidth and fine time resolution. Due to the fact that there is no synchronization between mobile unit and BS's only time-difference-of-arrival (TDoA) can be measured. For a UWB stand-alone solution a minimum of four BS 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 and will be presented in the paper.

In order to achieve information about distortion of the UWB signals in a real environment the one floor of the IHE institutes 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. The UWB-transmission in a realistic channel model has been simulated with Ray-Launcher. For details see [4]. 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 BS'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, a Step Length Update (SLU) is 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 combination of step length and the latest heading angle is a dead reckoning path and is used in the navigation filter in the UWB/INS integration which will be described in the next section.

## III. INS/UWB INTEGRATION

### A. *Loosely and Tightly Coupled integration*

In this work loosely and tightly-coupled UWB/INS integration is presented. The first integration technique for range measurements as known from GPS integration algorithms is the loosely coupled approach, where range measurements first go through the position calculation as can be seen in Fig. 1 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, where time difference measurements from UWB are directly processed in the navigation filter. Even one single range measurement can be processed in the filter. Notice that due to the Time Difference of Arrival approach a decorrelated Kalman filter measurement update for the UWB ranges must be implemented. The schematic representation of the UWB/INS integration process is shown in Fig. 1 where both, loosely and tightly coupled methods are presented.

Furthermore Step Length Updates prevent the inertial

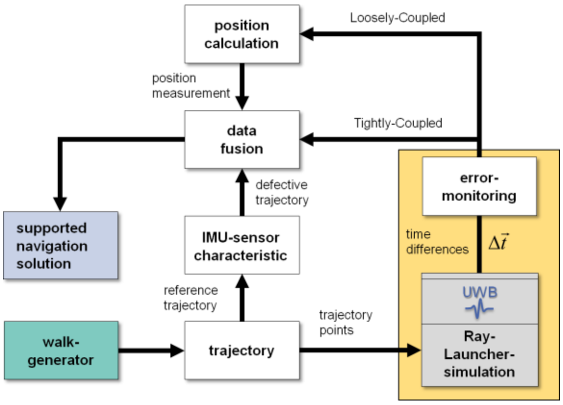


Figure 1: Integration scheme of an INS and UWB system - Loosely and Tightly Coupled Approach in the same scheme

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 detailed information on the integration of both systems will be given in the final manuscript.

### 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 compared for example with GNSS signals. The same effect is given during each initialization or re-initialization. In this case we propose the use of iterative

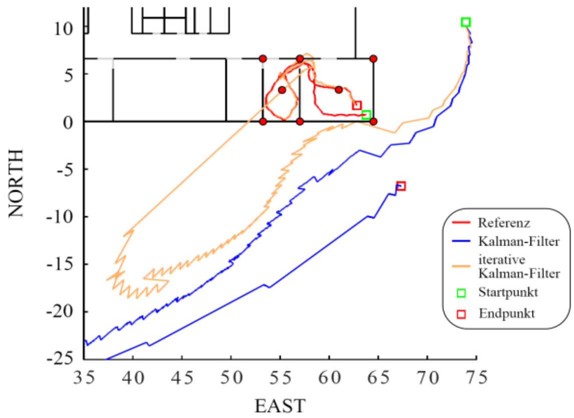


Figure 2 Improvement achieved by the use of Iterative Kalman filter

Kalman filter (KF) updates for position errors of more than 1 meter after an outage. In Fig. 2 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 initialize but with the iterative KF, the solution converges after some time.

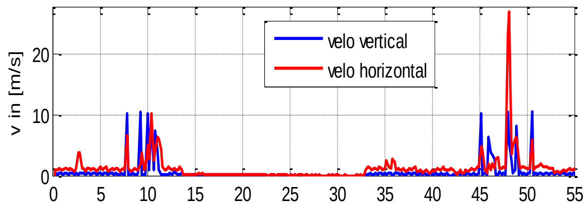


Figure 3: Velocity from position differences

## 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. 3 at t=[7s..12s , 45..51s]. This monitoring is used for rough fault detection before the navigation filter with 2 different thresholds for vertical and horizontal velocities.

## 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 and non-line of sight errors and shading effects. To detect faulty measurements, we propose a new method for integrity monitoring.

There are several integrity monitoring methods which are receiver autonomous (RAIM), e.g. the range comparison method but these do not use inertial data to improve their position by a prediction. So we have combined that method to an Innovation Based Integrity Monitoring (IBIM) to fit to our tightly coupled system with INS aiding and UWB TDoA measurements:

In TDoA applications range measurements between transmitter (user) and receivers (infrastructure) are differenced and 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, resulting in a residual vector:

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

Now as a rejection criterion we use the difference between the residual vector $\Delta\vec{Y}$ and the lowest residual min $(\Delta\vec{Y})$. This modified residual vector now is divided into logical LARGE and SMALL by a threshold. 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, errors in TDoA measurements can be observed and rejected if necessary.

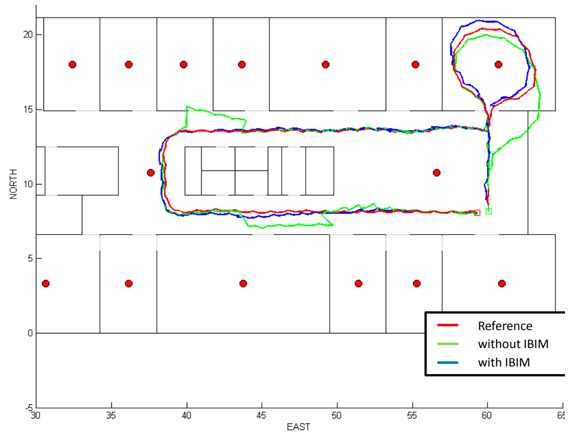


Figure 4: First results with IBIM: tightly coupled vs. tightly coupled with IBIM, more results in the paper, no step length updates

## VI. Results

In Fig. 4 our results for a deep indoor scenario are presented. 15 receivers are distributed in the hallway and in the rooms. In the hallway when only few line of sight receivers are visible, range errors occur. But with the presented Innovation Based Integrity Monitoring (IBIM) decision algorithm for TDoA cases we found promising results and robustness. In the full paper, also loosely coupled integration results will be discussed showing its limitation compared with the tightly coupled approach. Further discussion of results and of the approach will also be presented in the full paper.

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