Study on UWB/INS Integration Techniques

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***Abstract*—In this paper a simulation-based feasibility study on tightly UWB and inertial data integration is presented. Inertial measurement data is generated using a new pedestrian walk generator based on real inertial sensor data. UWB range measurements are generated from ray-launching simulations for different environments and 3D-maps. The final data fusion is realized by a Kalman Filter: Loosely vs. Tightly Integration Techniques are compared and the expected accuracy is presented.**

I. Introduction

The major advantage of an inertial navigation system (INS) is, that it is independent on its environment. It does not rely pre installed RF-infrastructure and does not suffer from NLOS situations. On the other hand though, inertial systems are only short-time stable due to low cost MEMS (Microelectromechanical System) sensors. Through a fusion of an INS with a UWB positioning system, that by its nature has a good long term stability, the precision of the over-all system should improve.

The aim of this work is to model an indoor UWB localization system and its tight coupling with an inertial navigation system. The modeling of the UWB infrastructure includes the Ray-Launcher channel simulation of a real building, the positioning algorithms, simulation of the INS and the integration of both systems. The main scope of this work is to identify and highlight the possibilities and the shortcomings of different systems configurations as well as to establish a firm basis for future hardware integration. Moreover the answers for questions like, what is the achievable accuracy or what are the general problems to be expected in real implementation, shall be found.

The paper is structured as follows: in section II the way in which the INS was modeled is presented, section III contains the detailed description about proposed methods of supporting the Kalman filter. The integration method of all subsystems is described in section IV. Finally the simulation results are presented in section V and in section VI the work is summarized and the conclusions are drawn.

II. Modeling of the INS

The generation of IMU signals is based on a real step sample recorded by an IPNS hardware (Integrated Pedestrian Navigation System) developed at ITE. The IMU is mounted on the torso of a test person. The recorded signal was filtered and modulated resulting in a step sample which can be adopted to a variable step length and a variable heading angle. The sample consists of one left and one right step and is depicted in Fig. 1.

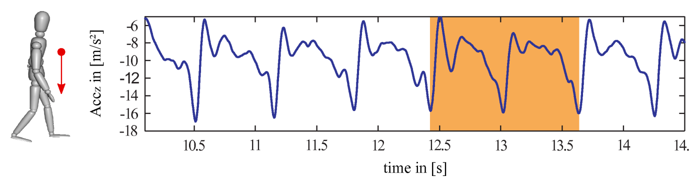

Fig. 1. Acceleration signal in z-direction. The sample is marked in orange.

This sample is used as a basis to create more complex trajectories through a building. Different maneuvers are possible like forward run, curve and stand, as well as a variable target velocity, from which the number of steps will be derived. It is also possible to define an arbitrary trajectory, which then the walk generator will approximate with human steps. The ground truth is derived by calculating the strap down of the ideal IMU data. It is the basis for the simulation of specific sensor noise parameters described in the following.

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 was modified with error statistics of two Inertial Measurement Units available on the market: ADIS16355-IMU from Analog Devices and NavChip-IMU ISNC01 from Intersense. At the time the first one is integrated in the navigation system developed by ITE [2].

The *Angle Random Walk* (ARW) and *Velocity Random Walk* (VRW) were modeled 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 $\sigma_M = 4°$. The barometer data is created from a known height superimposed with a WGN with a standard deviation $\sigma_B = 0.5\,m$.

As a result, the realistic (imperfect) characteristic of an inertial measurement system is obtained. As predicted and already known from experiments, this system has rather poor long term stability. In the following section two methods of improving INS long term stability will be introduced.

III. Filter support

A. UWB and Ray-Launcher simulation

First possibility to stabilize the INS over longer time period is to support the IMU with an information about the distance to the fixed point (one or more) in the room. This could be done by adding another sensor to the existing IMU unit, that is capable of measuring the relative distances between its self and infrastructure consisting of multiple base-stations. The wireless technology that seams to be optimal for this task is Ultra-Wideband (UWB). The UWB pulses are characterized by the large signal bandwidth, that depending on the regulation can reach up to $7.5\,GHz$, and fine time (and spatial) resolution. The optimal geometrical distribution of the UWB-base-stations should always be based on DOP-values (dilution of precision) in order to minimize the influence of possible measurement inaccuracies on the positioning precision. This topic as well as the implemented TDOA-based (Time Difference Of Arrival) localization algorithms are described in more details in [4].
The UWB-transmission between the INS and base-station has been simulated with 3D Ray-Launcher (RL). The RL is a wave propagation simulation tool developed at IHE. 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 be also 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 [1]. 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.
For the simulations of the proposed system, a 3D model of the real IHE Institute building has been used. The layout of the 3rd floor of this facility, together with properties of used construction materials, is depicted in Fig. 2.

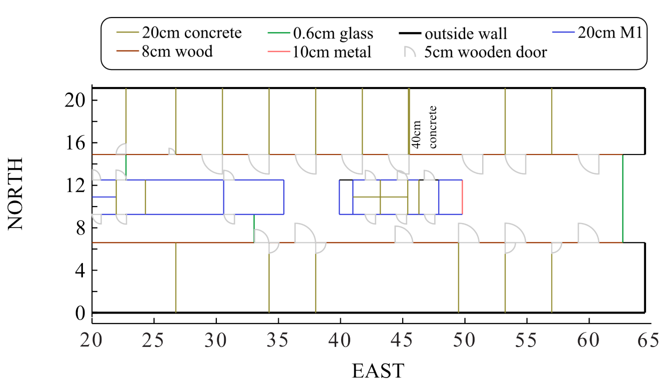

Fig. 2. Third floor of the Institut für Hochfrequenztechnik und Elektronik (IHE) at the Karlsruhe Institute of Technology.

In order to obtain a consistent simulation model, the generation of the trajectory has to be coupled with the Ray-Launcher simulation. For this purpose the trajectory generated by the walk-generator was sampled an the variable rate, that represents the update rate of the UWB positioning system. Depending on the simulation the UWB system delivers a solution with $1\,Hz$ or $5\,Hz$ rate. Those INS-positions were then transfered into RL, which in combination with the model of the building calculated the realistic time-domain signal. From those signals the arrival times of the UWB pulses were extracted and used to calculate the time differences, which serve as an input data for the previously mentioned TDOA localization algorithms. The calculated positioning solution can be used to support the INS (Loosely-Coupled-Integration), or alternatively the time-differences can be utilized (Tightly-Coupled-Integration). Loosely- and Tightly-Coupled-Integration will be covered in the next section. In Fig. 3 the flow-diagram of the simulation is presented.

B. Step-Length-Update

Another method to improve the long term stability is to provide the estimation of the traveled distance or walking speed. This can be achieved by incorporating the Step Length Update (SLU). For this purpose the step-recognition based on IMU accelerometer data was used. This algorithm identifies the positions of the acceleration peaks, that appear every time when the heel of the walking person touches the ground (e.g. at the beginning and end of the orange-colored area in Fig. 1). Based on this information the step-length-estimation is performed to obtain a predicted length of every single step. This estimation relies on such parameters as step-frequency and variance of the acceleration data.
Because of the fact that the generated IMU data are already approx. periodically identical and no varying step-frequencies were implemented, the step-length-estimation would not make much sense. To be able to use this filter-support, the step length was calculated based on the known reference trajectory and detected step moments. Those ideal step lengths were then superposed with a normally distributed noise with a standard deviation $\sigma_{SL} = 20\,cm$. The combination of such a simulated step length and heading angle leads to a dead reckoning path. This information, if coupled with a *velocity filter* [5], introduces an additional constraint and prevents the IMU from drifting away too fast.

IV. INS/UWB 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: 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. But to calculate a stand alone position solution from ranges, a minimum of 4 receivers is needed. 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 16 state Error

State Kalman Filter. The filter states are position, velocity, attitude and sensor biases of IMU and barometer. 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 receiver. Due to this Time Difference of Arrival approach a decorrelated Kalman filter measurement update is implemented as all TDOA measurements are correlated with the base receiver. The schematic representation of both processes is shown in Fig. 3.

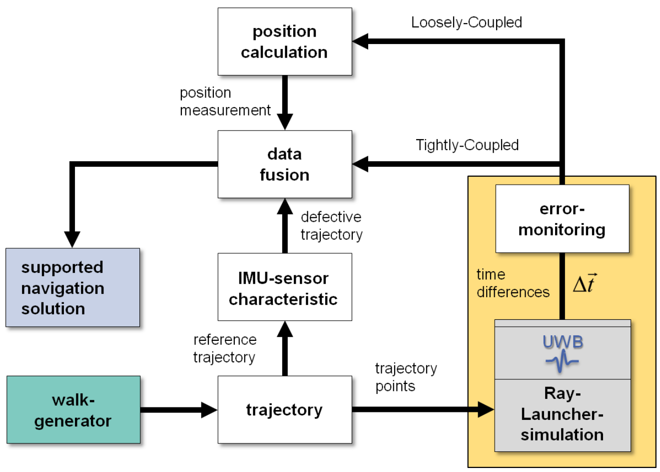

Fig. 3. Integration scheme of an INS and UWB system.

V. Results

At first the accuracy of the UWB localization in this scenario, as a stand-alone system, shall be verified. For this purpose the reception threshold of the radio signals has been lowered to a level that allows the detection of the pulses that traveled through walls. At the same time the logic that should detect NLOS cases is switched off, so that the time of arrival (TOA) of the strongest peak will be obtained independent if this was the first path or not. Also a Receiver Autonomous Integrity Monitoring (RAIM) and the before mentioned velocity-filter have been implemented. Those were however deactivated in order to find out the basic accuracy. The TDOA positioning equations were solved using the Levenberg-Marquardt algorithm without constraints and a Bancroft algorithm for initialization. The results are presented in Fig. 4.

The errors in the time measurements cause large position errors. The run of the original trajectory is not recognizable from the uncorrected UWB positioning solutions. The median of the position error is around $4\,m$ but the average error is much higher due to several outliers that are outside the figure.

At least 6 and up to 11 receivers are available during the entire runs, what certainly allows the 3D position calculation. Should a measurement with more than $10\,cm$ deviation from the actual distance be considered as erroneous, then around 30% of measurements were not useful. However it is worth noticing that despite inactive constraints, almost all (despite one) height calculations are smaller than the celling ($14.5\,m$).

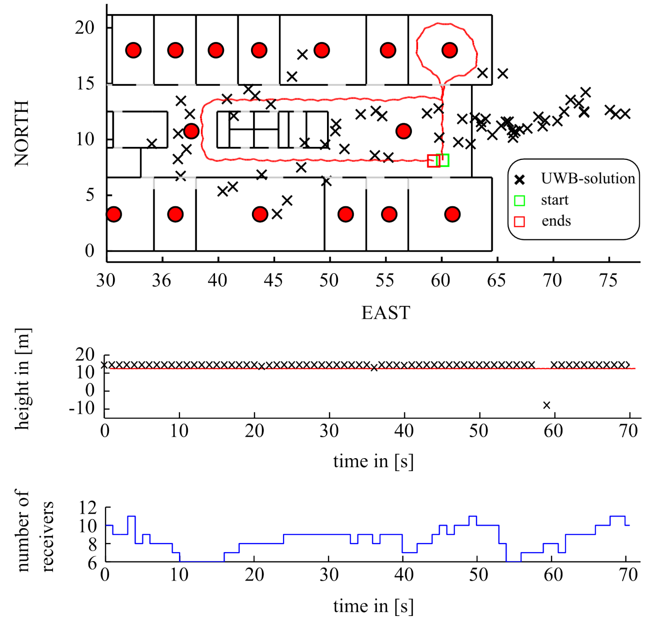

Fig. 4. Positioning approach utilizing UWB signals including through-wall propagation paths.

On the other hand almost no height could be estimated truly. In general this leads to a result that the positioning through concrete walls, causing massive signal delays, is not possible. There is a chance that the RAIM algorithm could identify some of the faulty measurements , however it is better to set the receiver threshold to a level where such signals will not be detected at all.

After evaluating the performance of the UWB system it is time to look at the positioning results of the integrated system. The main goal here is to manifest the performance difference of the two data merging approaches described in section IV. In Fig. 5 the comparison between two the tightly- and loosely-coupled approaches is shown. The trajectory runs through two rooms, whereat 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 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.

To investigate the potential of the second approach a similar simulation has been performed, however this time with the better sensor from Intersence. This should improve the results

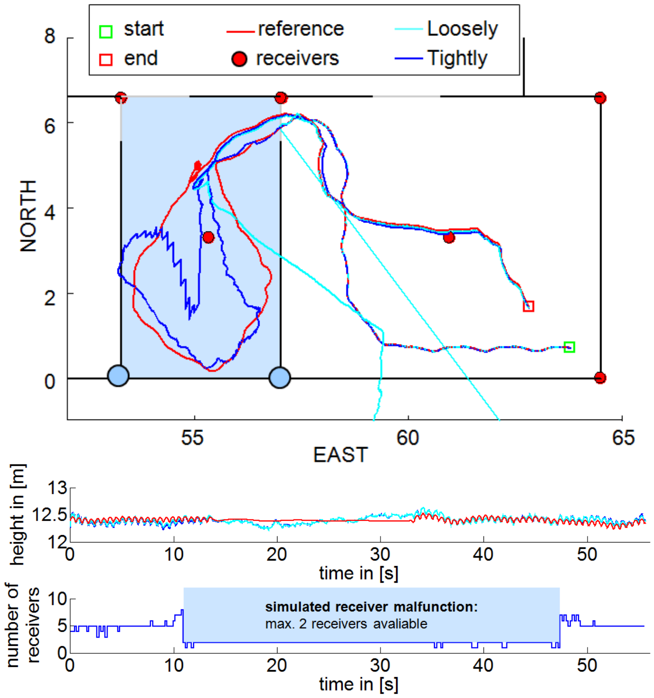

Fig. 5. Loosely vs. tightly for ADIS with two receivers.

in the phase where only few receivers are present. As presented in Fig. 6 the results of both sensor data merging approaches have improved. The lower drift of the ISNC IMU leads to a very close match between the calculated and the reference route.

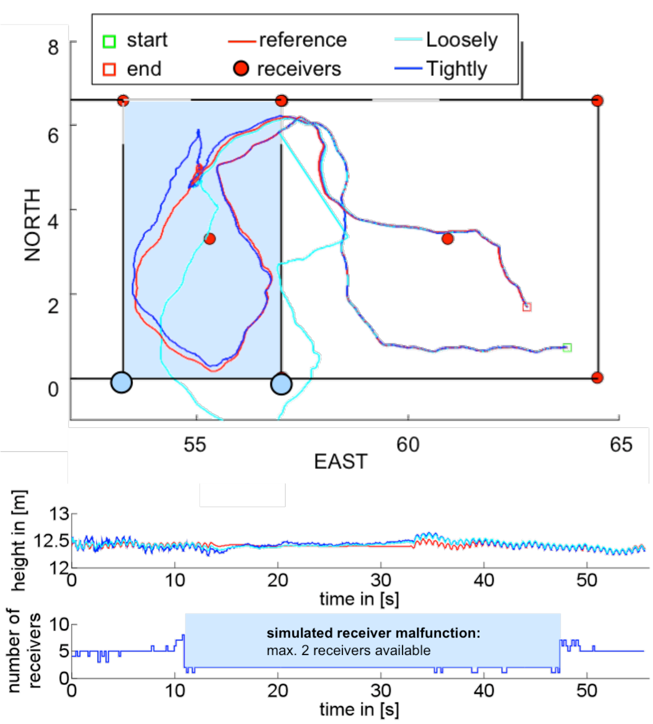

Fig. 6. Loosely vs. tightly for ISNC with two receivers.

Step-length-update was introduced in section III as another optional filter support, that offers additional positioning support by step identification and step length calculation. In case when a significant number of UWB-measurements is present then usage of this support does not help much. However mainly in the regions with poor UWB coverage and in combination with less performing sensors, the SLU can improve the navigation system. In order to demonstrate this, the performance of the IMU was degraded. The values of angular/velocity random walk and bias in-run stability were used, that are approximately one magnitude times higher than those of the ADIS16355-IMU. The results are presented in Fig. 7 and 8.

In Fig. 7 the tightly-coupled navigation solution is shown, whereby only UWB support is used. Due to the strong drift of the INS-solution during the intervals with less than 4 receivers, the tightly-coupled system (blue line) is not able to compensate the errors. Alternatively (green line) the navigation solution is presented that consists of INS and SLU, where no UWB measurements were used. The run of the solution is correct, however with the time a small drift appears that cannot be corrected by the step-length-update.

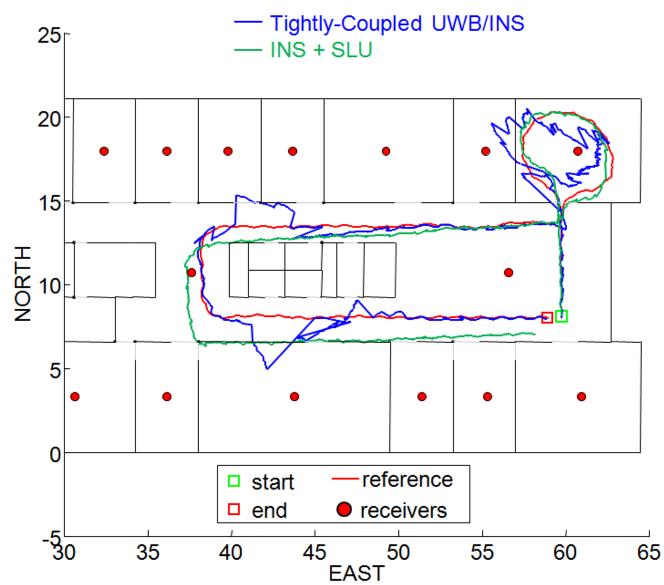

Fig. 7. Step-length-update vs. UWB support.

Fig. 8 shows the tracking results in case when the INS with SLU is additionally supported by the UWB system. In this case the mentioned drift is eliminated and a good solution during the entire run could be found. The most prominent improvement can be observed in room 1 (top right).

As the step length estimation is not a very accurate estimation process, it is advisable that in case when good quality sensors are used and sufficient UWB support is present, the SLU has rather negative influence on the positioning solution. In some cases the step-length-update and UWB-support can even work against each other, if they are not treated as differential measurements.

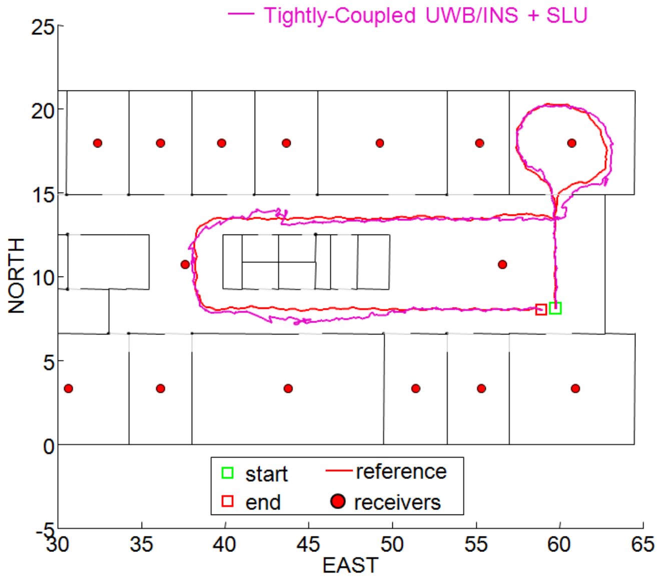

Fig. 8. Tightly-coupled solution, including both SLU and UWB.

VI. Summary and conclusions

In this work a set of different methods to support an IMU was presented and simulated based on real data. The Ultra-Wideband TDOA measurements as well as SLU seem to be a good choice for this purpose. Based on the presented results the Tightly-Coupled data fusion is advisable for practical realization of the navigation system. This approach gives namely the possibility to profit from UWB measurements even if no direct TDOA solution would be available and step-length-update to smooth the calculated trajectory between consecutive UWB updates.

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