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INDOOR POSITIONING BY ULTRA WIDE BAND RADIO AIDED INERTIAL NAVIGATION

Alessio De Angelis[1◇], *John-Olof Nilsson*[2], *Isaac Skog*[2], *Peter Händel*[2], *Paolo Carbone*[1]

[1]Department of Electronic and Information Engineering, University of Perugia, Italy, ◇deangelis@diei.unipg.it
[2]Signal Processing Lab, ACCESS Linnaeus Center, Royal Institute of Technology, Stockholm, Sweden

Abstract – In this paper, a research activity aimed at developing an indoor positioning system is presented. The realized system prototype uses sensor fusion techniques to combine information from two sources: a local Ultra-Wideband (UWB) radio based distance-measuring system infrastructure and an Inertial Navigation System (INS). The UWB system provides a measure of distance between two transceivers by measuring the time-of-flight of pulses. Its principle of operation is briefly described, together with the main features of its architecture. Furthermore, the main characteristics of the INS and of the Extended Kalman Filter information fusion approach are presented. Finally, some experimental results are provided, relative to static and dynamic position measurements.

Keywords: Ultra Wide Band, Indoor Positioning, Inertial Navigation.

1. INTRODUCTION

Connectivity is becoming a natural feature of contemporary electronic devices and communication networks is the basis of more and more services. Sensor networks with mobile nodes is a challenging research area, ensuring applications sharing real-time information in an efficient, affordable, and reliable manner.

In this context, the applications in which indoor position information is critical or beneficial are numerous, safety of life operations, efficient traveling, industrial automation, and cargo handling, to mention a few. Unfortunately, the global positioning system (GPS), the current paradigm of radio positioning, performs poorly in indoor environments. Further, indoor applications often require high position accuracy due to the nature of the environment, e.g. positional information of ± 1 meter might keep you on the road but it will not take you through a door post! Fortunately though, an indoor area is typically smaller and more controlled than an outdoor one and hence in many applications it might be feasible to rely on local preinstalled special purpose infrastructure.

The aim of this paper is to present our work towards a scalable indoor positioning system based on a combination of local infrastructure and inertial navigation. In this work we have built an Ultra Wide Band (UWB) distance measurement system which will support an Inertial Navigation System (INS) resulting in a robust complete (i.e. position, velocity and attitude information) navigation solution using sensor fusion techniques. This is primarily a system level presentation. A detailed describtion of the signal processing issues can be found in [1].

The main reason for using a UWB signal in indoor positioning applications is its fine time resolution and its resilience to multipath signal propagation [2][3][4]. Also the UWB system is designed to work below the noise floor of narrow band signal devices. Furthermore, an INS adds attitude information to the system, which might be critical in some applications, and makes it possible to compensate for directional dependent disturbances i.e. interference due to system carrier. The INS can also eliminate shadow areas where less than three UWB nodes are visible by tracking the position for a limited period of time without need for external measurement.

In the pulse-UWB positioning literature, some examples of experimental systems design and characterization research activities can be found, with some differences in the scope, methods and applications [2][5][6]. Furthermore, there is a relatively small number of proprietary UWB ranging solutions, mainly intended for industrial, security or logistics indoor applications [7][8][9]. The main performance specifications of such systems are an indoor accuracy in the order of 10 cm and a maximum operating range in the order of 100 m.

Moreover, regarding the specific field of information fusion methods for indoor geolocation, it is possible to find several approaches involving the integration of different information sources, such as GPS, INS and local radio technologies. The most widely studied techniques are based on Kalman filtering or particle filtering [10] [11] [12].

The outline of the paper is as follows. In Section 2 a system overview is presented and the main features of the system components outlined. Thereafter, in Section 3 the fusion between the information provided by the UWB-radio positioning system and the INS is discussed. In Section 4 the experimental setup used to test the system and test results are presented.

2. SYSTEM OVERVIEW

The indoor navigation system consists of two segments, the infrastructure segment and the user segment. The infrastructure segment comprises a set of UWB-radio nodes located at known positions within the area where the navigation system is to work. The user segment is the navigation unit, which aims to estimate its location and attitude by a combination of UWB-radio range measurements and inertial navigation. To achieve this task, the navigation unit comprises: an UWB distance measurement device (*master* unit, see section 2.1) to measure the ranges to UWB-radio nodes (*slave* units, see sec-

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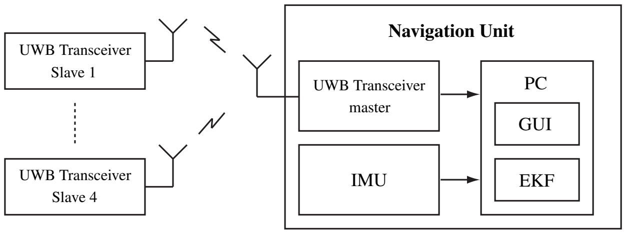


Fig. 1. Indoor navigation system architecture.

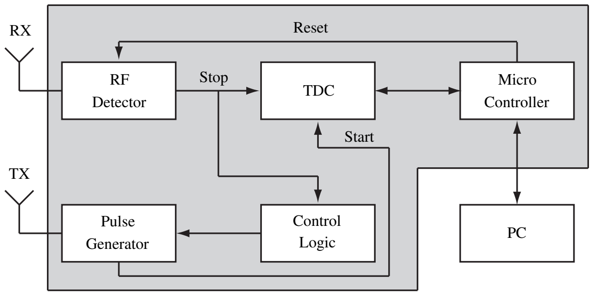
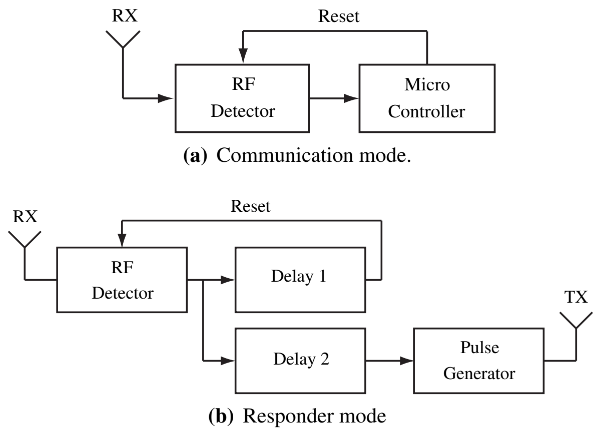


Fig. 2. Block diagram of the master device.

Table 1. System specifications.

UWB system	
Number of slave devices	4
Sampling rate (slave/s)	10 [Hz]
Range error (std)	4 - 20 [cm]
Maximum distance	12 [m]
IMU	
Sampling Rate IMU	100 [Hz]
Gyroscope bias stability	± 0.2 [°/s]
Gyroscope noise std.	0.3 [°/s]
Accelerometer bias stability	± 0.03 [m/s^2]
Accelerometer noise std.	0.01 [m/s^2]



(a) Communication mode.

(b) Responder mode

Fig. 3. Block diagram illustrating the two working modes of the slave device.

tion 2.1); an inertial measurement unit (IMU) providing acceleration and angular rate measurements for the INS; and a PC running an extended Kalman filter (EKF) used to combine and process the measurements into a navigation solution. Refer to Fig. 1 for an illustration of the system architecture and to Table 1 for system performance specifications.

2.1 Ultra wide band radio distance measurements

The principle of operation of the UWB ranging system is based on the indirect measurement of the distance between transceivers, obtained by measuring the round-trip time (RTT) of an UWB pulse [2]. This approach has the advantage of a looser synchronization requirement when compared to other commonly used strategies such as time-of-arrival or time-difference-of-arrival [3] [4]. However, when measuring the RTT, the latency introduced by the responder devices has to be accurately measured or estimated. In the present system, this issue is addressed by performing a calibration of each slave unit.

The system is composed of a *master* device and several *slaves*. The master transceiver is capable of measuring RTT. This time interval measuring function is performed by a commercial time-to-digital converter (TDC) integrated circuit, the TDC-GP2 by Acam Messelectronic GmbH, with an rms resolution of 50 ps. A block diagram of the master is shown in Fig. 2.

The slave devices are not able to perform time interval measurements, but will instead, on request, after a fixed delay answer a UWB short pulse when another UWB short pulse is received, thus providing a "round trip". The slave unit has two modes of operation: *communication* mode and *responder* mode. Fig. 3(a) shows a functional block diagram of the devices in communication mode, while the responder mode is illustrated in Fig. 3(b). By using logic circuits it is possible to switch between the two modes of operation. The control and timing functions are performed by a MSP430 low-power

Fig. 4. UWB positioning pulse transceiver prototype.

microcontroller from Texas Instruments. The circuit architectures of both the master and the slave devices are based on the system presented in [13], while the UWB pulse generator modules have been built using step recovery diodes using the circuit design presented in [14]. Furthermore, omnidirectional wideband disc-cone antennas have been used in the receiving and transmitting sections of each device. Fig. 4 shows a picture of one of the realized prototypes.

A timing diagram for the operation of the system is provided in Fig. 5. It is divided in two sequential phases: *addressing* and *measurement*. In the first phase the master sends a 8-bit unique slave identifier code, using on-off keying with UWB pulses. In this basic modulation scheme, if a pulse is

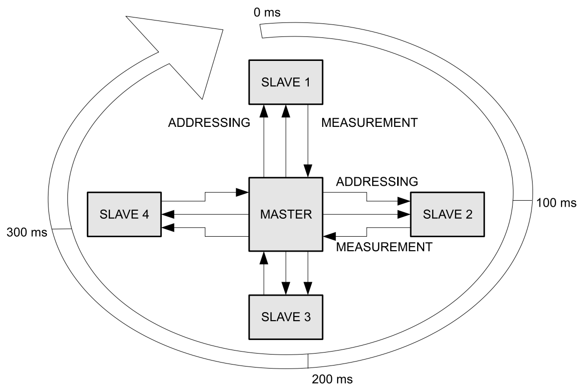


Fig. 5. Timing of the UWB ranging system.

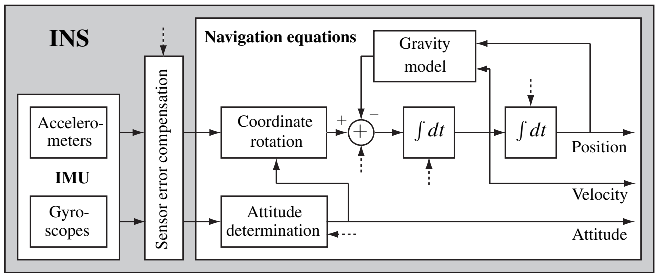


Fig. 6. Conceptional sketch of a strap-down INS. The dash arrows indicate possible points for insertion of calibration (aiding) data.

transmitted in a specific time slot, then it is interpreted as a "1" bit. The absence of a pulse is seen as a "0" bit. During the addressing phase all the slaves are in communication mode and receive this message. At the end of this phase only the slave corresponding to the unique identifier is activated and transitions to responder state, while all the other slaves are disabled for a fixed amount of time. Subsequently, during the measurement phase, the master sends 10 measurement pulses and measures the RTT. The measurement pulses are spaced approximately 5 ms apart. After each pulse the measurement result is sent to the PC through a serial interface. The whole procedure is repeated every 100 ms, therefore the system is able to obtain measurement sets (10 measurements) from slaves at a frequency of 10 Hz. The reason the measurements are done in groups of 10 is that the addressing phase is relatively long (approx. 40 ms) in comparison with the time of a single measurement (<5 ms).

2.2 Inertial navigation

The INS can be divided into a sensor part (the IMU), and a computational part. A block diagram of the INS is shown in Fig. 6.

In our case the IMU is an Inertia-Link from MicroStrain with a USB-interface. The IMU contains temperature compensated MEMS triaxial accelerometer and gyroscope. The computational part is implemented on a PC to which the IMU is connected. The PC propagates mechanization equations to achieve a navigation solution. The mechanization equations are the differential equations that relate the inertial measurements to the position, velocity, and attitude of the navigation platform. Descriptions of common mechanization equations can be found in standard inertial navigation literature [15][16].

Since the IMU in use has a strapdown configuration of the individual sensors, the measurements will be done in a sensor frame different from the navigation frame. Further, according to the equivalence principle, the gravitational acceleration of the navigational frame will be indistinguishable from a true acceleration in the accelerometer measurements and hence must be compensated for. This means that the propagation of the mechanization equations will have to be performed in several steps. As seen in Fig. 6, for each measurement instance we first integrate the gyroscope measurement to propagate the attitude (rotation between body frame and navigation frame) of the platform to the current instance. The accelerometer measurements are then transformed into the navigation frame, a gravity model is used to compensate for the gravitational acceleration, and finally the resulting value is integrated to achieve position and velocity in the navigation frame.

The INS is selfcontained and with the right state initialization capable of giving a complete set of navigational states (position, velocity, and attitude). Inertial measurements can be done at a high rate (100 Hz), giving a high dynamic range, and are essentially immune to external disturbances. However, due to the integrative nature of the INS, which amplifies low frequency noise, and to the low performance solid state sensors in use, the errors will swiftly grow beyond acceptable levels after only a few seconds of stand alone use.

3. INFORMATION FUSION

The objective of information fusion is to obtain more information than is present in any individual information source by combining information from different sources [17]. In practice, this means that by utilizing the complementary properties of the different information sources, the information fusion algorithm in a navigation application aims to reduce ambiguities in the measured information and thereby expand the spatial and temporal coverage in which the navigation system works.

As described in Section 2.2 the INS gives a complete set of navigational states (i.e., position, velocity, and attitude) and a high dynamic range, but has an unacceptable error growth rate as a stand alone system. The UWB radio range measurement system, described in Section 2.1, on the other hand, has a slow update rate, giving a low dynamic range, and does not provide a full set of navigational states (attitude difficult to observe), but provides position information with a bounded error. These complementary properties are utilized in the information fusion of the designed navigation system by implementing it using an UWB-radio range aided INS architecture. That is, the INS provides the main navigation solution and when a UWB-radio range measurement is available a range prediction is calculated based upon the current position estimate of the INS. The difference between the measured and predicted range is used as an observation for an EKF that houses a model for how the errors in the INS develop with time and how they relate to errors in the range predictions. The errors are estimated and fed back to the INS. An illustration of the system can be found in Fig. 7. Note that this type of system architechture is commonly used in GPS aided INS [15]. Also, this is a general standard procedure for inertial navigation with aids and a thorough description of this can be found in [16].

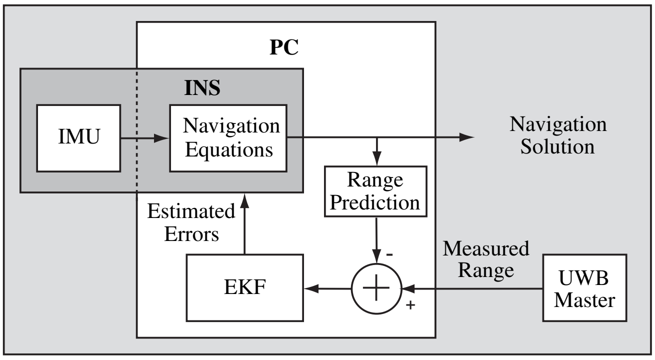


Fig. 7. Conceptional sketch of the information fusion.

4. TEST RESULTS

The measurement were all carried out in an a indoor office environment with line-of-sight conditions.

4.1 Calibration

The basic measurement in the UWB radio distance measurement system is the RTT of the radio pulse. The RTT depends on the distance the pulse has to travel plus a latency introduced by the hardware in the slave and master units. Due to manufacturing tolerances and varying cabling length this latency will vary slightly from slave to slave. Hence, to properly convert the RTT observations into distance estimates, each UWB slave unit will have to be calibrated individually. Moreover, for a proper information fusion in the EKF, the error variances of the distance measurements as a function of the true distances should be quantified during the calibration proceedure. To perform the calibration the slaves were placed at known distances from the master and for each distance 1000 RTT values relative to each slave were recorded. The resulting mean and standard deviation curves are shown in Fig. 8(a) and 8(b). A linear fit was performed on the data and subsequently used to transform the RTT measurement to distance measurement.

Further, due to self-interference from antenna cables and antenna stand the RTT showed a directional dependence. This dependence was measured by placing a slave unit at a fixed distance while turning the master. At each turning point 1000 RTT measurements were taken and the expected RTT based on the distance calibration was subtracted. The resulting deviation can be seen in Fig. 9. A sinus function was fitted to the data and subsequently used to compensate for the directional dependence.

4.2 UWB only positioning

To inspect the quality of the distance measurements and their stand-alone positioning performance, the following experiments were conducted:

- A static measurement setup where the four UWB slave units were located in the corners of a imageable square and the UWB master unit located in the center of the square. With this setup 5000 measurements cycles (i.e. distance measurement to all four slaves) were collected and for each cycle the master's position was calculated as a least squares solution. A histogram of calculated positions around mean is shown in Fig. 10 together with the corresponding covariances;

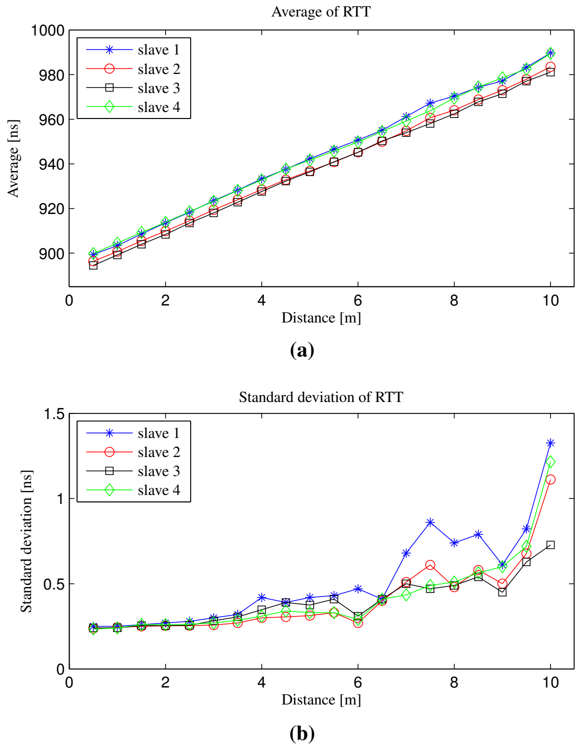


Fig. 8. RTT-to-distance and RTT variance calibration curves.

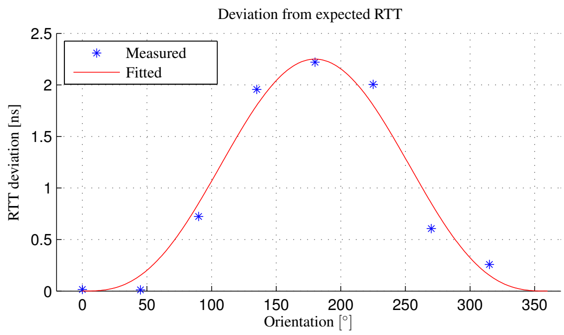


Fig. 9. Orientation dependent deviation from expected RTT.

- A low dynamic test in which the four UWB slave units were located in the corners of an imageable rectangle and the UWB master unit was slowly moved in an 1x1 meter square trajectory. See Fig. 11 for an illustration. The master was held in a constant orientation to facilitate the correction of the orientation dependence of the RTT. Modelling the acceleration of the UWB master unit as random walk a real-time tracking filter (an EKF) was implemented. The resulting estimated positions can be seen in Fig. 11.
- A high dynamic test with the same trajectory, slave constellation, and tracking filter, but in which the master was jerked from corner to corner. The resulting estimated position can be seen in Fig. 12. To make comparison with the combined UWB and INS positioning possible no directional correction was done. Because of this, systematic errors can clearly be seen. Also the limited dynamic range can be observed in the overshoots in the corners and in the jagged estimated trajectory.

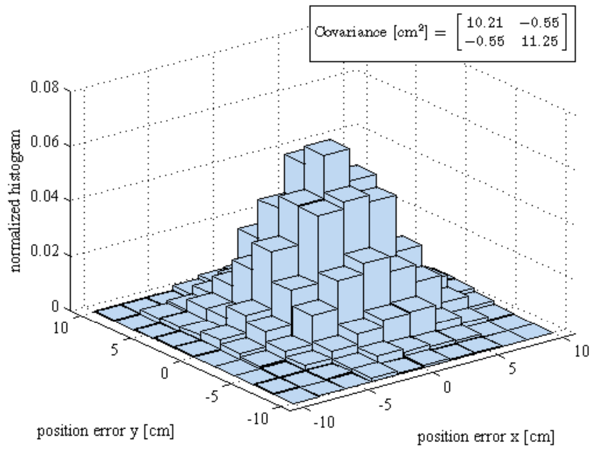


Fig. 10. Histogram of the position errors in the static measurement setup together with the corresponding sample covariance.

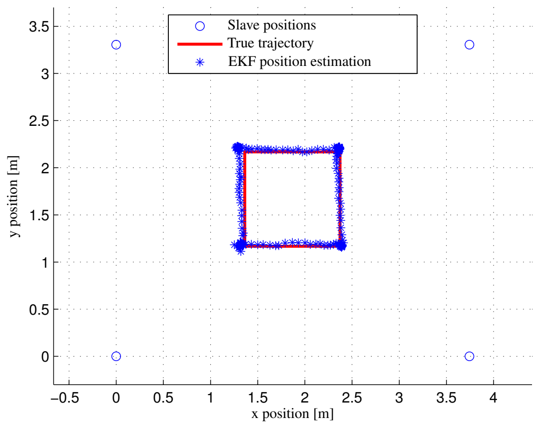


Fig. 11. Positioning result from low dynamic test in which only the UWB radio distance measurements were used and corrected for directional dependence and filtered by a trackingfilter.

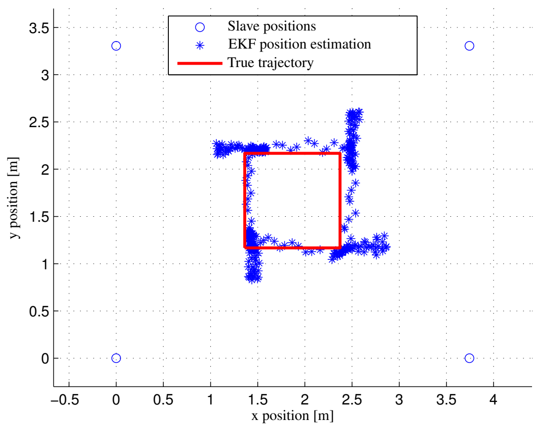


Fig. 12. Positioning result from high dynamic test in which only the UWB radio distance measurements were used and filtered by a trackingfilter. Correction for directional dependance not included.

4.3 *Combined INS and UWB positioning*

As for the UWB only positioning the master had to be held in a constant (or known) orientation to facilitate the correction of the orientation dependence of the RTT. Hence, the directional information that the combined INS and UWB positioning gives is not just valuable by itself but also eliminates the position error which would otherwise arise because of unknown orientation. Fig. 13 shows the result of the combined INS and UWB positioning for the same data as the high dynamic UWB only positioning test. The improved dynamic range and elimination of the systematic errors can clearly be seen.

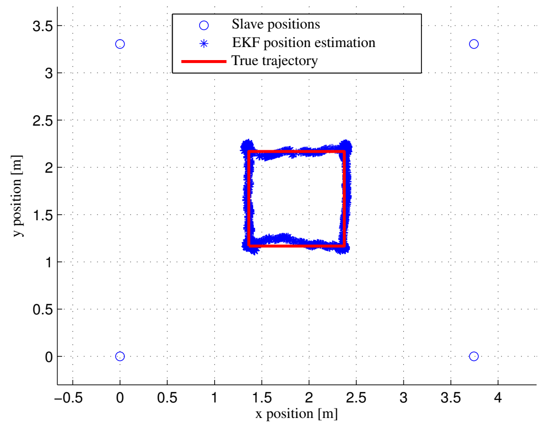


Fig. 13. Positioning results from high dynamic test in which the UWB radio distance measurement system is used to support the INS.

5. CONCLUSION

In this paper, an indoor positioning system has been presented, by describing its architecture and presenting some experimental results. The system is based on the integration between an UWB positioning section and an INS. Particular focus has been dedicated in this paper to the description of the system components and their principle of operation. The results from experimental test have shown the capability of the system of statically and dynamically measure the position with an accuracy of the order of centimeters in a controlled indoor environment.

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