Indoor-localization system using a Micro-Inertial Measurement Unit (IMU)

Fabian Höflinger[1], Rui Zhang[2], Leonhard M. Reindl[3]

Laboratory for Electrical Instrumentation
Department of Microsystems Engineering - IMTEK
Georges-Koehler-Allee 106, 79110 University of Freiburg, Germany
{[1]fabian.hoeflinger, [2]rui.zhang, [3]reindl}@imtek.uni-freiburg.de

***Abstract*—In this paper we present a wireless Micro-Inertial Measurement Unit (IMU) which is used for localization of people in indoor areas. The Micro-IMU is built especially for portable applications. The main target of the IMU design was to minimize the size, weight and power consumption, as much as possible whereas the performance is still comparable to commercially available wired IMUs. Through the minimum size the IMU can be integrated into clothes or shoes and provide the full functionality of pedometers. In an experiment the Micro-IMU was mounted on a shoe for detecting the human movement. With sensor data-fusion based on Kalman Filter and ZUPT (Zero Velocity Update) Algorithm we could track a person in an indoor area.**

***Index Terms*—Indoor-Localization system, Inertial Measurement Unit, wireless sensor**

I. INTRODUCTION

In recent years, localization systems for indoor areas are becoming more and more popular. To guide people in unknown indoor areas a localization system is needed. This is often useful, in airports to find specific gates, in supermarkets to navigate customers to chosen products and in fairs to navigate visitors to the exhibition stands.

For indoor areas many different localization technologies are available. A brief overview of localization systems is shown in Fig.1 and discuss below.

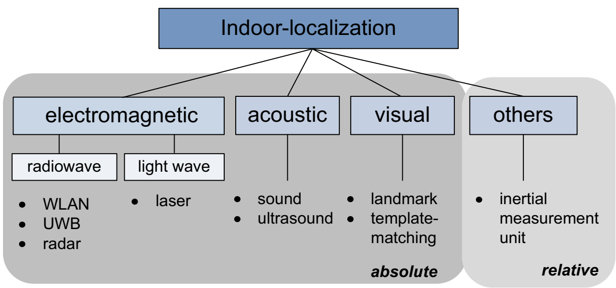

Fig. 1. Overview localization systems

Localization systems based on electromagnetic e.g. WLAN were used to localize people with smartphones and WLAN-Access Points [1]. The positions in such systems is calculated with Time of Flight (ToF) or with RSSI (Received Signal Strength Indication). Systems based on acoustics used ultrasound to locate people. In [2] a system is presented which is calculating the position with Time Difference of Arrival (TDoA) of sound. The disadvantages of electromagnetic and ultrasound systems are the required infrastructure and the accuracy of the system depends on multipath propagation. Visual systems use environment information to estimate the position. In [3] a localization system is presented which compares currently captured images with images in a database. The visual systems have problems to clearly identify positions in dynamic environments.

Relative systems e.g. Inertial Measurement Units (IMUs) detects the movement continuously. The systems rely on inertial sensors, which detects the actual movements with accelerometer, gyroscope and magnetometer. The sensor data is integrated, errors and measurement inaccuracies lead to positioning deviations. Relative systems are good for short distance tracking or for combination with absolute systems in shaded signal ranges.

II. INERTIAL MEASUREMENT UNIT (IMU)

Today many different commercially IMUs are available. Fig.2 shows a overview of the dimensions and data performances of state of the art IMUs and IMUs from research groups. Bandwidth, sensor drift, linearity and sample rate describes the performance of an IMU. For precise tracking an IMU with small dimensions and high performance is needed. IMUs with less sensor drift and a high data rate have large dimensions and communicate usually via wire to computers. The IMUs from LITEF are used in civil and military aviation and provides a high end data performance. The μIMU-I [4] is based on a fiber optic gyroscope that provides a high stability and a low drift Factor of $2.8*10^{-5\circ}/s$ in a size of $160\,\mathrm{cm}^3$. Most of the commercially available IMUs like the Xsens MTi [5] offer measurement data preprocessing and robust on-board sensor data fusion for 3D orientation. Research groups use these IMUs for developing their own algorithms. However, due to their size, weight, or power consumption, these IMUs are not ideally suitable.

Different research groups works to minimize the size and to use wireless transmission. Barton *et al.* demonstrated a cubic IMU design with a side length of 10 mm and wireless communication [6]. However, they employ analog sensors which demand for separate analog-to-digital converters. Lin *et al.* presented a system for the analysis of yaw movements with dimensions of 37 mm x 23 mm x 12 mm, integrated with a Bluetooth module and a lithium polymer battery which is comparably large and has limited sampling rate [7]. Tsai *et al.* presented a small wireless IMU without gyroscope in a size of 1 cm^3 [8].

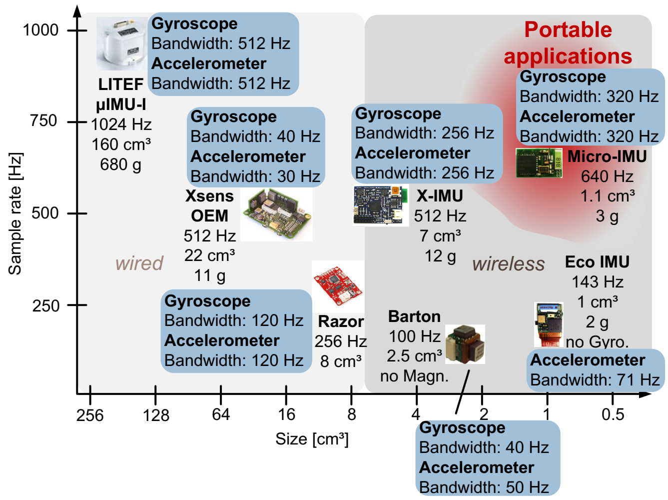

Fig. 2. Overview of size and data performances of state of the art IMUs and IMUs from research groups

III. Design of the Micro-IMU

The main target of the IMU design was to minimize the size, weight and power consumption, as much as possible whereas the performance is still comparable to commercially available IMUs e.g. Xsens MTi IMUs. For the design of the Micro-IMU, we combined the aim of an applicable IMU for portable application and improved the characteristics in size, weight, while the performance is still comparable to state-of-the-art commercially available MEMS IMUs. This becomes possible by using modern MEMS sensors. In our design we used accelerometers and gyroscopes feature three-axis technology and integrated analog-to-digital conversion with automatic temperature compensation in one-chip-design. This saves space in the IMU design as analog converters and 3D packaging are not necessary. Thus, a four-layer PCB is sufficient for integration of all inertial sensors and a microcontroller. Fig.3 shows the block diagram with the components of the IMU.

One important aspect of this design is to move data-processing from the IMU to a base station. Through this, the power consumption of the IMU is reduced, as the demanding computation of sensor data fusion filters and other algorithms to enhance the data quality is moved to more powerful computers with less constraints in size and weight.

A CC430 microcontroller sends the collected raw data to a base station wireless with a maximum sample rate of 640

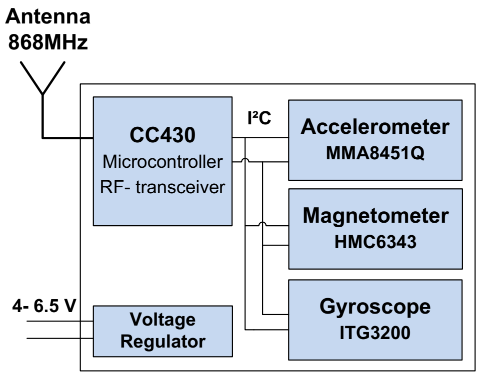

Fig. 3. Block diagram of the Micro-IMU

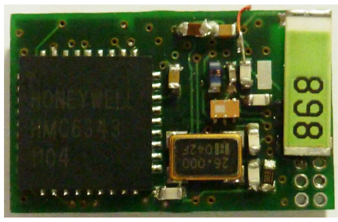

Fig. 4. Micro-IMU with radio cell with a dimension of 18 mm x 16 mm x 4 mm

samples per second. The power consumption of the Micro-IMU is three times lower than the commercially available IMUs. Thereby, the IMU performance is optimized by moving data post processing to the base station. This development offers new possibilities in portable applications with limited size, weight-requirements and battery powering where the position information is not needed on the moving subject.

Fig.4 shows the developed wireless Micro-IMU with an integrated antenna. The presented Micro-IMU with a size of 1.1 cm^3 is 20 times smaller and provides full control over the data of a three-axis accelerometer, a three-axis gyroscope, and a three-axis magnetometer. The Micro-IMU meets the design prerequisites of a space-saving design and eliminates the need of a hard-wired data communication while still being comparable to state of the art commercially available MEMS IMUs.

IV. Performance of the sensor data

For the data processing it is important to have a high raw sampling rate. The performance of the raw data is very important for the accuracy of the algorithm. The data quality of the measurement data of the IMU is determined by bias-drift and noise of the sensors. Allan variance approach was used to process the drift and noise information of the sensor. We used the Allan variance to compare the Micro-IMU with the commercial Xsens-MTi IMU [9]. The obtained curve is shown in Fig.5 and the precise characteristics can be found in Table I.

For the gyroscope the Micro-IMU performs better than the MTi concerning drift and noise. The noise level is on average

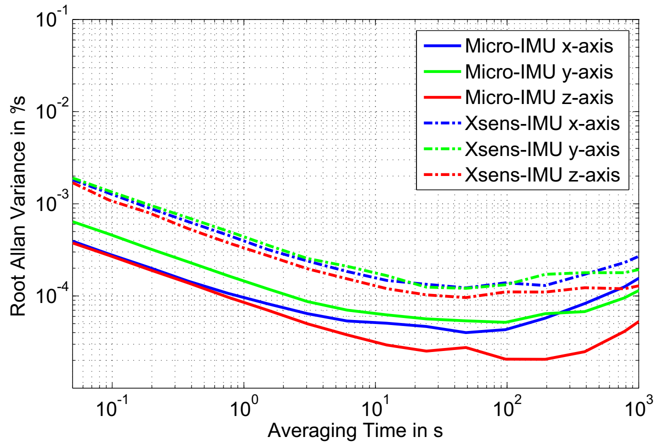

Fig. 5. Allan variance of the Gyroscope of Xsens MTi and Micro-IMU

TABLE I
COMPARISON BETWEEN XSENS [5] AND MICRO-IMU

	Micro-IMU	Xsens MTi
Interface	Wireless	RS232/USB
Sampling Rate	640 sample/sec	100 sample/sec
Bandwidth Acc.	320 Hz	30 Hz
Bandwidth Gyro.	320 Hz	40 Hz
Power Consumption	110 mW	350 mW
Size (OEM)	18 x 16 x 4 mm^3	48 x 33 x 15 mm^3
Weight (OEM)	3 g	11 g
Gyroscope		
Noise in $°/s/\sqrt{Hz}$		
x-axis	0.0055	0.045
y-axis	0.0082	0.041
z-axis	0.0049	0.036
Drift in $°/s$		
x-axis	0.0023	0.0070
y-axis	0.0030	0.0069
z-axis	0.0012	0.0055

six times lower for the Micro-IMU than for the MTi and the drift is lower by a factor of three.

V. SOFTWARE FOR TRACKING

Software part includes three sections. Firstly calibration of sensor is implemented in order to obtain the stable, bias-free, calibrated sensed data from the raw sensed data. Secondly, orientation especially the heading angle is determined by fusing the inertial sensors and magnetic field sensor using Kalman filter. Thirdly, the correct position information is obtained by combining the orientation information and corrected velocity information, which is achieved by "'Zero Velocity Update"' (ZUPT) method.

A. *Sensor calibration method*

The sensor calibration method is to remove the bias of all the sensors and adjust the orthogonal coordinate of magnetic field sensor. By keep the sensor model still for some time, the bias of gyro and acceleration sensors can be calculated by averaging the sensed data during calibration period. The magnetic field sensor is calibrated by using Merayos technique with a non-iterative algorithm [10], which tries to find the best 3D ellipsoid that fits the sensor data set and returns the parameters of this ellipsoid. The raw data of the magnetic field sensor is shown in Fig.6. Fig.7 shows the result after the calibration with Merayos technique.

After the steps above, a second-order low pass filter is applied for all the sensors so as to remove the noise outliers.

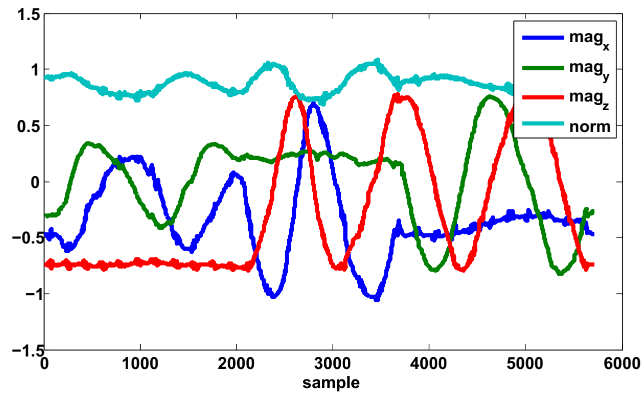

Fig. 6. Raw data of the magnetic field sensor

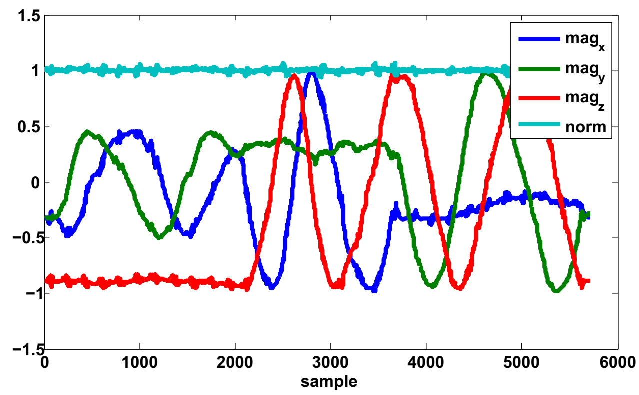

Fig. 7. Output data of the magnetic field sensor after calibration

B. *Orientation determination*

The study for sensor data fusion include a modified Kalman filter is used, which consists of two functions: the complementary separate-bias Kalman filtering for the motion modeling avoidance and data fusion; the magnetic disturbance detection and minimization for robustness and stability when experiencing local magnetic disturbances. In the complementary Kalman filter the integration of the Euler angles is performed outside of the Kalman filter. The advantage of this structure is that requires a much lower sampling rate and guarantees that the rapid dynamic response of the inertial system will not be compromised by the Kalman filter [11]. The idea of magnetic disturbance detection and minimization is that if magnetic disturbances are detected, the date fusion result will not depend on magnetometers, whose detail can be found in [12].

C. Position calculation

After determining the correct orientation information, the rotation matrix can be obtained to transform the acceleration from sensor body fixed frame to earth fixed frame. After two times integration, the position information can be obtained. However, the accumulated acceleration error will heavily pollute the position data, since the position information is no more correct.

In the whole phases of a stride during normal walking, there exists a time period when the foot is not moving related to the ground. This time period is called sill phase. Ojeda *et al.* [13] showed that the velocity value should be reset when still phase is detected, thus the accumulated errors from the accelerometer output could be effectively removed. This method is called Zero Velocity Update (ZUPT). Experimentally the best indication for still phase could be obtained by observing the three outputs of gyroscopes. If the norm value of gyroscopes outputs is smaller than the predefined threshold, we assume that the foot is experiencing still phase and the velocity can be reset. Fig.8 shows the difference of data output with ZUPT and without ZUPT algorithm.

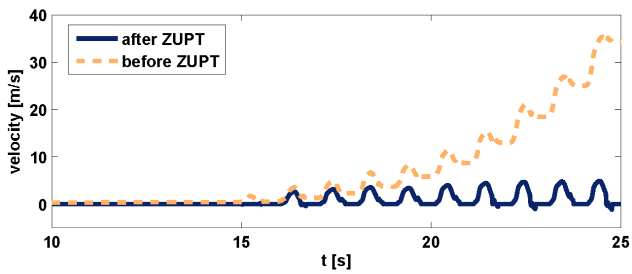

Fig. 8. Comparison between ZUPT applied and not applied velocity determinations

VI. Experiment

In an experiment the Micro-IMU was mounted on a human foot (Fig.9) for detecting a walk of 30 m distance in a floor of a building. During this experiement the yaw angle was oriented around 90 degrees (1.57 rad) four times. The measurement is shown in Fig.10

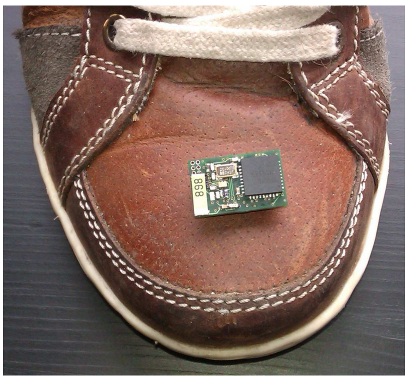

Fig. 9. For an experiment the Micro-IMU was mounted on a shoe

Fig.11 shows the calculated trajectory of the Micro-IMU with sensor data-fusion based on Kalman filter and ZUPT (Zero Velocity Update) Algorithm. The maximum deviation from the real track was 1 m.

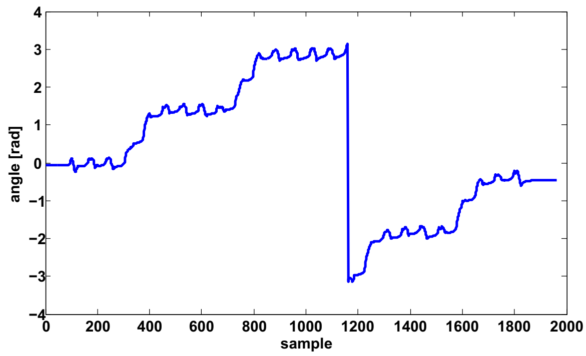

Fig. 10. Yaw angle measurement

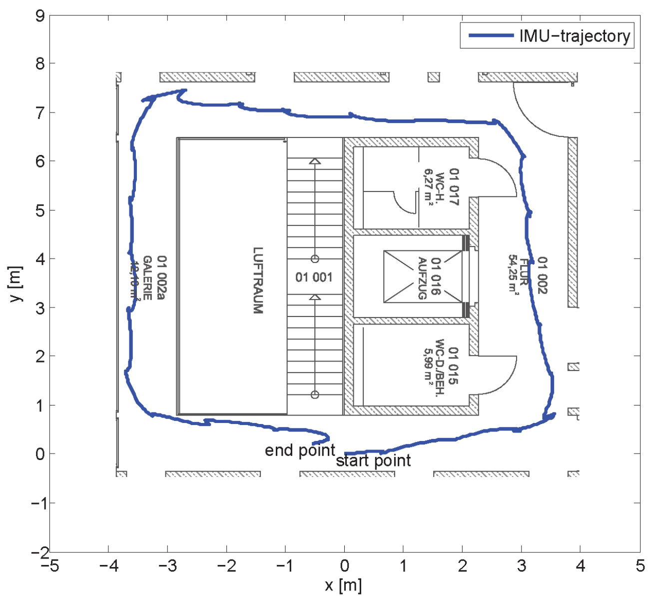

Fig. 11. Measured trajectory of the Micro-IMU from a walk in a floor of a building

VII. Conclusion and Future Work

In this paper, we presented the design of a wireless Micro-IMU that features minimum size and weight. By using highly integrated digital sensors and relocating data post-processing from the IMU to a base station, we are capable of competing with state-of-the-art commercial MEMS IMUs such as the Xsens MTi. This achievement is important for tracking people precisely in indoor areas. In the presented work the miniature size of the designed Micro-IMU made it possible to integrate the IMU into clothes or shoes. In an experiment the Micro-IMU was mounted on a shoe to track a person in a building. After a walk of 30 m the maximum deviation from the real track was 1 m.

In future we will use a motion capture system to measure the real walking track and to improve the filter parameters. Furthermore we will investigate the properties for localization of humanoids with limited load.

ACKNOWLEDGMENT

This work has been supported by the German Research Foundation (DFG) within the Research Training Group 1103 (Embedded Microsystems).

REFERENCES

[1] P. Bahl and V. Padmanabhan, “Radar: an in-building rf-based user location and tracking system,” in *INFOCOM 2000. Nineteenth Annual Joint Conference of the IEEE Computer and Communications Societies. Proceedings. IEEE*, vol. 2, 2000, pp. 775 –784 vol.2.

[2] N. B. Priyantha, A. Chakraborty, and H. Balakrishnan, “The Cricket Location-Support System,” in *MobiCom ’00: Proceedings of the 6th annual international conference on Mobile computing and networking*, 2000, pp. 32–43.

[3] G. Borriello, A. Liu, T. Offer, C. Palistrant, and R. Sharp, “Walrus: wireless acoustic location with room-level resolution using ultrasound,” in *Proceedings of the 3rd international conference on Mobile systems, applications, and services*, ser. MobiSys ’05. New York, NY, USA: ACM, 2005, pp. 191–203. [Online]. Available: http://doi.acm.org/10.1145/1067170.1067191

[4] “Litef LITEF,” 2011, [accessed 2012/04/20]. [Online]. Available: http://www.northropgrumman.litef.com/fileadmin/downloads/ Datenblatt$_{u}IMU-I.pdf$

[5] “Xsens MTi,” 2011, [accessed 2011/11/04]. [Online]. Available: http://www.xsens.com/en/general/mti

[6] J. Barton, A. Gonzalez, J. Buckley, B. O’Flynn, and S. O’Mathuna, “Design, fabrication and testing of miniaturised wireless inertial measurement units (IMU),” in *Electronic Components and Technology Conference, 2007. ECTC ’07. Proceedings. 57th*, 29 2007-june 1 2007, pp. 1143 –1148.

[7] Z. Lin, M. Zecca, S. Sessa, L. Bartolomeo, H. Ishii, K. Itoh, and A. Takanishi, “Development of the miniaturized wireless inertial measurement unit wb-4: Pilot test for mastication analysis,” in *System Integration (SII), 2010 IEEE/SICE International Symposium on*, dec. 2010, pp. 420 –425.

[8] Y.-L. Tsai, T.-T. Tu, and P. H. Chou, “Ecoimu: A compact, wireless, gyro-free inertial measurement unit based on two triaxial accelerometers.” in *IPSN*, X. D. Koutsoukos, K. Langendoen, G. J. Pottie, and V. Raghunathan, Eds. IEEE, 2011, pp. 133–134. [Online]. Available: http://dblp.uni-trier.de/db/conf/ipsn/ipsn2011.htmlTsaiTC11

[9] F. Höflinger, J. Müller, M. Törk, L. Reindl, and W. Burgard, “A Wireless Micro Inertial Measurement Unit (IMU),” in *Proceedings of the IEEE International Instrumentation and Measurement Technology Conference (I2MTC)*, 2012.

[10] J. M. G. Merayo, P. Brauer, F. Primdahl, J. R. Petersen, and O. V. Nielsen, “Scalar calibration of vector magnetometers,” *Measurement Science and Technology*, vol. 11, no. 2, p. 120, 2000. [Online]. Available: http://stacks.iop.org/0957-0233/11/i=2/a=304

[11] E. Foxlin, “Inertial head-tracker sensor fusion by a complementary separate-bias kalman filter,” *Proceedings of the IEEE 1996 Virtual Reality Annual International Symposium*, vol. 96, pp. 185–194, 1996. [Online]. Available: http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=490527

[12] R. Zhang and L. Reindl, “Pedestrian motion based inertial sensor fusion by a modified complementary separate-bias kalman filter,” in *Sensors Applications Symposium (SAS), 2011 IEEE*, feb. 2011, pp. 209 –213.

[13] L. Ojeda and J. Borenstein, “Non-gps navigation for security personnel and first responders 1,” *Journal of Navigation*, vol. 60, pp. 391–407, 2007.