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Günther Retscher

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Geodäsie und Geophysik
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CONTENTS

Foreword

This collection of papers shows an important part of the author's research in the areas of personal navigation and location-based services during the past years. Thereby the papers concentrate on the use of multi-sensor systems and the integration of different location techniques and positioning sensors in navigation systems. These papers have been published in international journals and were peer reviewed. The list of the paper source can be found at the end of this publication. Some papers have contributions from other people, reflecting todays cooperative style of research. The author gratefully acknowledges their valuable input:

- Prof. Dr. Esmond Mok, The Hong Kong Polytechnic University, PR China, and his colleague Mr. Lawrence Lau contributed to the work performed in a joint research project[1] on the improvement of vehicle navigation systems. As a project leader Prof. Mok also contributed to the paper about sensor fusion and integration for modern navigation systems.
- Mr. Michael Thienelt, Vienna University of Techology, Austria, contributed with his work on pedestrian navigation systems in the research project NAVIO[2].
- Dr. Allison Kealy, The University of Melbourne, Australia, contributed with her research findings for developing of intelligent vehicle navigation systems using Augmented Reality (AR).
- Mr. Denis Vredeveld, Dr. Dirk Heberling and Mr. Jörg Pamp from the company IMST GmbH, Kamp-Lintfort, Germany, and Mrs. Eva Moser were involved in testing of the WiFi (or WLAN) indoor location system 'ipos' performed in the localization test bed of IMST in course of a diploma thesis at the Vienna University of Techology, Austria.

The papers are reproduced here in their original form. Only the links are updated, a few expressions are clarified and some typing errors are eliminated. Recurring figures and textual overlaps are accepted.

This work is dedicated to my parents Herta and Josef Retscher.

Guenther Retscher
Vienna, August 2007

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[1] Research project B.34.37.Q329 entitled "A satellite based multi-sensor system for intelligent land vehicle navigation and tracking system suitable in a dense high-rise environment" founded by the Research Grants Council RGC of the Hong Kong SAR Government, PR China.

[2] Research project P16277-N04 entitled "Pedestrian Navigation Systems in Combined Indoor/Outdoor Environments" founded by the Austrian Science Fund (Fonds zur Förderung wissenschaftlicher Forschung FWF).

About the Author

Since 2001 Dr. Günther Retscher has been Assistant Professor at the Institute of Geodesy and Geophysics, Reseearch Group Engineering Geodesy, of the Vienna University of Technology, Austria. He conductes research, teaches, supervises graduate students and manages the teaching of the research group. His main research interest is in the application of multi-sensor systems and the intergration of sensors and positioning methods in engineering geodesy and navigation. This collection of research papers gives an overview of his work in the area of personal navigation and location-based services. The courses he teaches deal with applied geodesy and engineering surveying, satellite positioning and navigation as well as location-based services.

Dr. Retscher chairs the working group WG 4.1.2 on “Indoor and Pedestrian Navigation” under Sub-Commission 4.1 “Multi-sensor Systems” in Commisssion 4 (Positioning and Applications) of the International Association of Geodesy (IAG). He was also Member-at-Large of this Sub-Commission and Secretary of Sub-Commission 4.2 on “Applications of Geodesy in Engineering” until 2007. In the FIG (International Federation of Surveyors) he is Vice-Chairman of Ad-hoc Group WG-5.33 “Multi-Sensor Systems” of FIG WG 5.3 on “Kinematic and Integrated Positioning” under Commission 5 (Positioning and Measurement). He was chairman of the organizing committee of several international conferences and workshops, among them the 5th and 7th International Conference on “Optical 3-D Measurement Techniques”, the 2nd and 3rd International Symposium on “Geodesy for Geotechnical and Structural Engineering”; he was member of the scientific committee of the 4th International Symposium on “Mobile Mapping Technology” and of the 3rd Symposium on “LBS and TeleCartography”; and he was session chair at the ION (The Institute of Navigation) GNSS 2005 Conference. Currently he is involved in the organization of the 4th International Symposium on “LBS and TeleCartography” to be held at the Hong Kong Polytechnic University in November 2007. Dr. Retscher is member of the Editorial Board of the Journal of Global Positioning Systems and the Journal of Geospatial Engineering and he is also Editorial Secretary of the new Journal of Applied Geodesy.

Dr. Retscher studied Geodesy at the Vienna University of Technology, Austria, specializing in engineering geodesy. He received his diploma in 1992, with a thesis on positioning of hydrographic survey vessels. He then worked as Research and Teaching Assistant at the Department of Engineering Geodesy, Vienna University of Technology, Austria. He received his Ph.D. from the same university in 1995, with a thesis on the application of multi-sensor systems for railway track surveying. From 1997 to 1998 he was Lecturer at the Department of Land Surveying and Geo-Informatics of the Hong Kong Polytechnic University.

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Introduction

Personal mobility assistance and *location-based services* (LBS) have been identified as main research areas worldwide in recent years. Most developments have started with emerging navigation and tracking systems in the area of vehicle guidance in the early 1980's. Since the announcement of the full operational capability of GPS in early 1994, the use of GPS sensors and their integration with other existing techniques (e.g. with dead reckoning DR sensors) has become a common integration scenario. As a consequence, the use of GPS and other satellite positioning systems (e.g. GLONASS and future GALILEO) has significantly changed the navigation and surveying market in the last decades.

The earliest vehicle location and navigation systems date back some 2000 years to the ancient civilizations of Egypt, Greece, Rome and China. The most famous of these is the *Chinese South Pointing Carriage* which is credited to Chang Heng (circa 120 A.D.) and Ma Chün (circa 255 A.D.). In this ancient navigation system already the principle of *differential odometry* was used. By keeping track of how much more (or less) one wheel moves than the other, the ancient Chinese could keep track of the change in heading and distance of a two-wheeled carriage as it moves across vast, featureless tracts of land. This motion was mechanically compensated for, thereby keeping the outstreched arm of a statue mounted on the carriage continuously pointed toward the south or some other reference direction [Krakiwsky, 1991].

It was not until the early 1970's that this principle for navigation and orientation determination was applied again using emerging technologies such as wheel rotation and heading sensors. The resulting *automatic vehicle location and navigation* (*AVLN*) *systems* used terrestrial dead reckoning (DR) sensors coupled with map matching techniques in which the vehicle's dead reckoned path is correlated to an onboard digital map of the road network. In the following development two different trends were present, i.e., the first trend concentrated on terrestrially based AVLN systems which relied heavily on dead reckoning and map matching, and the second employed GPS satellite technology for absolute position determination. Terrestrially based AVLN, however, have two serious shortcomings, i.e., firstly the need to initialize the system at a starting location before commencing travel and secondly a mismatching of the vehicle's dead reckoned path to a nearby parallel street can happen when the position error grows too large. This lost situation will also occur when travelling into an uncharted area or e.g. a parking lot. Purely terrestrial based systems have therefore not proven to be as robust as necessary for the mass consumer market. Intergration of GPS could make AVLN systems more robust, accurate and userfriendly. Then the blockage of satellite signals caused by obstructions in urban canyons, tree-covered areas and tunnels can be bridged by dead reckoning. Therefore nowadays mainly multi-sensor solutions are employed.

Based on the development and research in the area of AVLN systems the author started to work on the analysis and improvement of location techniques for any kind of personal navigation in the early 1990's. In a journal paper published in 1995, European developments in emerging vehicle navigation systems were analyzed and the integration of GPS and dead reckoning in future intelligent vehicle navigation systems (IVNS) has been discussed [Retscher, 1995]. Further research in this field and practical tests were published in Retscher and Koppensteiner [1996]. Apart from satellite positioning systems and dead reckoning the author investigated very early the use of alternative location techniques and sensors, e.g. the integration of *cellular phone positioning technologies* using 2nd generation wireless networks (such as GSM[3]) into vehicle navigation systems. This research was conducted in cooperation with colleagues from the Department of Land Surveying and Geo-Informatics of the Hong Kong Polytechnic University under the research project entitled “A satellite based multi-sensor system for intelligent land vehicle navigation and tracking system suitable in a dense high-rise environment[4]”. In this project the author worked on the development of alternative location techniques for vehicle navigation in urban canyons. Especially the test sites were very challenging as they are located in urban environment in the city of Hong Kong with many high-rise buildings. The concept of the integration of wireless location techniques was presented at international conferences [see e.g. Retscher and Mok, 2001] and in the Appendix of the journal paper “Development of an Event-Reporting Intelligent Vehicle Navigation System for Areas with Urban Canyons” [Mok et al., 2002] (see page 23 ff.).

The transition from intelligent vehicle systems to *intelligent transportation systems* (ITS) by not only addressing vehicles but also discussing the tracking of people on foot both outside and inside buildings was a logical next step. This facilitates also the multimodal aspect of travelling, e.g. by foot or car, then by train or other public transport, and then returning by a combination of means. Clearly, one must have access to an ITS for this arrangement to work efficiently – hence the need to couple positioning and navigation-related information with other kinds of data [Krakiwsky and Mc Lellan, 1995]. This application is being achieved by combining GPS with complimentary electronic devices and digital information, such as compasses, rate gyros, odometers, barometers, and onboard or in-laptop digital maps. Thereby for communication and tracking cellular phones play also a major role, e.g. in the case of position reporting, messaging and personal-safety applications. This *personal-safety and assistance services* have turned GPS into a mass consumer item and has led to the integration of satellite positioning into cellular phones and other mobile devices, e.g. for locating a person in need of assistance, such as in the case of an emergency call. For the localization of an emergency call the Telecommunication Industry Association (TIA) has issued the following standards: using handset-based positioning techniques (where an independent positioning system such as GPS or Assisted-GPS (A-GPS)[5] is employed) a positioning accuracy of ± 50 m at the 67 % reliability level and ± 150 m at the 95 % reliability level; using network-based positioning techniques (where positioning is done with signals and hardware only of the wireless system) ± 100 m at the 67 % reliability level and ± 300 m at the 95 % reliability level has to be achieved. In addition, the U.S. Federal Communication Commission (FCC) has declared that at least 25 % of all new admitted mobile phones must provide automatic location identification features by December 2001, and this value has to be increased up to 95 % after that date in the next years [see e.g. Balbach 2000, CGALIES 2001, Retscher, 2002a]. These telecommunication initiatives have generated a lot of interest in applications and services that are a function of a users’s location.

The methods for location determination of cellular phones are fundamental for the development of *location-based services* (LBS) [Schiller and Voisard, 2004]. If a cellular phone’s current location can be determined, apart from emergency caller location determination, a wide range of services that utilise location information can be provided by

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[3] GSM stands for Global System for Mobile Communication.

[4] Research project B.34.37.Q329 founded by the Research Grants Council RGC of the Hong Kong SAR Government, PR China (2000-2002).

[5] Using Assisted-GPS the wireless network provides assistance data such as satellite position data, time aiding and position aiding to reduce the time necessary for obtaining a position fix and to improve the overall performance of satellite positioning in cellular phones.

the mobile phone network providers (e.g. mobile tourist and city guides, location dependent enquires in yellow pages and other directories, guidance to service facilities, etc.). The performance of location determination of cellular phones or other mobile devices has been investigated in our research and the underlying technology was presented in a journal paper [Retscher, 2002b]. Location methods in wireless networks include cell-based positioning (i.e., Cell of Origin CoO), signal strength measurements in the network cell, measurement of Time of Arrival (ToA), Time Difference of Arrival (TDoA) or Angle of Arrival (AoA) of the signals in the network, as well as intergration of GPS in the handset. These methods provide different positioning accuracies for the location determination of the cellular phone; they range from ± 50 m up to several kilometres for network-based positioning techniques in the 2nd generation wireless networks [see e.g. Duffett-Smith and Craig, 2004] and on the several metre level for GPS and Assisted-GPS. In the analysis it was found that an integration of LBS services into modern navigation systems can enhance the performance and reliability of continuous position determination in urban canyons and areas where satellite positioning is not available, although their achievable positioning accuracies do not reach the level of GPS. In the following conducted research, the concept of a multi-sensor fusion model integrating DR observations with GPS or mobile phone location services (MPLS) was introduced and investigated. A description of this approach can be found in the paper "Sensor Fusion and Integration using an Adapted Kalman Filter Approach for Modern Navigation Systems" [Retscher and Mok, 2004] (see page 35 ff.). Considering the recent implementation of the 3rd generation of wireless networks (such as UMTS[6] in Europe) this approach is feasible as in the UMTS network a significant improvement of positioning accuracies is gained by using some of the positioning methods described above. Further analysis of LBS services was conducted in a study about their performance in a city with high mobile phone penetration, i.e., the city of Hong Kong [see Retscher et al., 2005]. This study was part of the research project "An Intelligent Geolocation Algorithm for Location-based Services[7]" were the author was a co-investigator.

In preparation of the research project NAVIO ("Pedestrian Navigation Systems in Combined Indoor/Outdoor Environments[8]") the author started to work on the challenging task of *location determination of pedestrians*. In the work package 'Integrated Positioning' of NAVIO different aspects of location determination of a pedestrian in a combined indoor and outdoor urban environment have been investigated. Before the start of the project a study was conducted to investigate the possible sensors that are suitable to be integrated in a pedestrian navigation system. It was found that a pedestrian navigation system should include at least a GPS receiver for absolute position determination and DR sensors for relative positioning such as a heading sensor and accelerometers for measurement of the direction of motion and the distance travelled as well as a barometric pressure sensor for altitude determination. The main results of this study were presented in a journal paper in 2003 [Retscher and Skolaut, 2003]. The three main challenging tasks that were addressed in the project NAVIO are to provide continuous position determination in urban areas, to achieve a seamless transition for location determination of a user entering a building and to locate the user in 3-D in a multi-storey building by integrating different suitable location sensors and methods. A multi-sensor system has been developed in the project and first tests of the integrated location sensors have been presented in the paper "NAVIO – A

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[6] UMTS stands for Universal Mobile Telecommunication Service.

[7] Research project BQ-936 founded by the RGC Research Grant of the Hong Kong SAR Government (2005-2006).

[8] Research project P16277-N04 founded by the Austrian Science Fund (Fonds zur Förderung wissenschaftlicher Forschung FWF) (2004-2006).

Navigation and Guidance Service for Pedestrians" [Retscher and Thienelt, 2004a] (see page 45 ff.). Further investigations of the system and sensor tests are contained in the last contribution of this collection of research papers entitled "Test and Integration of Location Sensors for a Multi-sensor Personal Navigator" [Retscher G., 2007c] (see page 103 ff.). In the presented research it could be shown that different location methods can be deployed and integrated for personal navigation services. A user of the NAVIO system can be located continuously in outdoor urban environments with a positioning accuracy of a few metres.

Starting with the NAVIO project a main focus of the author's research work deals with *indoor location techniques* as navigation systems are getting more popular and a navigation and guidance in challenging indoor environments (e.g. in large office buildings, airports, etc.) is very important nowadays. Indoor environments present opportunities for a rich set of location-aware applications such as navigation tools for humans and robots, interactive virtual games, resource discovery, asset tracking, location-aware sensor networking, etc. [see Kolodziej and Hjelm, 2006]; e.g. also our daily life will make use of indoor location techniques in the near future, i.e., the location determination of goods and shopping carts in a supermarket [see Retscher and Thienelt, 2004b] to name just one example. Especially in the case of emergency services (e.g. to locate firefighters in a rescue situation inside a building) this research area is very challenging and higher positioning accuracies and reliabilities are required than in outdoor environments. Most applications demand that a user can be located in a certain room inside the building. As a consequence the required positioning accuracies depend on the typical room size in the applied area; e.g. considering an office building usually an accuracy of better than 3 m for the location determination in 2-D is necessary in navigation applications. In addition, the system must be able to locate the user on the correct floor in a multi-storey building. The accuracy requirement in height depends on the ceiling height of the building; typically better than 2.5 to 3 m for modern office buildings.

Fortunately, over the past decade, advances in location positioning technology have made it possible to locate users and objects indoors. Different types of indoor location technolgies have been developed and are available on the market which use signals such as infrared, ultrasonic, radio signals and visible light. Their principle of operation, application and performance was analyzed in our research and a result of this study was presented in the journal paper Retscher and Kistenich [2006]. A short overview about the investigated technologies can also be found in the contribution "Augmentation of Indoor Positioning Systems with a Barometric Pressure Sensor for Direct Altitude Determination in a Multi-storey Building" [Retscher, 2007b] (see page 81 ff.) in this collection of research papers. Most of the described indoor locating systems, however, have the disadvantage that they require expensive installations of a larger number of receivers or transmitters inside the building. For indoor location determination in an office building at our University an approach was choosen in our research which makes use of already available infrastructure, i.e., the use of already installed Wireless LAN (WLAN or WiFi[9]). The WiFi location system '*ipos*' developed by the German research company IMST GmbH[10] has been employed. For that purpose a cooperation agreement with IMST GmbH has been signed. The system ipos is jointly analyzed and further improvements have been made to the system design. Performance tests have first been conducted in a localization test bed of

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[9] WLAN or WiFi (Wireless Fidelity) uses radio signals and is standardized under IEEE 802.11 2004 defined by the Institute of Electrical and Electronics Engineers (IEEE), see http://grouper.ieee.org/groups/802/11/ for futher information.

[10] System 'ipos' of IMST GmbH, Kamp-Lintfort, Germany, see http://www.centrum21.de/.

IMST GmbH and the main results of these tests are reported in the paper “Performance and Accuracy Test of a WiFi Indoor Positioning System” [Retscher et al., 2007] (see page 69 ff.). Further testing of ipos was conducted recently in our office building [see Retscher, 2007d]. Apart from ipos also another WiFi positioning system available on the market, i.e., the Ekahau positioning engine from the Finish company Ekahau[11], was employed and investigated in the research project “An Intelligent Geolocation Algorithm for Location-based Services[7]” at the Hong Hong Polytechnic University where the author is the co-investigator [Retscher and Mok, 2006]. In all tests it could be shown that a mobile device of a user can be located with an accuracy of 1 to 3 m in indoor environment.

As most indoor locating systems provide only 2-D location capability, the system ipos has been augmented with a barometric pressure sensor for direct observation of the altitude of the user. Performance tests of a barometric pressure sensor for direct observation of the altitude of a user inside a building were conducted and are presented in the paper “Augmentation of Indoor Positioning Systems with a Barometric Pressure Sensor for Direct Altitude Determination in a Multi-storey Building” [Retscher, 2007b] (see page 81 ff.). Using a hig end, more precise barometric pressure sensor we were able to locate the user on the correct floor.

For the optimal estimation of the current position, velocity and orientation of a user of a multi-sensor navigation system suitable sensor *integration algorithms* have to be employed. Therefore the integration of all sensor observations in modern intelligent navigation services is another main topic of the author’s research. Sensor integration is usually based on a Kalman filter approach. In a cooperation with the Department of Geomatics of the University of Melbourne, Australia, the author was involved in the development of an intelligent vehicle navigation concept where a set of rules that humans use on a day-to-day basis are integrated into the Kalman filter approach. The concept is described in the paper “Ubiquitous Positioning Technologies for Modern Intelligent Navigation Systems” [Retscher and Kealy, 2006] (see page 57 ff.). The sensor integration is discussed in two case studies, i.e., an augmented reality application to enhance vehicle safety while driving under bad visibilty conditions (e.g. during fog, at night, etc.) and in pedestrian navigation for the guidance of visitors of our University.

In the NAVIO project the development of a new multi-sensor fusion model that makes use of knowledge-based systems has been started. The underlying idea was first presented at an international conference in 2005 [Retscher, 2005] and in Thienelt et al. [2005]. In this new approach the available sensor observations are tested in a knowledge-based preprocessing filter where gross errors and outliers can be detected and eliminated in the measurements. All suitable sensor observations as identified in the preprocessing step are then employed in a central Kalman filter for the optimal estimation of the current user’s position, its velocity and direction of motion. This approach is discussed more in detail in the contribution “A Knowledge-based Kalman Filter for an Intelligent Pedestrian Navigation System” [Retscher, 2007a] (see page 89 ff.) and was implemented in the final stages of the NAVIO project [see e.g. Retscher and Thienelt, 2006]. Further refinement and the inclusion of other location techniques is also part of the new FWF research project “Ubiquitous Carthograpy for Pedestrian Navigation (UCPNAVI)[12]”.

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[11] Ekahau Positioning Engine, Ekahau, Helsinki, Finland, see http://www.ekahau.com/.

[12] Research project P19210-N15 founded by the Austrian Science Fund (Fonds zur Förderung wissenschaftlicher Forschung FWF) (2007-2009).

In the UCPNAVI project not only passive positioning systems are used that are installed on the user's device and frequently position them as the user moves along, but also *positioning in active environments* is employed. New technologies originated in ubiquitous computing[13] can enrich navigation and guidance systems by including information captured from an active environment. This would mean that the user is perceived by a ubiquitous environment and receives location based information that is suitable for the respective device or is supplied with helpful notes via a public display or similar presentation tools. Additionally to the function of information transmission poles, these smart stations could possibly substitute or complement traditional indoor positioning methods by sending coordinates of the station instead of locating the user. Based on the concept of *active landmarks*, which actively search for the user and build up a spontaneous "ad-hoc network" via an air-interface, an *ubiquitous solution*, where an information exchange between different objects and devices are accomplished, can be investigated for the use in navigation. This concept enables a revolutionary opportunity for navigation systems. Within the last few years a lot of research and development has taken place concerning LBS which could now be supplemented and expanded with the help of ubiquitous methods, and maybe in the future they could even be replaced. Yet research is still in the early development stage that still meet many new challenges.

Positioning and tracking of pedestrians in smart environments function differently from conventional navigation systems, since not only passive systems, that execute positioning on demand, need to be considered. Moreover a combination of active and passive positioning methods should be the basis of a ubiquitous navigation system. Such a multi-sensor system for position determination should therefore be able to include both types of location determination and as a result lead to an improvement of positioning accuracy. A first approach is the equipage of active landmarks with *active RFID* (*Radio Frequency Identification*)[14] tags. A concept for the location placement of RFID tags in an indoor environment has been developed and can be found at the end of the paper "Test and Integration of Location Sensors for a Multi-sensor Personal Navigator" [Retscher, 2007c] (see page 103ff.). In the UCPNAVI project long range active RFID tags and a reader in form of a PC card (see Figure 1) have been acquired and system testing has recently begun. Using RFID cell-based positioning can be performed. If a user is in the read range of a RFID tag which is placed at a known location then he can retrive the tags information with its current location. The mobile user has to carry only the PC card reader which can be plugged in a mobile device (e.g. a pocket PC). Using Cell of Origin (CoO) the achievable positioning accuracy depends on the size of the cell and is therefore usually several metres up to 10's of metres in the case of long range active RFID tags. To improve the achievable positioning accuracy we have started to investigate other approaches in our research. In a first attempt, the deduction of ranges to the RFID tags from received signal power levels is

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[13] The term "ubiquitous computing" was first created in the late 1980's by Mark Weiser and stands for a post-desktop model of human-computer interaction in which information processing has been thoroughly integrated into everyday objects and activities. As opposed to the desktop paradigm, in which a single user consciously engages a single device for a specialized purpose, someone "using" ubiquitous computing engages many computational devices and systems simultaneously, in the course of ordinary activities, and may not necessarily even be aware that they are doing so [Wikepedia, 2007a]. In other words, a great number of computers will be omnipresent in our everyday life and they will be interconnected in an ubiquitous network.

[14] RFID is an automatic identification method. An RFID tag is a transponder that can be attached to or incorporated into a product, animal, or person for the purpose of identification using radiowaves. Other system components include a reader (i.e., a transceiver) with antenna. Coinsidering the tags, passive, active and semi-passive tags can be distinguished. Further information about the underlying technology can be found in Finkenzeller [2002].

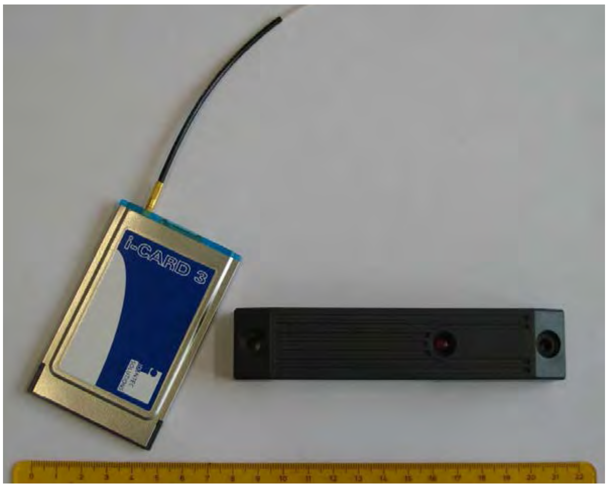

Fig. 1. Example of a long range active RFID tag (right) and a RFID PC card reader with antenna (left) from Identec Solutions [2006]

investigated. Then the position fix can be obtained using trilateration if range measurements to several tags are performed. As an alternative also location fingerprinting can be employed where the measured signal power levels are used directly to obtain a position fix (similar to WiFi fingerprinting (see page 69 ff.) [Retscher et al., 2007]). Using fingerprinting usually positioning accuracies on the few metre level can be achieved. The most precise location method using RFID is based, however, on Time of Arrival (ToA) and Angle of Arrival (AoA) measurements of the signals from the RFID tags. A system developed by Trolley Scan[15] shall be investigated which can provide accuracies on the decimetre level. To implement these new emerging location technique, however, further investigation and testing is required. It is planned that all the testing will be performed in the localization test bed at the Vienna University of Technology at our Institute. RFID can be employed not only indoors but also to augment satellite positioning in areas with no satellite visibilty (e.g. in tunnels, under bridges, etc.) in outdoor environment.

In the future research work of the author also other techniques, such as *Ultra Wide Band* (*UWB*)[16] will be investigated more in detail and their integration into the system design of a navigation system will be analyzed. The main advantage of this new wireless radio signals in the UWB band will be the improved performance and positioning accuracy compared to the current WLAN standard as these signals are not so seriously affected by multipath than WiFi due to their large bandwidth. With large bandwiths a higher positioning accuracy can be achieved, e.g. using Time Difference of Arrival (TDoA) and Angle of Arrival (AoA) measurements of UWB signals. Using UWB positioning accuracies on the dm-level can be achieved in the future for the first time in indoor environments. A system named ILTIS has been developed by our cooperation partner IMST GmbH [see e.g. Schmidt, 2006]. It is planed to perform extensive testing of the system performance in the near future. UWB positioning systems can be employed either as permanent installations inside buildings or as mobile systems for situations where a precise indoor location system is required. Figure 2 shows such a mobile concept, e.g. for a rescue situation in the case of an emergency inside a building. Mobile base stations can be installed temporarilly around the building. Firefigthers and rescue personnel are carrying a

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[15] RFID-radar from Trolley Scan (Pty) Ltd., South Africa, see http://www.rfid-radar.com/.

[16] Ultra wide band (UWB) systems, which exploit bandwidths in excess of 1 GHz, are developed for high speed data transmission over short distances. It has been standardized in IEEE 802.15.3a and will be available soon worldwide; see http://www.ultrawidebandplanet.com/ for further information.

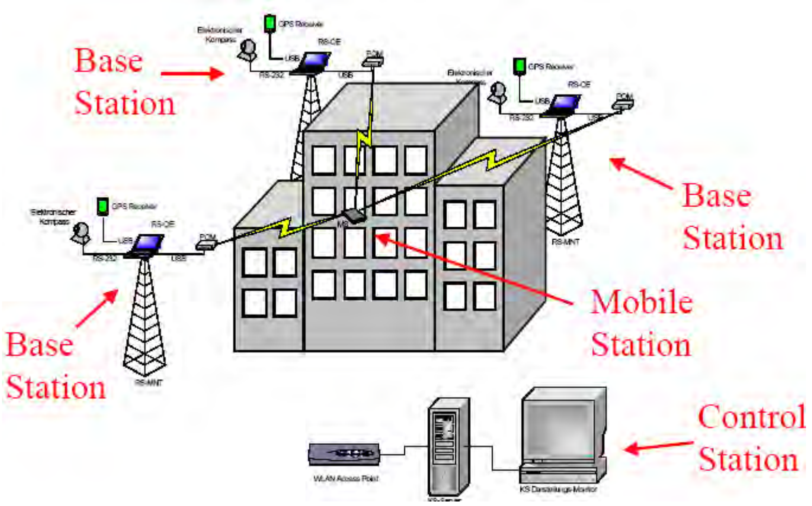

Fig. 2. Mobile concept for location determination inside buildings using temporary installation of UWB base stations around the building [after Romme, 2005]

mobile station which is located using TDoA and AoA measurements at the base stations. Their location is then transmitted to the control station.

Concerning UWB location systems, further research is also conducted in cooperation with the Department of Land Surveying and Geo-Informatics of the Hong Kong Polytechnic University in the research project "Investigation into Seamless Indoor and Outdoor Positioning Based on UWB-GNSS Integration[17]". In Hong Kong the 3.1 to 10.6 GHz band of UWB has been released by the Office of the Telecommunications Authority (OTFA) of the Hong Kong SAR government for technical trial already in mid 2005. So Hong Kong is an ideal location for the setting up of a test bed for UWB location systems. The main objective of this project is to investigate algorithms for low-cost seamless high precision outdoor and indoor positioning based on a fusion of the emerging technologies including UWB, WiFi and high sensitivity GPS (HSGPS[18]). To enable successful development of such an integrated system, it requires investigations into characteristics and performance of UWB in indoor and outdoor environments as well as UWB-GNSS integration algorithms.

Further research work will focus on the *improvement of dead reckoning* (*DR*). Despite of the advantages in MEMS[19]-based Inertial Navigation Systems (INS), their application in pedestrian positioning is still a challenge. Instead, most of the pedestrian positioning systems nowadays use a combination of digital compasses and gyros for heading determination and acclerometers for obtaining the distance travelled [see e.g Mezentsev et al., 2005; Renaudin et al., 2007; Retscher, 2007c] rather than low-cost INS to avoid the significant noises and biases from these low-cost sensors which result in very large drifts after short time when GPS is unavailable. On the other hand, the commonly used DR systems have also a main drawback, i.e, it is very difficult to determine the distance

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[17] Research project B-Q02F founded by the RGC Research Grant of the Hong Kong SAR Government (2006-2008).

[18] High Sensitivity GPS receivers use large banks of correlators and digital signal processing to search for GPS signals very quickly. This results in very fast times to first fix when the signals are at their normal levels, for example outdoors. When GPS signals are weak, for example indoors and in confined environments, the extra processing power can be used to integrate weak signals to the point where they can be used to provide a position or timing solution [Wikepedia, 2007b].

[19] MEMS stands for micro-electro-mechanical systems and is the technology of the very small devices that are merged at the nano-scale into "Nanoelectromechanical" Systems [Wikepedia, 2007c].

travelled and the position accurately from the pedestrian step detection when the pedestrian moves smoothly. In the NAVIO system, tri-axis accelerometers are mounted at the back of the user at the belt and it therefore requires a walk ‘with swaying hips’ to be able to detect the steps correctly and the step length has to be calibrated using GPS. Recent technological developments in MEMS accelerometers and steadily improving MEMS gyros technology, with the target of achieving 1°/hour gyro stability, however, would lead to improved low-cost INS in the next few year. Therefore their use should be investigated more in detail and a new integration algorithm to estimate the position accurately during smooth movements of the pedestrian developed. Grejner-Brzezinska et. al. [2007] have already proposed to use a MEMS IMU (Inertial Measurement Unit) together with a digital barometer, electronic compass, human pedometry and GPS to provide navigation and tracking of military and rescue ground personnel. In the project UCPNAVI[12] it is foreseen to purchase a low-cost INS and to integrate it with other DR sensors and GNSS. In this context also a cooperation with the School of Mathematical and Geospatial Science of the RMIT (Royal Melbourne Institute of Technology) University in Australia has been established to work together on the challenging task of improvement of pedestrian positioning using MEMS IMU’s. First tests of a newly developed module named MAXX5 integrating a GPS receiver, a low-cost INS and three magnetometers aligned with three orthogonal axes will be presented at an International Conference at the end of this year [see Zhu et al., 2007]. The system is a prototype developed by the Satellite Positioning and Tracking (SPOT) research group at RMIT University in collaboration with other research partners [Zhang et al., 2004]. It has been developed primary to monitor the movements of athletes as the INS provides a high sampling rate of 100 Hz. But of course it can also be employed for tracking of a walking pedestrian. The dimension of the module MAXX5 is approximately 8 × 5 × 4 cm (see Figure 3) and it is carried on the shoulder of the pedestrian. The already very small size of the MAXX5 GPS/INS module is also a milestone in the *miniaturization of the sensors and system components* for pedestrian tracking. But for the widespread use of pedestrian navigation systems in practice also a further reduction in size of high performance sensors has to be achieved, e.g. such as the high end barometric pressure sensor employed in the NAVIO system.

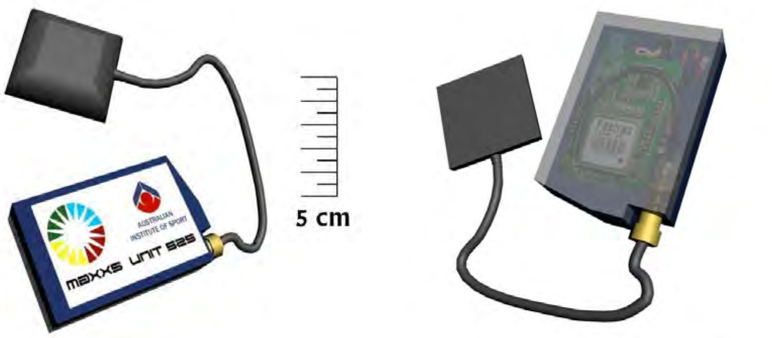

Fig. 3. The MAXX5 GPS/INS module for pedestrian tracking [after Zhu et al., 2007]

Performance tests reported in Zhu et al. [2007] showed that a user can be located with an average positioning accuracy of 4.3 m with a standard deviation of ± 2.2 m using the MAXX5 GPS/INS module if GPS is available and a new INS/GPS integration algorithm is employed. But one of the *main challenges in using MEMS-based IMU’s* can be formulated in the following question: What can be done if satellite positioning is not available and no continuous update of the sensor drift of the INS can be performed? Then an update of the drift rates using other absolute location methods (e.g. WiFi, UWB or RFID) has to be performed or new self calibration routines for the DR sensors have to be employed. Grejner-Brzezinska et. al. [2007] proposed to calibrate the DR observations (step length and step frequency from the MEMS-based IMU as well as the heading from the digital compass and the altitude from the barometer) under GPS signal blockage using the knowledge of the human locomotion model when GPS is available. In other words, a training mode under GPS availability is used to calibrate the human dynamics model (step length and step frequency) as well as the digital compass and barometer with artificial neural networks [see e.g. Wang et al., 2006] and fuzzy logic [see e.g. Abdel-Hamid et al., 2006] and the calibrated observations are then used in the DR navigation if GPS is unavailable. Training data that feed the artificial neural network or a fuzzy logic based adaptive knowledge systems are collected for each operator separately, and functions, such as step frequency, rate of step frequency, terrain slope, operator’s locomotion pattern (e.g., standing, walking, jogging, sprinting, climbing, etc.), as a function of sensor outputs are analyzed to form the fuzzy rules that are subsequently used in the actual DR navigation mode. This approach is very promising, but it is still in the development stage and further investigations are therefore required.

In our Extended Kalman filter (EKF) approach developed in NAVIO a loose coupling of the sensors was performed as the positions from GPS were integrated with DR measurements. As an alternative, tightly coupled EKF for the integration of the sensor observation at the measurement level have been developed. In this case, e.g. GPS carrier phase and pseudorange measurements in the double difference mode can be integrated with compass heading, and INS-derived position and attitude information as well as barometric height. As the scope of applications of the navigation technologies has expanded from the typical open sky environment (where GNSS is the primary navigation means) to indoor and confined environments, such as urban and underground settings, however, the traditional EKF approach to *multi-sensory data integration* may no longer be able to properly handle the often non-Gaussian and nonlinear measurement models and more complex dynamic models. As a result, nonlinear Bayesian Filters, such as Unscented Kalman Filter (UKF) [see e.g. Wan and van der Merwe, 2001] and Particle Filter (PF) [see e.g. Ristic et al., 2004], as well as nontraditional approaches to sensor integration and modeling, such as artificial neural networks [see e.g. Wang et al., 2006] and fuzzy logic [see e.g. Abdel-Hamid et al., 2006] are being introduced to navigation algorithms [Grejner-Brzezinska et. al., 2007]. One approach is to use a knowledge-based component for outlier detection in the observation data and the quality analysis and calibration of the multi-sensor system [see e.g. Thienelt et al., 2006]. Another strategy is to extend or even replace the EKF with an alternative solution, e.g. a Fuzzy Kalman Filter which distinguishes between a human locomotion model training mode and DR navigation mode [see Grejner-Brzezinska et. al., 2007]. Further investigation and development of suitable sensor fusion models is therefore a main research topic for the coming years.

The sensor integration at the measurement level enables also the further extension of positioning concepts. Consider the situation that pseudorange observations to only one or two GPS satellites are possible (which would not give a position fix in standalone GPS mode) and also ranges to ground based transponders (e.g. an active landmark equipped with a RFID tag) or transmitters (e.g. an WiFi access point or an UWB base station) at a particular location can be obtained. Then these observations should be used together to determine an absolute position fix. Mok and Lau [2001] proposed an algorithm that is able to estimate positions even with three or less satellites, i.e., the “*Minimum Range Error Algorithm*” (*MRERA*). MRERA was originally developed for vehicle tracking to locate vehicles in dense high-rise environments without the use of DR sensors. But it can also be employed for general geolocation positioning applications. The basic principle of MRERA is illustrated in Figure 4 (a) on the left. Consider that a series of “road points” with known coordinates in WGS84 are stored in a road network database. When travelling along a section of road and continuously receiving GPS signals from at least one satellite, the pseudorange observations and the geometric range computed from the known satellite and road point positions can be obtained. After applying proper error corrections[20] to the pseudorange data, the difference between the geometric range and the measured GPS pseudorange can be calculated. This range difference will vary depending on the distance of the GPS receiver from the road point. In other words, if the GPS user is travelling towards a particular road point, the range difference will decrease. The difference will reach its minimum value when the user is nearest to the road point, then increasing when the user is moving away from the road point. This phenomenon is illustrated in Figure 4 (b) on the right. Improvement of the MRERA is under investigation for it to be practically used to supplement the GPS alone method when less than four satellites are visible, or when the receiver-satellite geometry is poor (large DOP value). An integration of other wireless technolgies, such as WiFi and UWB, into MRERA was first proposed by Mok and Xia [2005]. In simulations it could be seen that an integration of GPS pseudoranges and ranges to ground transmitters can be performed under the MRERA. Apart from WiFi and UWB also ranges to active landmarks equipped with active RFID tags will be tested in the near future [see Mok et al., 2007]. The location of the active landmark serves then in the MRERA algorithm as the road point with known coordinates and the respective range to the landmark can be used together with the GPS pseudoranges for obtaining the position fix. This approach will be further investigated by the author under the umbrella of the research project “Investigation into Seamless Indoor and Outdoor Positioning Based on UWB-GNSS Integration[17]”. The concept is presented at an International Conference in September 2007 [see Retscher, 2007e].

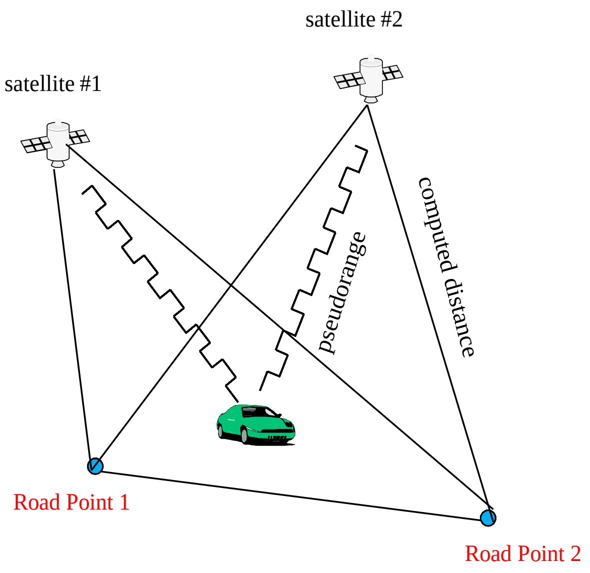

Fig. 4 (a). Principle of the MRERA approach showing a vehicle’s position between road points 1 and 2 [after Mok et al., 2007]

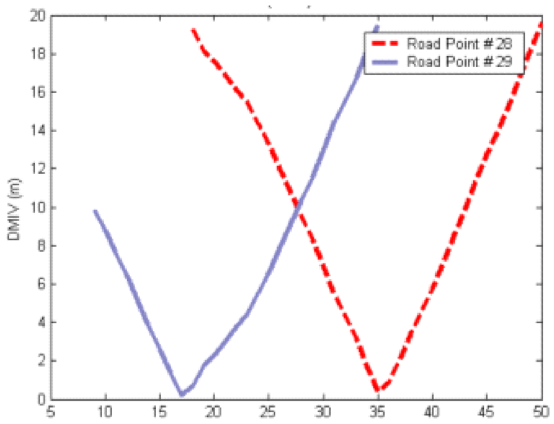

Fig. 4 (b). The minimum of the difference between the measured and the geometrical range to one satellite arises when the GPS receiver is nearest to the road point’s location [after Mok et al., 2007]

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[20] The major corrections include ionospheric, tropospheric, multipath and receiver clock errors.

A new emerging application which requires mobile positioning is node localization determination in *intelligent wireless sensor networks* (WSN)[21]. Wireless ad-hoc networks for high-speed mobile communications require an accurate positioning of the nodes and mobile devices in the network. Each node in a sensor network is typically equipped with a radio transceiver or other wireless communication device, a small microcontroller, and an energy source, usually a battery. Our research group is a partner investigator in the planned "Competence Center for Information and Communication Technologies (ICT)[22]" at the FTW (Forschungszentrum Telekommunikation Wien) in such an application in the field of strategic research on signal and information processing in WSN's where our expertise in indoor location technolgies and sensor fusion is brought in. For localization determination in WSN's, INS will be coupled with wireless systems such as WiFi, UWB, RFID and Bluetooth to meet the accuracy requirements of better than 3 m for node and sensor localization determination in indoor environments. The research in this field will be carried out in the next five years.

To summarize it can be said that a lot of improvement has been achieved already in terms of positioning accuracy and system performance in the field of personal navigation and location-based services in recent years. Our reasearch in this field has achieved already international recognition which is shown by invitations of the author to give seminars in this field of research at Universities and during international conferences. We will continue our work in the years to come at our University and in cooperation with other institutions. To increase the acceptance of pedestrian navigation systems and LBS by the public, however, not only the achievable location accuracy as well as the reliability of position determination and the integrity of the systems but also the practical suitability and the ease of use of these systems are important. The author believes that still a lot has to be done in this field of research in the coming years. Also the introduction of the future GALILIEO system and its services will have a significant impact for navigation systems. If GALILIEO and GPS (or other GNSS) will be augmented by alternative techniques and location sensors as shown by the author in his work, navigation and location-based services can be offered that will assist us in our daily life. Such services will be very useful for users who try to find their way in an unfamiliar environment no matter if it will be in an urban or a combined indoor/outdoor environment.

Günther Retscher

References

Abdel-Hamid W., T. Abdelazim, N. El-Sheimy, G. Lachapelle, 2006. Improvement of MEMS-IMU/GPS Performance Using Fuzzy Modeling, GPS Solutions, No. 10/06, pp. 1-11.

Balbach O., 2000. UMTS – Competing Navigation System and Supplemental Communication System to GNSS. in: Papers presented at ION GPS Meeting 2000, Salt Lake City, Utah, U.S.A., September 19-22, 2000.

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[21] A wireless sensor network (WSN) is a wireless network consisting of spatially distributed autonomous devices using sensors to cooperatively monitor physical or environmental conditions, such as temperature, sound, vibration, pressure, motion or pollutants, at different locations. Typical civilian application areas include environment and habitat monitoring, healthcare applications, home automation, and traffic control [Wikepedia, 2007d].

[22] See http://www.ict-proposal.at/ for further information.

CGALIES, 2001. Co-Ordination Group on Access to Location Information by Emergency Services. Work Package 1 Report, 2001, see http://www.telematica.de/cgalies/ (Last date accessed: November 2001).

Drane C., M. Macnaughtan, C. Scott, 1998. Positioning GSM Telephones. IEEE Communications Magazine, April 1998, pp. 46-59.

Duffett-Smith P. J., J. Craig, 2004. Matrix, and Enhanced Satellite Positioning, in: Papers presented at the 5th IEE International Conference on 3G Mobile Communication Technologies, London, UK, October 18-20, 2004, 4 pgs.

Finkenzeller K., 2002. RFID Handbook: Fundamentals and Application in Contactless Smart Cards and Identification, Carl Hanser Verlag, Munich, Germany.

Grejner-Brzezinska D., C. Toth, S. Moafipoor, 2007. Pedestrian Tracking and Navigation Using an Adaptive Knowledge System Based on Neural Networks, Journal of Applied Geodesy, Vol. 1, No. 3.

Identec Solutions, 2006. Intelligent Long Range® (ILR®) RFID System, Product Information, http://identecsolutions.com/ (Last date accessed: July 2007).

Krakiwsky E. J., 1991. GPS and Vehicle Location Navigation, GPS World, May 1991, pp. 50-53.

Krakiwsky E. J., J. Mc Lellan, 1995. Making GPS Even Better with Auxiliary Devices, GPS World, March 1995, pp. 46-53.

Kolodziej K.W., J. Hjelm, 2006. Local Positioning Systems: LBS Applications and Services, Taylor and Francis, Boca Raton, U.S.A.

Mezentsev O., G. Lachapelle, J. Collin, 2005. Pedestrian Dead Reckoning - a Solution to Navigation in GPS Signal Degraded Areas, Geomatica, Vol. 59, No. 2, pp. 175-182.

Mok E., L. Lau, 2001. GPS Vehicle Location Tracking in Dense High-Rise Environments with the Minimum Range ERror Algorithm (MRERA), in: Papers presented at the ION GPS 2001, Salt Lake City, Utah, U.S.A., September 11-14, 2001, CD-Rom Proceedings, pp. 2564-2570.

Mok E., G. Retscher, L. Lau, 2002. Development of an Event-Reporting Intelligent Vehicle Navigation System for Areas with Urban Canyons, Survey Review, Vol. 36, No. 284, April 2002, pp. 398-409.

Mok E., L. Xia, 2005. Strategies for Geolocation Optimization in Urban Regions, in: Papers presented at the International Symposium on GPS/GNSS, Hong Kong, December 8-10, 2005, CD-Rom Proceedings.

Mok E., G. Retscher, L. Xia, 2007. MRERA (Minimum Range Error Algorithm): RFID – GNSS Integration for Vehicle Navigation in Urban Canyons, in: Papers presented at the 5th Symposium on Mobile Mapping Technology, Padova, Italy, May 29-31, 2007, CD-Rom Proceedings, 7 pgs.

Renaudin V., O. Yalak, P. Tomé, 2007. Hybridization of MEMS and Assisted GPS for Pedestrian Navigation, Inside GNSS, January/February 2007, pp. 34-42.

Retscher G., 1995. Europäische Entwicklungen im Bereich der Navigation von Automobilen, Österreichische Zeitschrift für Vermessung und Geoinformation, VGI 3/95, pp. 120-126.

Retscher G., J. M. Koppensteiner, 1996. Die Rolle von GPS in europäischen Autonavigationssystemen, Vermessungswesen und Raumordnung, Ferd. Dümmler Verlag, Bonn, VR 58/2, pp. 186-197.

Retscher G., E. Mok, 2001. Integration of Mobile Phone Location Services into Intelligent GPS Vehicle Navigation Systems, in: Papers presented at the 3rd Workshop on Mobile Mapping Technology, Cairo, Egypt, January 3-5, 2001, CD-Rom Proceedings.

Retscher G., 2002a. Diskussion der Leistungsmerkmale von Systemen zur Positionsbestimmung mit Mobiltelefonen als Basis für Location Based Services (LBS), in: Kelnhofer F., M. Lechthaler, K. Brunner (Eds.): Geowissenschaftliche Mitteilungen, Schriftenreihe der Studienrichtung Vermessungswesen und Geoinformation, TU Wien, Heft 58, pp. 41-58.

Retscher G., 2002b. Einsatz von Location Based Services (LBS) als Navigationshilfe: Integration in moderne Navigationssysteme, Österreichische Zeitschrift für Vermessung und Geoinformation (VGI), Vol. 90, No. 1, pp. 2-12.

Retscher G., G. Skolaut, 2003. Untersuchung von Messsensoren zum Einsatz in Navigationssystemen für Fußgänger, Zeitschrift für Geodäsie, Geoinformation und Landmanagement (ZfV), 128. Jahrgang, Heft 2/2003, pp. 118-129.

Retscher G., E. Mok, 2004. Sensor Fusion and Integration using an Adapted Kalman Filter Approach for Modern Navigation Systems, Survey Review, Vol. 37, No. 292, April 2004, pp. 439-447.

Retscher G., M. Thienelt, 2004a. NAVIO – A Navigation and Guidance Service for Pedestrians, Journal of Global Positioning Systems, CPGPS, Vol. 3, No. 1-2, pp. 208-217.

Retscher G., M. Thienelt, 2004b. Die Zukunft des Einkaufens – Was können Geodäten dazu beitragen? Allgemeine Vermessungs-Nachrichten, Wichmann Verlag, Heidelberg, AVN 11/12, pp. 387-393.

Retscher G., 2005. A Knowledge-based Kalman Filter Approach for an Intelligent Pedestrian Navigation System, in: Papers presented at the ION GNSS 2005 Conference, Long Beach, California, U.S.A., September 13-16, 2005, CD-Rom Proceedings, pp. 1433-1443.

Retscher G., E. Mok, W.-Y. Yan, 2005. Performance Test of Location-based Services in Hong Kong, European Journal of Navigation, Vol. 3, No. 3, August 2005, pp. 22-27.

Retscher G., A. Kealy, 2006. Ubiquitous Positioning Technologies for Modern Intelligent Navigation Systems, The Journal of Navigation, Vol. 59, No. 1, January 2006, pp. 91-103.

Retscher G., M. Kistenich, 2006. Vergleich von Systemen zur Positionsbestimmung und Navigation in Gebäuden. Zeitschrift für Geodäsie, Geoinformation und Landmanagement (ZfV), 131. Jahrgang, Heft 1/2006, pp. 25-35.

Retscher G., E. Mok, 2006. Investigation and Testing of Location Systems Using WiFi in Indoor Environments, in: Papers presented at the IAIN/GNSS 2006 Conference, Jeju Island, South Korea, October 18-20, 2006, Vol. 2, pp. 83-88.

Retscher G., M. Thienelt, 2006. Test and Integration of Location Sensors for Position Determination in a Pedestrian Navigation System, in: Papers presented at the IAIN/GNSS 2006 Conference, Jeju Island, South Korea, October 18-20, 2006, Vol. 1, pp. 251-256.

Retscher G., K. Zhang, S. Zhang, Y. Wang, 2006. RFID and GNSS for Indoor and Outdoor Positioning - Two Different Case Studies. European Journal of Navigation, Vol. 4, No. 5, November 2006, pp. 49-54.

Retscher G., 2007a. A Knowledge-based Kalman Filter for an Intelligent Pedestrian Navigation System, Survey Review, Vol. 39, No. 306, October 2007.

Retscher G., 2007b. Augmentation of Indoor Positioning Systems with a Barometric Pressure Sensor for Direct Altitude Determination in a Multi-storey Building, Journal of Cartography and Geographic Information Science (CaGIS), Vol. 34, No. 4, October 2007.

Retscher G., 2007c. Test and Integration of Location Sensors for a Multi-sensor Personal Navigator, The Journal of Navigation, Vol. 60, No. 1, January 2007, pp 107-117.

Retscher G., 2007d. Investigations of Selected Systems for Indoor and Pedestrian Navigation, Österreichische Zeitschrift für Vermessung und Geoinformation (VGI), Vol. 95, No. 2, Special Issue: Austrian Contibutions to IUGG 2007, Perugia, Italy, pp. 166-172.

Retscher G., 2007e. Integration of RFID, GNSS and DR for Ubiquitous Positioning in Pedestrian Navigation, in: Papers presented at the ION GNSS 2007 Conference, Fort Worth, Texas, U.S.A., September 25-28, 2007, CD-Rom Proceedings.

Retscher G., E. Moser, D. Vredeveld, D. Heberling, J. Pamp, 2007. Performance and Accuracy Test of a WiFi Indoor Positioning System, Journal of Applied Geodesy, Vol. 1, No. 2, pp. 103-110.

Ristic B., S. Arulampalam, N. Gordon, 2004. Beyond the Kalman Filter: Particle Filters for Tracking Applications, 1st edition, Artech House, Boston, London.

Romme J, 2005. A Low Datarate Localization System, Presentation at the Workshop on UWB for Sensor Networks UWB4SN 2005, Lausanne, Switzerland, November 4, 2005.

Schiller J., A. Voisard (Eds.), 2004. Location-Based Services, Morgan Kaufmann Publishers, San Francisco, U.S.A.

Schmidt N., 2006. ILTIS – Indoor Location Tracking and Information System: Ein System zur Lokalisierung und Kommunikation mittels Ultrabreitbandfunk, IMST GmbH, Kamp-Lintfort, Germany.

Thienelt M., A. Eichhorn, A. Reiterer, 2005. Konzept eines wissensbasierten Kalman-Filters für die Fußgängerortung (WiKaF), Österreichische Zeitschrift für Vermessung und Geoinformation (VGI), Vol. 93, No. 2, pp. 96-104.

Thienelt M., A. Eichhorn, A. Reiterer, G. Roberts, 2006. Pedestrian Positioning without Map Matching Methods – Prototype of a Knowledge-based Kalman Filter, in: Papers presented at the Joint symposium of Seoul Metropolitan Fora and 2nd International Workshop on Ubiquitous Pervasive and Internet Mapping, Seoul, South Korea, October 23-25, 2006, pp. 148-156.

Wan E. A., R. van der Merwe, 2001. Kalman Filtering and Neural Networks, Chapter. 7: The Unscented Kalman Filter, Wiley Publishing, Eds. S. Haykin, 50 pgs.

Wang J. J., J. Wang, D. Sinclair, L. Watts, 2006. A Neural Network and Kalman Filter Hybrid Approach for GPS/INS Integration, in: Papers presented at the IAIN/GNSS 2006 Conference, Jeju Island, South Korea, October 18-20, 2006, Vol. 1, pp. 277-282.

Wikepedia, 2007a. Ubiquitous Computing, see http://en.wikipedia.org/wiki/Ubiquitous_computing (Last date accessed: July 2007).

Wikepedia, 2007b. High Sensitivity GPS, see http://en.wikipedia.org/wiki/High_Sensitivity_GPS (Last date accessed: July 2007).

Wikepedia, 2007c. Microelectromechanical Systems, see http://en.wikipedia.org/wiki/MEMS (Last date accessed: July 2007).

Wikepedia, 2007d. Wireless Sensor Network, see http://en.wikipedia.org/wiki/Wireless_sensor_networks (Last date accessed: July 2007).

Zhang K., R. Deakin, R. Grenfell, Y. Li, J. Zhang, W. N. Cameron, D. M. Silcock, 2004. GNSS for Sports – Sailing and Rowing Perspectives, in: Papers presented at the GNSS Sydney 2004 Conference, Sydney, Australia, December 6-8, 2004, CD-Rom Proceedings.

Zhu M., K. Zhang, F. Wu, W. Cartwright, G. Retscher, 2007. An Investigation of Pedestrian Positioning Algorithms Based on Integrated Low-cost INS, GPS and Magnetometer, in: Papers presented at the IGNSS 2007 Conference, Sydney, Australia, December 4-6, 2007, CD-Rom Proceedings, 11 pgs.

Development of an Event-Reporting Intelligent Vehicle Navigation System for Areas with Urban Canyons

Esmond Mok, Günther Retscher and Lawrence Lau

Abstract

Common vehicle navigation systems employ mostly GPS satellite positioning to track the vehicle's position and velocity. The tracked position can be dynamically shown on a digital map or automatic route guidance can be performed. So-called "Intelligent GPS Vehicle Navigation Systems", simply speaking, are extensions of common GPS vehicle navigation systems. It can be said, that they are GPS vehicle positioning systems with embedded intelligence. From the authors' point of view, an intelligent system should be able to detect the changes of the real-world situation and to give an appropriate response to the changes. Therefore, an Intelligent GPS Navigation System should have all the basic functionality of a common GPS navigation system, and be able to detect and react to the conditions that are of concern of the driver or the vehicle manager. To achieve this, an intelligent GPS navigation system should be integrated with different types of sensors and communication devices that are able to monitor and perform event reporting to the vehicle's real-word situation. Hence, event reporting is an essential component of an Intelligent Vehicle Navigation System (IVNS). With regard to the navigation part of the system, it is essential that the vehicle’s trajectory can be continuously tracked to provide necessary guidance for the driver. However, for GPS-alone systems a reliable position determination in urban canyons may not always be possible, therefore it is necessary to investigate the integration of other vehicle tracking devices and methods.

After the discussion of the potential applications of an event reporting IVNS, a more detailed description of a prototype system will be given. Such a system is being developed in a research project at the Department of Land Surveying and Geo-informatics of the Hong Kong Polytechnic University. Finally, field test results of the prototype IVNS conducted in Hong Kong are presented and the integration of wireless location services for positioning and a new GPS-alone position tracking method for urban canyons are briefly discussed.

Keywords: Intelligent Vehicle Navigation Systems (IVNS), GPS, Dead Reckoning (DR), Event Reporting, IQEvent Engine (IQEE), Alternative Positioning Methods, Wireless Location Services, Network-based Positioning Techniques, Global System for Mobile Communication (GMS), Universal Mobile Telecommunication Service (UMTS)

1 Introduction

With the integration of GPS more than one decade ago [see e.g. Krakiwsky, 1991], modern vehicle navigation systems have developed and their application has become quite popular with professional and private users. GPS for position determination in vehicle navigation systems in stand alone mode only works well for open areas. In the case of obstruction of the satellite-receiver visibility, either the position accuracy is bad or no position determination is possible. Especially in cities with high-rise buildings, the satellite visibility is a very critical issue for vehicle navigation systems. Therefore GPS and other positioning techniques such as dead reckoning (DR) are combined with map matching in most of the systems.

An "Intelligent GPS Navigation System" (IVNS) should have all the basic functionality of a GPS navigation system, and be able to detect and react to the conditions that are of concern of the driver. For example, if the water or fuel level is lower than an acceptable threshold, or if the vehicle is unexpectedly outside a pre-defined area, a warning message will be sent to the control office. To achieve this, an intelligent GPS navigation system must be integrated with different types of sensors and radio communication devices to monitor and respond to the real-word situation.

With regard to telecommunications, truck radios may be used. However, this approach involves high power radio transmission, and have very restricted licensing control. They are normally used by companies requiring control of a large number of vehicles, such as bus companies or for fleet management. For the management of a single or small number of vehicles, it is more appropriate to use the event reporting approach.

Although the current GSM (Global System for Mobile Communication) Short Message Service (SMS) is popularly used as a means for sending messages and reports, the airtime charge can be high. Its application is therefore not economical for continuous communication. The concept of event reporting can reduce the telecommunication cost down to an affordable level, since reports are only sent under the conditions specified by vehicle drivers or vehicle managers. For example, when the vehicle is outside the pre-defined region, or if an emergency button is triggered, the status and position of the vehicle will be sent to the control office.

2 Potential Applications of Event-Reporting IVNS

Here, potential applications of event reporting IVNS will be highlighted and analyzed. Most of the systems are still at the development stage, but governmental and private users in many countries commonly discuss their applications.

2.1 Electronic Toll Collection (ETC)

There are a number of suggestions on the design of Road Pricing or Electronic Toll Collection (ETC) systems; one common suggestion is the use of a GPS-based IVNS and another is the use of an automatic toll collection system based on wireless communication. If a wireless Intelligent Card (IC) is installed in a vehicle and the car is approaching the tollbooth, the toll will be paid automatically through radio communication between the IC and the ETC terminal [see e.g. Watanabe, 1999]. Compared to the IC card ETC system, an IVNS-based system has some advantages. In this case, the real-time position of the vehicle can be continuously monitored by GPS. If the vehicle enters or leaves the pre-defined pay-toll regions, a report which may include the vehicle's identification number, time of entering and leaving regions, will either be sent to the control office, or stored in a memory device for later downloading. This concept is illustrated in Figure 1. Drivers can pay tolls through this automatic reporting system without the need to stop at tollbooths, hence it helps to save energy and reduce air pollution. The system does not require roadside installations and tollbooths at fixed locations.

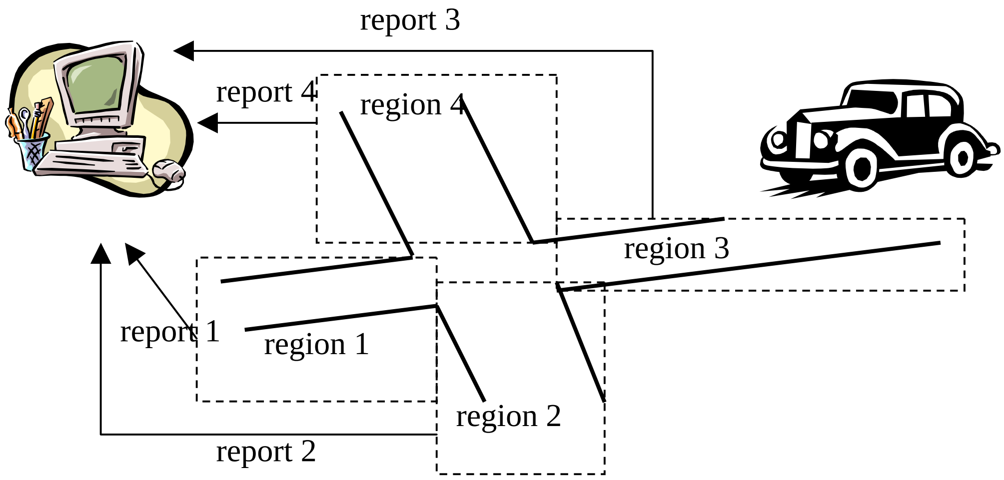


Fig. 1. Event-reporting IVNS applied to Electronic Toll Collection (ETC)

2.2 Monitoring of Vehicular Movements

To monitor a small number of vehicles, e.g. three or four vehicles, some companies may want to set up a small-scale vehicle monitoring system where the demand for real-time location of their vehicles may not be as essential and critical as for emergency services. Furthermore, the use of trunked radio communication seems not to be practicable because of the restricted licensing control on high power radio transmissions. The event reporting IVNS could be a solution for such a small-scale vehicle monitoring system.

2.3 Security Control

An IVNS can be interfaced with different sensors for detecting anomalies of the vehicle condition. It is possible to set up a user-defined intelligent security-reporting system, e.g., in cases when the door has been unexpectedly unlocked, or the GPS navigated position of the vehicle is outside a pre-defined zone, indicating possible occurrence of theft. In the case that a robbery has occurred in a vehicle, another possible option would be that the driver can activate a button to send an alarm to the control office for emergency assistance. Such an interface can be seen in Figure 3 (b).

2.4 Car Safety Control

By integrating multi-sensors, users can monitor the status of a vehicle. For example, if the water or fuel level is lower than an acceptable threshold, or if the temperature of the engine of the vehicle is higher than an acceptable temperature, an event (e.g. an alarm) and report will be sent to the driver and/or the control office. This can avoid the occurrence of accidents due to malfunction of the vehicle.

3 Development of a Prototype of an Event-Reporting IVNS

A prototype of an event-reporting IVNS has been developed. It features two main parts. The first part is the satellite navigation system; the second part is the event-reporting communication system.

3.1 Main System Components

The hardware used is Trimble's CrossCheck XR GPS receiver. The system consists of the satellite positioning hardware as well as an event-reporting communication component. Its small size has the advantage that it can be conveniently placed anywhere inside the vehicle (see Figure 2).

A GPS antenna is connected to the GPS Antenna port and a GSM modem is connected to the radio port. This enables event reports to be sent by the mobile phone's GSM SMS (Short Message Service) technology. Configuration of the CrossCheck receiver is achieved by connecting the MDT/RTCM port to a PC. The RTCM standard is employed for receiving differential GPS (DGPS) correction data for more precise position determination. If Dead Reckoning (DR) sensors are integrated into the system, the DR's output would be connected to the Heading Sensor port. The digital I/O port, when connected with external inputs or outputs, can control the activation of the sending of event reports if pre-set sensor conditions are detected. Finally, the power port is connected to the car battery. A Power divider can provide power supply for the CrossCheck XR, the GSM modem, and a ProBeacon receiver. The ProBeacon receiver is used if the DGPS positioning technique is employed.

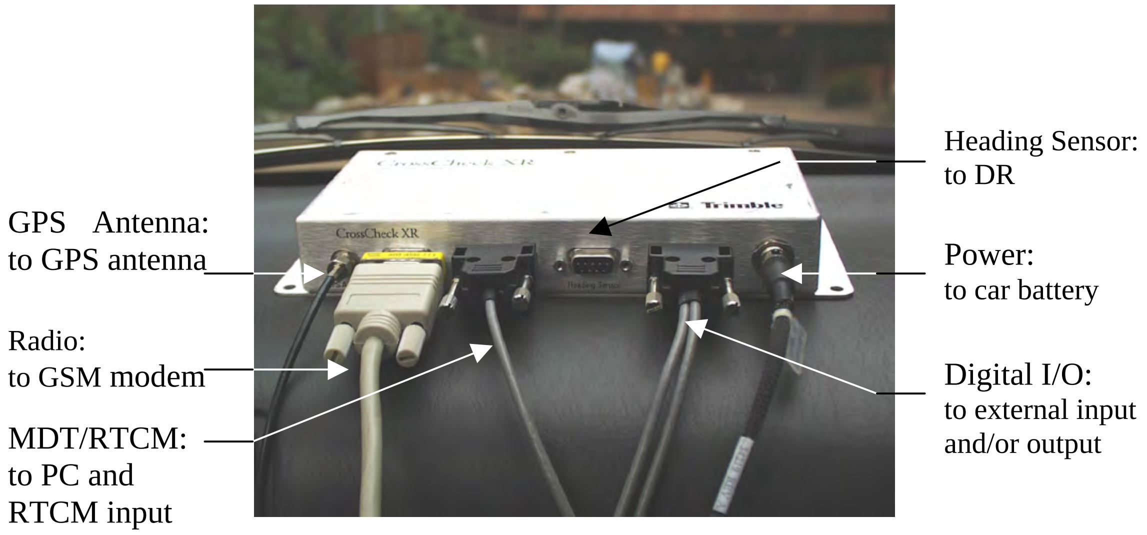


Fig. 2. Ports and connections of Trimble CrossCheck XR

The employed Wavecom GSM modem is a radio communication device capable of transmitting event reports using GSM's SMS. To enable communication between the vehicle and the control office, two Wavecom GSM modems are necessary. With both GSM SIM cards inserted into the modem, one is connected to the computer situated at the control office, another one is connected at the GPS receiver side.

For the program development MapObjects from ESRI is employed. The software package is a GIS developer's tool which consists of an ActiveX Control (OCX). Once installed, a wide variety of GIS functions in the form of ActiveX Automation Objects can be called in different popular programming environments such as Visual C++, Visual Basic and Delphi [ESRI, 1998]. Another advantage is that, once the program is compiled, the executable (*.EXE) file can be run without the presence of MapObjects and other ESRI products [ESRI, 1999].

3.2 Event Activation Methods

Figs. 3 (a) and (b) show two event activation methods. The first one is a trigger used for detecting the unexpected opening of a vehicle door (Figure 3 (a)), and the second a trigger used as emergency button (Figure 3 (b)). A change of the state of the buttons will activate the system to send an event report from the vehicle to the control office.

Fig. 3 (a). Trigger for detecting unexpected door opening

Fig. 3 (b). Emergency buttons

CrossCheck XR contains many event-driven functionalities, including the reception of signals from external sensors and the activation of events; giving pre-defined responses to events, and making a phone call to specified numbers. How CrossCheck XR will react to the pre-defined conditions and transmit a TAIP (Trimble ASCII Interface Protocol) is subject to proper configuration of Trimble's IQEvent Engine (IQEE). Once the hardware and software have been installed and configured, the system operates automatically to report events except when the users want to modify or add events. The IQEE menu window can be seen in Figure 6.

Event reports in short message format can be received and read by any GSM device. Since the event reports are in TAIP code, the interpretation of the TAIP code is required to enable the receiver side to understand the actual meaning of the message.

The program "Navigator 1.0" has been developed to perform the interpretation of the received event reports and to display the vehicle positions on a digital map. The flow chart of Navigator 1.0 is shown in Figure 4.

Further information on the hardware and software components used to develop the navigation system engine can be found in Mok et al. [2000] or Mok and Lau [2000].

4 System Testing and First Results

Two different tests were carried out. The first was a field test of the GPS navigation system, and the second test of the event reporting. In the following, the main results of the field tests are summarized.

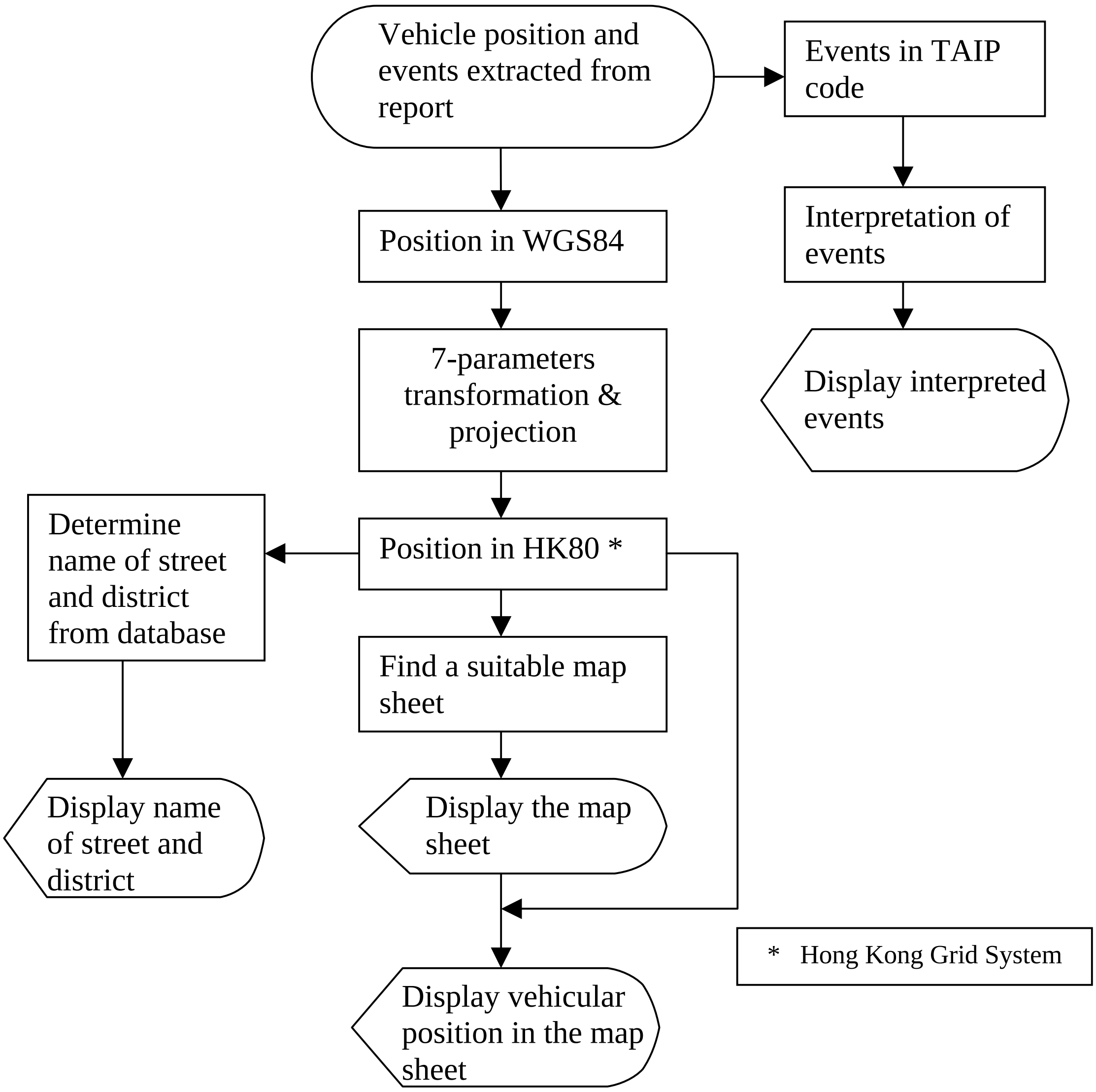


Fig. 4. Flow chart of Navigator software

4.1 Test of GPS Navigation System

A series of field tests were carried out with the prototype IVNS on main roads at Central District, Wan Chai and North Point of Hong Kong Island. In these tests, the dead reckoning (DR) system was not used to show the condition at some locations with insufficient satellite visibility, and where large DR accumulation errors may occur during position fixing. Typical test results are shown in Figs. 5.

Figure 5 (a) is a picture taken in the Central District of Hong Kong, showing how easily satellite signals can be obstructed in this area by dense high-rise buildings, causing impossible or incorrect position determination with satellites. The situation is even worse in the area of Wan Chai. The results shown in Figure 5 (b) for the Central District indicate that the satellite fixed positions are quite scattered, and some positions were incorrectly determined. However, the trend of the trajectory is still traceable. Better position fixing results can be achieved in the area of North Point (Figure 5 (d)), where the Victoria Harbor in the north of the road provides free sky visibility. Figure 5 (c) shows the worst result which is obtained in the Wan Chai area. Because of serious canyon effects, a large percentage of the position fixing was impossible or incorrect. Under this condition, the combination with alternative positioning techniques such as the use of wireless location services (see Appendix) or radio beacon systems [Mok et al., 2000] in combination with Kalman filtering and map matching would be the solution.

Fig. 5 (a). A scene along a main road of the Central District of Hong Kong

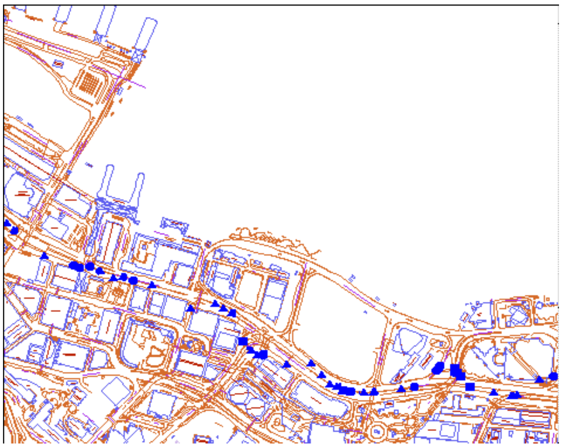


Fig. 5 (b). Central District

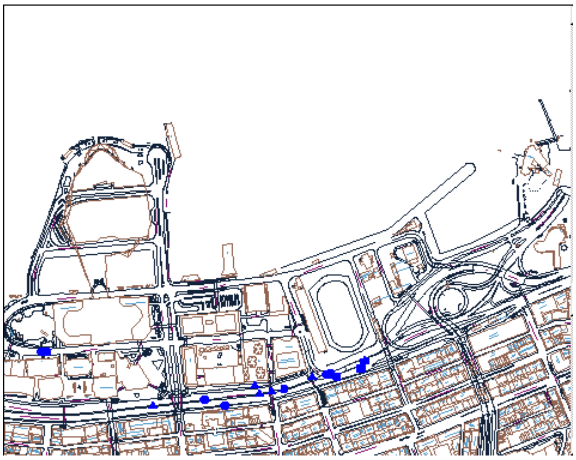


Fig. 5 (c). Wan Chai

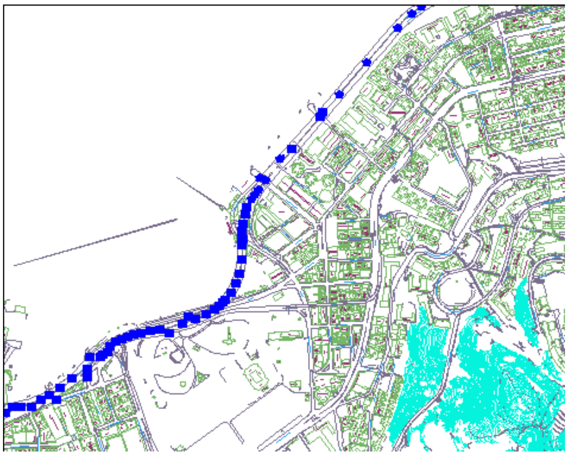
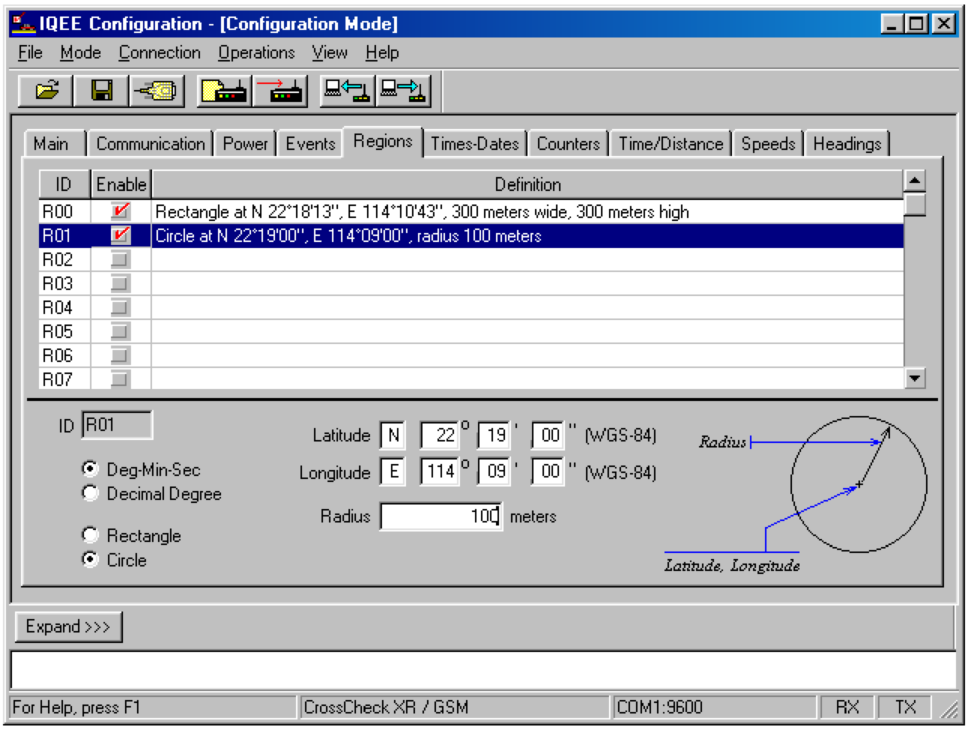


Fig. 5 (d). North Point

4.2 Event-Reporting Test

Two pre-defined regions were set as shown in Figure 6, with their identification given as R00 and R01. The first region R00 is a square with the coordinates of the left bottom corner, the width and the height defined as shown in the figure. The second region R01 is a circle with the coordinates of the centre and the radius defined as shown in the figure.

Event reporting is more cost effective than continuous or periodic reporting, since the transmission of reports is necessary only when significant events occur using short messages (SMS) at low costs (e.g. HKD 1.00 or less for one SMS in the current Hong Kong GSM network). The General Packet Radio Service (GPRS) mobile phone technology has been launched recently in Hong Kong GSM networks. In the near future, other cheaper communication media or technologies such as 3G mobile communication (in the Universal Mobile Telecommunication Service UMTS network) will become popular. By that time continuous reporting of vehicle position using mobile communications at an affordable and acceptable cost will be possible.



ID	Enable	Definition
R00	☑	Rectangle at N 22°18'13", E 114°10'43", 300 meters wide, 300 meters high
R01	☑	Circle at N 22°19'00", E 114°09'00", radius 100 meters
R02	☐	
R03	☐	
R04	☐	
R05	☐	
R06	☐	
R07	☐	

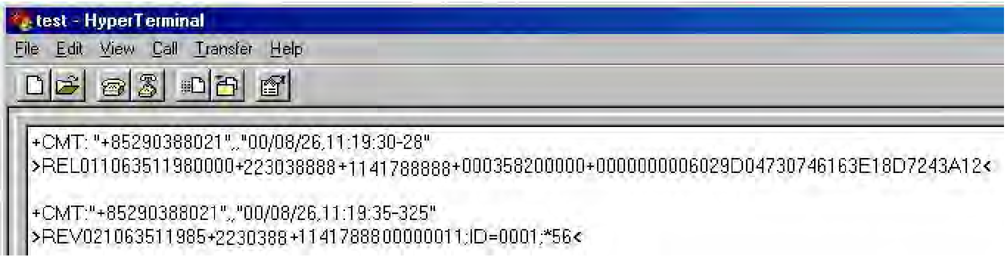
ID: R01

● Deg-Min-Sec
○ Decimal Degree

○ Rectangle
● Circle

Latitude: N 22° 19' 00" (WGS-84)
Longitude: E 114° 09' 00" (WGS-84)
Radius: 100 meters

Fig. 6. Setting of regions using IQEvent Engine (IQEE)



```
+CMT: "+85290388021",,"00/08/26,11:19:30-28"
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+CMT:"+85290388021",,"00/08/26,11:19:35-325"
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```

Fig. 7. Region event report

5 Concluding Remarks and Outlook

The results of the field test of the GPS navigation system and the event-reporting show that the developed prototype of an event-reporting IVNS is successful in performing the required functions. The field tests and previous tests carried out by Chao et al. [1999] have proven how difficult position fixing with navigation satellites would be in urban areas. The problem of satellite visibility due to canyon effect is very troublesome for GPS positioning in a city such as Hong Kong. Satellite visibility conditions can generally be classified as follows:

1. Condition One: Sufficient number of satellites are available for position determination.
2. Condition Two: In a short period of time, there are insufficient number of satellites available for position determination.
3. Condition Three: In a long period of time, there are insufficient number of satellites available for position determination.

The degree of difficulty in position determination under each of the above conditions can vary quite significantly.

Condition one is quite straightforward. The GPS derived coordinates will be automatically computed by the GPS receiver firmware. The DGPS solution can normally provide accuracies at the 2 to 5 m level, under the assumption that the satellite-receiver geometry is good (e.g. GDOP < 6) and no serious multipath effects occur.

In condition two, if an insufficient number of satellites is available in a short period of time, the missing positional information can be estimated as follows: GPS derived positions in this period will be missing. Then the positions will be determined by a combined GPS/Dead Reckoning (DR) system [see e.g. He et al., 1999]. A simple low-cost DR system usually consists of a digital compass and an odometer. The DR's heading information can be seriously distorted by sources of changing magnetic fields in the vehicle surrounding environment, and the reliability of the odometer-derived distance would be reduced if the travel distance is long due to accumulation of errors. Therefore they can only be used for a very short time period to bridge GPS outages. In the situation that large DR accumulation errors occur under this condition, adoption of a suitable Kalman filter for trajectory determination, and a map matching approach to force the trajectory on the correct road alignment is suggested.

For condition three, where insufficient numbers of satellites are available for a longer period of time, the combination of wireless location techniques, map matching and Kalman filter was suggested in e.g. Mok et al [2000], Retscher and Mok [2001]. Further information concerning wireless positioning techniques and their integration in vehicle navigation systems are given in the Appendix.

Mok and Lau [2001] further proposed the Minimum Range ERror Algorithm (MRERA) to track vehicle’s position under this condition. This algorithm makes full use of the coordinate information available on digital maps, and GPS code range measurement data to identify which road section the vehicle is located.

The design of a low-cost IVNS suitable for urban canyons is under development. This includes investigation of suitable position prediction and filtering models, map matching methods, implementation of MRERA, and correction models for the integration of a low-cost heading sensor and odometer. Such system integration requires refinements through continuous field tests and verification of positioning reliability in urban canyons. Performance analysis of the system and details on field test results will be presented elsewhere.

Acknowledgements

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Appendix: Integration of Wireless Location Services

A.1 Principle of Operation

A straightforward method for location determination in wireless networks is the so-called Cell of Origin (CoO) technique. Using CoO, the cell area of the wireless network is used as the location identification of the caller and therefore positioning accuracy depends upon the size of the cell (i.e., down to 150 m in urban areas). As it requires no modification to the handset or networks, the CoO is able to be used as positioning method for existing subscribers and therefore is widely deployed in wireless networks today. For most services, however, the positioning accuracy is not sufficient enough. Therefore the European Telecommunications Standards Institute (ETSI) and the American National Standards Institute (ANSI) recently ratified three wireless location services which operators could use in addition to the cell of origin technique for location dependent services. These were:

- Assisted GPS (A-GPS) or GNSS,
- Enhanced Observed Time Difference (E-OTD), and
- Time of Arrival (ToA).

In terms of implementation, GPS requires additional equipment or modification to mobile station (i.e., the handset); E-OTD and ToA require mainly network station modification (modern handsets do not require hardware modification; for E-OTD software modification in the handset is required) [see also Mobile Lifestream, 2000]. In general, the system implementation for location-based services in the network architecture can be categorised into 3 groups, i.e.,

- Network-based positioning techniques,
- Handset-based positioning techniques, and
- Hybrid positioning techniques.

Using network-based positioning techniques, positioning is done with signals and hardware only of the wireless system. Typical examples for network-based positioning techniques are the above named ToA and E-OTD techniques. Their geometrical principles are based on classical terrestrial navigation techniques [Retscher and Mok, 2001]. For handset-based positioning techniques an independent positioning system (e.g. GPS or GNSS, DGPS) is integrated into the handset. Hybrid positioning techniques combine both technologies using several independent positioning systems (e.g. GPS or GNSS, ToA or E-OTD etc.). Further information regarding these technologies can be found in 3GPP [1999], Balbach [2000], Drane et al. [1998], Hein et al. [2000], and Sage [2001].

A.2 Integration Concept

It follows from the specifications of wireless location services given by manufacturers that suitable network-based positioning techniques will soon be available to provide the possibility for continuous position determination in areas with a high network density. Therefore these services should be integrated in common vehicle navigation systems using GPS and/or DR sensors (i.e., rate gyroscope, digital compass, odometer and accelerometer) to increase the reliability of absolute position determination in urban canyons where no GPS positioning is possible. In most common navigation systems, however, not an integrated position determination is performed. The resulting trajectory is determined mainly based on the dead reckoning observations and GPS is only used for updating and resolving the systematic error growth of the DR observations [see e.g. Retscher, 1995]. With the following approach a real mathematical integration of all available observations can be achieved.

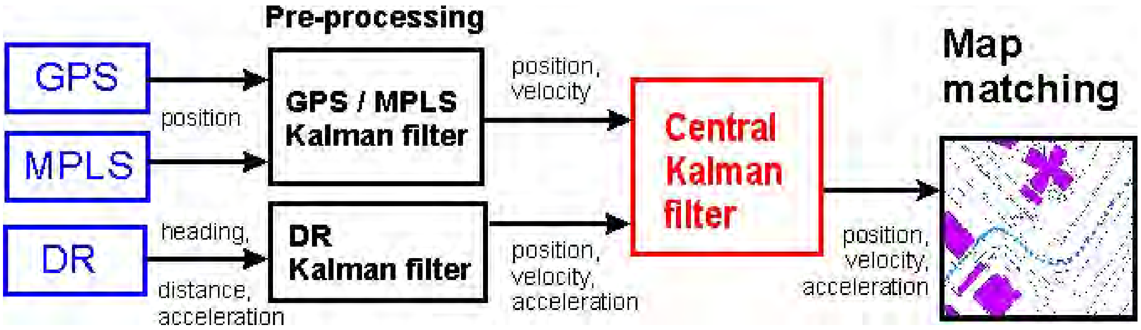

Fig. 8. Integration concept using a cascaded Kalman filter system

In this approach (see Figure 8), the determination of the trajectory of the vehicle is carried out by a cascaded filter system which is divided into a pre-processing step followed by a central Kalman filter. This approach has been applied by Sternberg [see Sternberg et al., 1998; Sternberg et al., 1999] for the trajectory determination of a mobile mapping system to integrate GPS and INS observations. For our application it can be adapted to integrate GPS and wireless or mobile phone location service (MPLS) observations with the dead reckoning (DR) measurements. In a pre-processing step the observations of the sensors are corrected or converted and smoothed in separate Kalman filters. Thereby the positions derived from GPS or MPLS are used as input values for the GPS/MPLS Kalman filter; and the heading angle from the gyroscope and digital compass, the travelled distance in direction of motion from the odometer and the acceleration from the accelerometer for the DR Kalman filter respectively. The observation of the MPLS will be used to replace the GPS measurements during long periods where an insufficient number of satellites is available for the position determination. The filtered positions and velocity of the GPS or MPLS from the pre-processing step; and the relative positions, the velocity and acceleration from the DR are transferred as pseudo-observations to the central Kalman filter. In this filter the position, velocity and acceleration are estimated directly as components of the state vector representing the final trajectory of the vehicle. Finally, the resulting vehicle trajectory is matched to the digital road map.

References

3GPP, 1999. 3rd Generation Partnership Project (3GPP): Technical Specification Group Radio Access Network, Stage 2 Functional Specification of Location Services in UTRAN, Paper No. 3G TS 25.305, see also http://www.3gpp.org/TSG/status_list/Oct_status_list.htm (Last date accessed: May 2001).

Balbach O., 2000. UMTS – Competing Navigation System and Supplemental Communication System to GNSS, in: Papers presented at ION GPS Meeting 2000, Salt Lake City, Utah, U.S.A., September 19-22, 2000.

Chao C.H., Y.Q. Chen, X.L. Ding, Z.L. Li, 1999. Vehicle Positioning in Very Dense Urban Areas: How Modern Technologies Fare in Hong Kong, The First Hong Kong Symposium on Satellite Positioning System Applications, Hong Kong, December 1999, pp. 13-22.

Drane C., M. Macnaughtan, C. Scott, 1998. Positioning GSM Telephones, IEEE Communications Magazine, April 1998, pp. 46-59.

ESRI, 1998. MapObjects, Embeddable GIS and Mapping Components for Application Developers, Product Information.

ESRI, 1999. Building Applications with MapObjects, Product Information.

He X., T. I. Fossen, Y. Q. Chen, 1999. Development of a Low-Cost DGPS/DR System for Vehicle Tracking, in: Papers presented at the International Workshop on Mobile Mapping Technology, Bangkok, Thailand, April 21-23, 1999, pp. 7B.4.1-7B.4.12.

Hein G., B. Eissfeller, V. Oehler, J. O. Winkel, 2000. Synergies Between Satellite Navigation and Location Services of Terrestrial Mobile Communication, in: Papers presented at ION GPS Meeting 2000, Salt Lake City, Utah, U.S.A., September 19-22, 2000.

Krakiwsky E. J., 1991. GPS and Vehicle Location and Navigation, GPS World, May 1991, pp. 50-53.

Mok E., G. Retscher, Y.-Q. Chen, 2000. Conceptual Design of an Intelligent GPS Vehicle Navigation System Suitable for Hong Kong, HKIS Journal, Vol. 11, Issue 3, September 2000, pp 4 - 13.

Mok E., L. Lau, 2000. A Prototype of Event-Reporting Intelligent Vehicle Navigation System, in: Papers presented at the 5th Meeting of the Hong Kong Society of Transportation Studies “Transportation Science and Technology in the 21st Century, Hong Kong, December 2, 2000, pp. 282-295.

Mok E., L. Lau, 2001. GPS vehicle location tracking with the Minimum Range ERror Algorithm (MRERA), in: Papers presented at ION GPS 2001, Salt Lake City, Utah, U.S.A., September 11-14, 2001.

Retscher G., 1995. Europäische Entwicklungen im Bereich der Navigation von Automobilen. Österreichische Zeitschrift für Vermessung und Geoinformation, VGI 3/95, pp. 120-126.

Retscher G., E. Mok, 2001. Integration of Mobile Phone Location Services into Intelligent GPS Vehicle Navigation Systems, in: Papers presented at the 3rd Workshop on Mobile Mapping Technology, Cairo, Egypt, January 3-5, 2001.

Sage A., 2001. Future Positioning Technologys in the Application to the Automotive Sector. The Journal of Navigation, Vol. 54, No. 3, pp. 321-328.

Sternberg H., W. Caspary, H. Heister, 1998. Determination of the Trajectory Surveyed by the Mobile Surveying System KiSS, in: Papers presented at the Symposium Geodesy for Geotechnical and Structural Engineering, Eisenstadt, Austria, April 20-22, 1998, pp. 361-366.

Sternberg H., W. Caspary, H. Heister, 1999. Filteralgorithms for Optimal Determination of Position and Attitude of the Mobile Mapping System KiSS, in: Papers presented at the International Workshop on Mobile Mapping Technology, Bangkok, Thailand, April 21-23, 1999, pp. 2.2.1-2.2.6.

Trimble, 1998. Cross Check XR. Product Information, see also http://www.trimble.com/gps/index.htm (Last date accessed: May 2001).

Watanabe K., 1999. Latest trends and future prospects of ITS, in: Papers presented at the Asia-Pacific Electronics Symposium 1999 and Intelligent Transport System Technologies Forum, Hong Kong, October 13-15, 1999, pp. 144-151.

Sensor Fusion and Integration using an Adapted Kalman Filter Approach for Modern Navigation Systems

Günther Retscher and Esmond Mok

Abstract

Modern navigation systems require the integration of different sensors that are either employed as primary navigation method (e.g. dead reckoning in car navigation) or to provide position information at regular time intervals (e.g. satellite based positioning for providing a start position and regular absolute position updates) as well as additional backup sensors. In most common systems, however, sensors are mainly employed in a stand-alone mode and no integrated position determination is performed. In our study, a new sensor fusion model based on an adapted Kalman filter has been developed to obtain an optimal estimate from the measurements of all available sensors. The concept for the integration and combined position determination has been employed for the combination of observations of GPS, wireless or mobile phone location services (MPLS) and dead reckoning (DR) sensors employed in vehicle navigation systems. In the following, it has been used for pedestrian navigation and guidance. The results of simulation studies are presented in the paper. The concept can also be extended to vehicle navigation in dense high-rise urban environments, where positioning problems due to blockage of GPS signals could be solved either by DR prediction or updating with MPLS (where higher positioning accuracy is expected to be achieved using the 3G network), and the combination of the two.

1 Introduction

The sensors employed in modern navigation systems can be classified into relative and absolute sensors. Relative or so-called DR (dead reckoning) sensors are employed for continuous position determination from a given start position. Typical DR sensors are the rate gyroscope, digital compass, odometer and accelerometer. Absolute position determination is required to provide the start position and position updates at regular intervals to counteract the error growth of the DR sensors. In most systems, GPS is employed as primary absolute position sensor. To increase the reliability of absolute position determination in urban canyons, where no GPS positioning is possible, other absolute position sensors such as wireless or mobile phone location services (MPLS) can be integrated.

2 Development of a Multi-Sensor Fusion Model

In most common vehicle navigation systems, no integrated position determination, using observations of all available sensors, is performed. The resulting trajectory is determined mainly based on the dead reckoning observations; GPS is only used for updating and resolving the systematic error growth of the DR observations. With the development of a multi-sensor fusion model, a real mathematical integration of all available observations can be achieved. In this approach (see Figure 1), the determination of the trajectory of the vehicle is carried out by a cascaded filter system which is divided into a pre-processing step followed by a central Kalman filter. This approach has been applied by Sternberg [see

Sternberg et al., 1998; Sternberg et al., 1999] for the trajectory determination of a mobile mapping system to integrate GPS and INS observations. For our application, it can be adapted to integrate GPS and wireless or mobile phone location service (MPLS) observations with the dead reckoning (DR) measurements. In a pre-processing step, the observations of the sensors are corrected or converted and smoothed in separate Kalman filters. The positions derived from GPS or MPLS are then used as input values for the GPS/MPLS Kalman filter. The heading angle from the gyroscope and digital compass, the distance travelled in the direction of motion from the odometer and the acceleration from the accelerometer for the DR Kalman filter. The observation of the MPLS will be used to replace the GPS measurements during long periods where an insufficient number of satellites is available for the position determination. The filtered positions and velocities of the GPS or MPLS from the pre-processing step; and the relative positions, the velocity and acceleration from the DR are transferred as pseudo-observations to the central Kalman filter. In this filter the position, velocity and acceleration are estimated directly as components of the state vector representing the final trajectory of the vehicle. Finally, the resulting vehicle trajectory is matched to the digital road map.

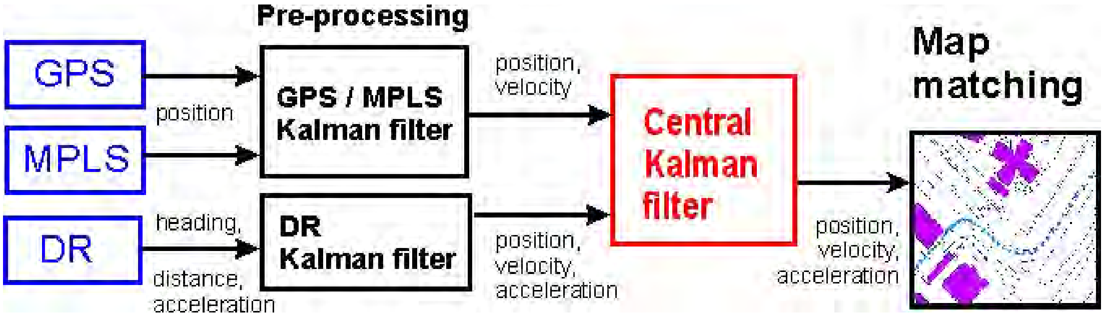

Fig. 1. Integration concept using a cascaded Kalman filter system

2.1 Adapted Kalman Filter Approach

The Kalman filter is applied in the evaluation procedure for real-time applications where an optimal estimation of time-dependent measurements for the state of dynamic systems is obtained. Its application is well known for the estimation of the position, velocity and acceleration of a moving body, e.g. in GPS orbit determination. The filter provides an exact solution to the linear Gaussian filtering problem. The problem is characterized completely by its state vector and covariance matrix. The filtering process is reduced to the prediction and updating of these two statistical parameters. In this paper, the fundamentals of the Kalman filter will not be described as they can be found in several publications, e.g. in Gelb [1986] and Schrick [1997].

The predictive equations for the state vector $\vec{x}(k)$ and its covariance matrix $\mathbf{\Sigma}_{xx}$ in the interval [k, k+1] are:

$$\vec{x}(k+1) = \mathbf{T}(k) \cdot \vec{x}(k) \tag{1}$$

$$\mathbf{\Sigma}_{xx}(k+1) = \mathbf{T}(k) \cdot \mathbf{\Sigma}_{xx}(k) \cdot \mathbf{T}^{T}(k) + \mathbf{\Sigma}_{ww}(k+1) \tag{2}$$

where $\mathbf{T}$ is the transition matrix and $\mathbf{\Sigma}_{ww}$ is the covariance matrix of the system noise. The transition matrix $\mathbf{T}$ incorporates the physical laws governing the dynamic process, and the covariance matrix $\mathbf{\Sigma}_{ww}$ the errors of the model. After new measurements $\vec{l}(k+1)$ have been performed, a new state vector $\vec{x}'(k+1)$ and covariance matrix $\mathbf{\Sigma}'_{xx}$ can be estimated. The update equations are as follows:

$$\vec{x}'(k+1) = \vec{x}(k+1) + \mathbf{K}(k+1) \cdot \left[\vec{l}(k+1) - \mathbf{A}(k+1) \cdot \vec{x}(k+1)\right] \tag{3}$$

$$\mathbf{K}(k+1) = \mathbf{\Sigma}_{xx}(k+1) \cdot \mathbf{A}^T(k+1) \cdot \left[\mathbf{\Sigma}_{ll}(k+1) + \mathbf{A}(k+1) \cdot \mathbf{\Sigma}_{xx}(k+1) \cdot \mathbf{A}^T(k+1)\right]^{-1} \tag{4}$$

$$\mathbf{\Sigma}'_{xx}(k+1) = \mathbf{\Sigma}_{xx}(k+1) - \mathbf{K}(k+1) \cdot \mathbf{A}(k+1) \cdot \mathbf{\Sigma}_{xx}(k+1) \tag{5}$$

where **K** is the Kalman gain matrix and $\mathbf{\Sigma}_{ll}$ is the covariance matrix of the measurement noise. The influence of the new measurements on the state vector $\vec{x}'(k+1)$ is given by the Kalman gain matrix **K** which includes the covariance matrix of the measurement noise $\mathbf{\Sigma}_{ll}$, the system noise $\mathbf{\Sigma}_{ww}$ and the estimated state vector $\mathbf{\Sigma}'_{xx}$. Using these covariance matrices, the weightings of the measurements and the model can be defined and modified [Retscher, 1996 and 1998; Schrick, 1977].

The main advantage of this approach is the recursive relation between the state vector (including position, velocity and acceleration) and the observations from the different sensors. Therefore it can also be applied for the evaluation in real-time. After new measurements have been performed, the state vector is updated and the estimates of the positions are improved. In general, two different Kalman filter approaches can be distinguished:

- Integration of all observations of the navigation sensors in one centralized Kalman filter approach or
- A cascaded filter system with pre-processing steps for each sensor and a central Kalman filter (see Figure 1).

In the first approach, the raw observations of GPS, MPLS, dead reckoning and other sensors should be integrated using one centralized Kalman filter approach for determination of position, velocity and acceleration. Although this approach would lead to the optimum estimation for the state vector, in most common navigation systems the position determination is based mainly on the dead reckoning observations and GPS is only used for updating and resolving the systematic error growth in the resulting trajectory.

In the second approach, the determination of the trajectory is carried out by a cascaded filter system which is divided into a pre-processing step followed by a central Kalman filter (see Figure 1). In the pre-processing step, the original observations of the sensors are corrected, converted to pseudo-observations and smoothed. All sensor data are pre-processed separately. Then the positions and velocity of the GPS or MPLS observations, the rotation angles from the attitude sensors, the velocity in direction of motion from the odometer or step counter and other data are transferred as pseudo-observations to the central Kalman filter. Finally, the position and velocity of the vehicle are estimated directly in the filter [Sternberg, et al. 1998; Sternberg, 2000].

The main advantage of the first approach is that all raw observations are used in one filter process to estimate the optimal solution for the state vector. On the other hand, the integration of all different types of observations in one centralized Kalman filter approach might be very difficult to achieve due to the different nature of the observations of each measurement sensor in the navigation system. Especially the weighting of the different observations in the stochastic filter model has to be estimated beforehand using empirical analysis of the behavior of the sensors. The cascaded filter system has the advantage that the observations of the sensors are firstly analyzed in the pre-processing step and then in the central filter. Therefore the model is simplified and has a higher data integrity. Simulation studies have shown that the result is not significant different from that of the centralized approach.

While it has been assumed until now that the optimal filter, once selected, is held fixed in any application, it is entirely reasonable to ask whether information acquired during system operation can be used to improve upon the a priori assumptions that were made at the start of the filter process. This leads us to the topic of adaptive filtering where the innovations property (i.e. the difference between the real measurement value and the predicted measurement $\vec{l}(k+1) - \mathbf{A}(k+1) \cdot \vec{x}(k+1)$ in equation (3)) is used as a criterion to test for optimality. Employing tests for whiteness, mean and covariance, the experimentally measured steady-state correlation function is processed. For further information regarding adaptive filtering the reader is referred to Gelb [1986]. This approach has to be implemented in our cascaded filter process.

2.2 Kinematic Models of the State Vector

The type of the model depends on the number of parameters in the state vector $\vec{x}(k)$. The following parameters can be used to describe the state of the system:

- 3-D coordinates of the current position y, x, z,
- 3-D velocities v_y, v_x, v_z,
- 3-D accelerations a_y, a_x, a_z,
- direction of motion (heading) φ in the ground plane xy,
- velocity v in the ground plane xy,
- radial acceleration a_{rad} in the ground plane xy.

Table 1 compares the parameters for the state vector, the system noise and the observations for three different models. Model 1 describes a constant linear movement where the state vector includes 6 components. Model 2 includes also the acceleration and describes a constant accelerated movement. Model 3 describes a constant radial movement and employs different parameters in the state vector. Using these models the filter predicts different the movement of the system where in Model 1 compared to Model 2 no accelerations are used and in Model 3 a radial movement without tangential accelerations a_{tan} is employed.

	Model 1	Model 2	Model 3
State vector	y, x, z, v_y, v_x, v_z	$y, x, z, v_y, v_x, v_z, a_y, a_x, a_z$	$y, x, z, \varphi, v, a_{rad}, v_z$
System noise	a_y, a_x, a_z	$\dot{a}_y, \dot{a}_x, \dot{a}_z$	$a_{tan}, \dot{a}_{rad}, a_z$
Observations	$y, x, z, v_y, v_x, v_z, \varphi, v$	$y, x, z, v_y, v_x, v_z, a_y, a_x, a_z, \varphi, v, a_{tan}, a_{rad}$	$y, x, z, v_y, v_x, v_z, \varphi, v, a_{rad}$

Tab. 1. Comparison of the parameters for three different kinematic models

The transition matrix **T** for Model 1 results in

$$\mathbf{T}=\begin{bmatrix} 1 & 0 & 0 & t_{k+1}-t_k & 0 & 0 \\ 0 & 1 & 0 & 0 & t_{k+1}-t_k & 0 \\ 0 & 0 & 1 & 0 & 0 & t_{k+1}-t_k \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \tag{6}$$

for Model 2 in

$$\mathbf{T}=\begin{bmatrix} 1 & 0 & 0 & t_{k+1}-t_k & 0 & 0 & \frac{(t_{k+1}-t_k)^2}{2} & 0 & 0 \\ 0 & 1 & 0 & 0 & t_{k+1}-t_k & 0 & 0 & \frac{(t_{k+1}-t_k)^2}{2} & 0 \\ 0 & 0 & 1 & 0 & 0 & t_{k+1}-t_k & 0 & 0 & \frac{(t_{k+1}-t_k)^2}{2} \\ 0 & 0 & 0 & 1 & 0 & 0 & t_{k+1}-t_k & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & t_{k+1}-t_k & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & t_{k+1}-t_k \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \tag{7}$$

and for Model 3 in

$$\mathbf{T}=\begin{bmatrix} 1 & 0 & 0 & T_{14} & (\sin\varphi)_k\cdot(t_{k+1}-t_k) & \frac{1}{2}\cdot(\cos\varphi)_k\cdot(t_{k+1}-t_k)^2 & 0 \\ 0 & 1 & 0 & T_{24} & (\cos\varphi)_k\cdot(t_{k+1}-t_k) & -\frac{1}{2}\cdot(\sin\varphi)_k\cdot(t_{k+1}-t_k)^2 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & t_{k+1}-t_k \\ 0 & 0 & 0 & 1 & -\frac{(a_{rad})_k}{v_k^2}\cdot(t_{k+1}-t_k) & \frac{t_{k+1}-t_k}{v_k} & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \tag{8}$$

with $T_{14}=\left(v_k\cdot(\cos\varphi)_k-\frac{1}{2}\cdot(a_{rad})_k\cdot(\sin\varphi)_k\cdot(t_{k+1}-t_k)\right)\cdot(t_{k+1}-t_k)$ and

$$T_{24}=-\left(v_k\cdot(\sin\varphi)_k+\frac{1}{2}\cdot(a_{rad})_k\cdot(\cos\varphi)_k\cdot(t_{k+1}-t_k)\right)\cdot(t_{k+1}-t_k).$$

2.3 Stochastic Filter Model

The stochastic filter model is characterised by the system and measurement noise. For the estimation of the stochastic model, the assumption is used that the measurement and system noise are Gaussian white noise and are independent of each other. Further information can be found in Wang [1997], for example. For the simulations described in section 3, the stochastic model for the Kalman filter was estimated empirically using the assumed precisions of the sensors given in Table 2.

The result of the filter process depends mainly on the careful selection of the stochastic filter model. Especially the degree of the system and the standard deviation of the system noise have a significant influence on the filter result [see Retscher, 1996 and 1998]. For the degree of the system higher values than three are normally not used. A filter model of third degree means that the first and the second derivatives of the state vector, i.e., the velocity and acceleration of the position vector, are included (see Model 2 in Table 1). The system noise for the components of each filter model given in Table 1 can be described in percentage of the standard deviation of the observations. This value has to estimated using empirical simulations. In case of GPS observations a value of 30 % was used in the following simulations in section 3. The selection of a small value for the standard deviation of the system noise (less than 30 % in the case of GPS observations) would result in a higher degree of smoothing of the observations. In this case, high frequency or short periodical parts of the measurement series would also be eliminated together with the measurement noise. On the other hand, a larger value for the standard deviation (> 30 % of the GPS positioning accuracies) produces a filter result which almost coincides with the original measurements. In this case, the filter would not be effective.

3 Simulation Studies

3.1 Comparison of Different Filter Models

Figure 2 shows the filter results for GPS observations (position and velocity) along a curved track which consists of a straight line, clothoide, circle, clothoide, circle, clothoide and straight line. The filter results are calculated using the kinematic filter models for the state vector described in Section 2.2 (see Table 1). As can be seen from Figure 2, the result of the Models 1 and 2 are very similar. Only the result of Model 3 differs slightly from the result of the two other models. The result of Model 3, however, does not achieve a higher smoothing of the observations, although the state vector includes the azimuth and the radial acceleration. The standard deviation of the filter result for all models is in the range 1.4 m and the maximum deviation from the given line is around 3.2 m. As the results are very similar, the Kalman filter approach achieves an improvement of the positioning independent of the selected kinematic filter model.

3.2 Practical Example

As a practical example, the guidance of a visitor to the Vienna University of Technology, from a public transport stop to the Department of Applied and Engineering Geodesy was investigated. It is assumed that the visitor uses a pedestrian navigation system where different sensors are combined. Table 2 gives an overview about the sensors that can be integrated into the system. For absolute position determination, primarily GPS is employed. In the case where GPS is not available, location techniques using mobile phones (MPLS) or indoor positioning systems (e.g. a so-called Local Positioning System LPS) can be used. Apart from these sensors, relative DR sensors are employed for the observation of the distance travelled (from velocity and acceleration measurements), direction of motion or heading and height difference. The observables and their accuracies are summarised in Table 2.

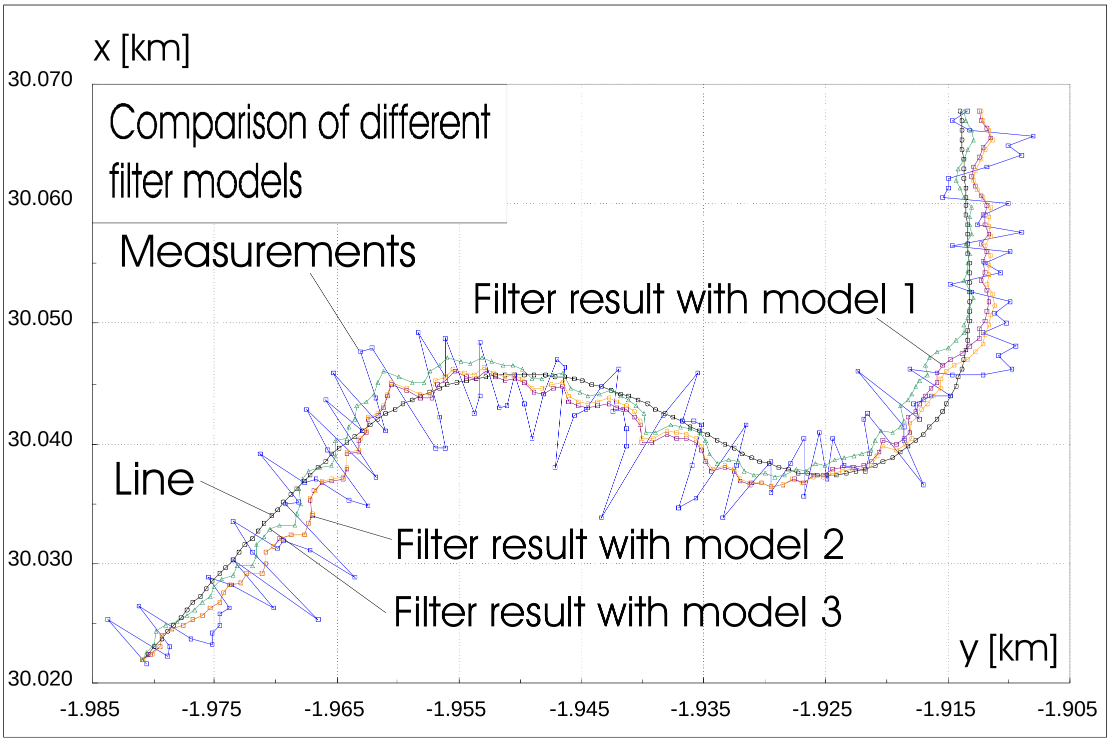

Fig. 2. Comparison of three different models for the state vector

Method	**Sensor**	**Observations**	**Accuracy**
GPS	e.g. Garmin GPS 35 DGPS	y, x, z	6-10 m 1-4 m
LPS	e.g. Syptech HF LPS 007	y, x, z	0,3-1 m
MPLS	GSM UMTS	y, x y, x	> 50 m > 10 m
Barometer	e.g. Campbell Scientific Pressure sensor	H	1-3 m
Pedometer	e.g. Crossbow IMU 600 CA	$v^{(*)}$	~ 0,1 m/s
Direction of motion (Heading)	e.g. Leica DMC SX (compass) combined with Crossbow IMU 600 CA (gyro)	φ	~ 1°
Velocity from GPS	e.g. Garmin GPS 35	v_y, v_x v_z	~ 0,05 m/s ~ 0,2 m/s
Acceleration	e.g. Crossbow IMU 600 CA	a_{tan}, a_{rad}, a_z	> 0,1 m/s²

Tab. 2. Sensors for a pedestrian navigation system with their accuracies
$^{(*)}$ Velocity v deducted from acceleration measurements

Figure 3 shows the result of the simulation of the guidance of a visitor from the underground station Karlsplatz to a building at the Vienna University of Technology and onward to the Secretary of the Department in the 3rd floor of the building. The length of the path is approximately 500 m. Thereby the first part of the path (about 30 m) is in the underground station, where the position is determined using MPLS and dead reckoning. Outside the underground station GPS positioning is available and therefore the position changes quite significantly. After that, short GPS outages are bridged by the dead

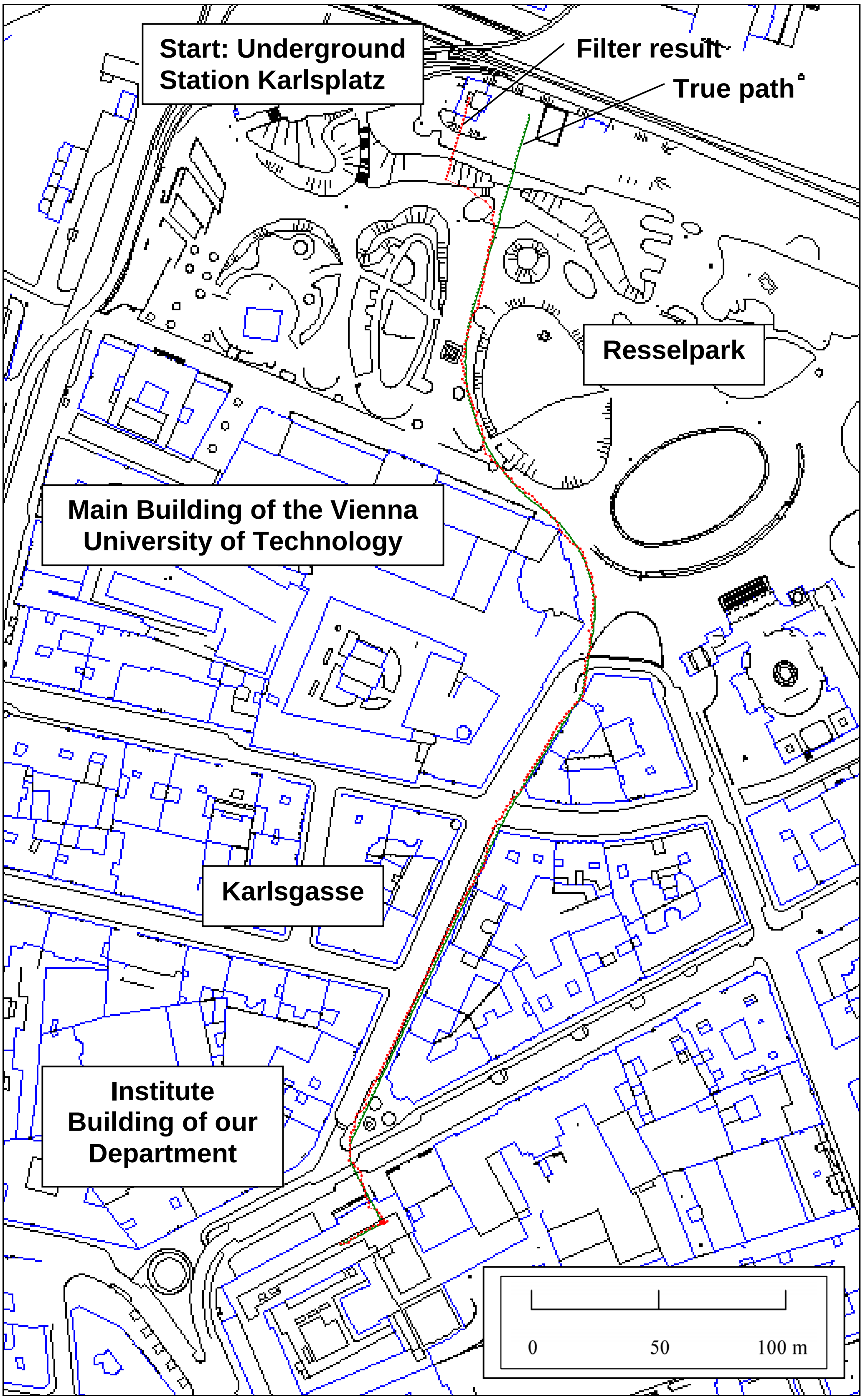

Fig. 3. Filter result of the path from the underground station Karlsplatz to the Secretary of the Research Group Engineering Geodesy at the Vienna University of Technology

reckoning observations. The last part of the path (about 40 m) is in the building of our University. In this case, a LPS is employed for determination of absolute location. The height is observed with a barometer. All available observations are used to get an optimal estimate of the current location from the Kalman filter. In comparison with Figure 1, however, no map matching is employed in this practical example. Apart from the first part, the deviation of the path from the true value is in the range of a few metres although two GPS outages with a length of approximately 30 m and 90 m were simulated.

4 Summary and Further Refinement of the Approach

The multi-sensor fusion model seeks to improve the accuracy and reliability of position determination by integrating all available single sensor observations. The resulting user state from the filter at a certain time (epoch) does not only rely on primary sensor observations available at that time (e.g. from GPS or DGPS). The model has been developed so that its extended filter model is capable to calculate the user state from all available measurement data, also when only incomplete observations from a single sensor are available (e.g. if insufficient numbers of satellites are available due to obstructions for GPS positioning). Any single observation can then contribute to improve the previous state of a tracked user by updating the prediction in the filter model. This approach provides the advantage to estimate the user state recursively also if an individual positioning method would fail by refining the estimate of the solution using single observations together with the observations of the relative DR sensors (i.e. orientation, distance travelled, velocity or acceleration and height difference) as well as from other sensors (e.g. in the case of availability range measurements to pseudolits, transponders, beacons or base transmitter stations of wireless phone networks).

A simulation study conducted earlier showed promising results for the adaptation of the filter model for different navigation application, such as vehicle navigation in dense high-rise urban environments, where GPS signals are frequently obstructed by surrounding building structures.

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References

Gelb A. (Editor), 1986. Applied Optimal Estimation, The MIT Press, Cambridge, Massachusetts and London, England, 9th print, 374 pgs.

Mok E., G. Retscher, L. Lau, 2002. Development of an Event-Reporting Intelligent Vehicle Navigation System for Areas with Urban Canyons, Survey Review, Vol. 36, No. 284, April 2002, pp. 398-409.

Retscher G., 1996. 3D-Gleiserfassung mit einem Multisensorsystem und linearen Filterverfahren, Geowissenschaftliche Mitteilungen, Nr. 44, Abteilung Ingenieurgeodäsie, Technische Universität Wien, Austria, 103 pgs.

Retscher G., 1998. Evaluation Concepts for Applications of Multi-sensor Systems, in: Papers presented at the XXI International Congress FIG’98, Brighton, UK, July 19-26, 1998, Commission 6, pp. 104-117.

Retscher G., E. Mok, 2001. Integration of Mobile Phone Location Services into Intelligent GPS Vehicle Navigation Systems, in: Papers presented at the 3rd Workshop on Mobile Mapping Technology, Cairo, Egypt, January 3-5, 2001, pp. S17-1.1-12.

Schrick K.-W., 1977. Anwendungen der Kalman-Filter-Technik, Methoden der Regelungstechnik. R. Oldenbourg Verlag, München, Wien.

Skolaut G., 2002: Untersuchung von Messsensoren zum Einsatz in Navigationssystemen für Fußgänger, Diplomarbeit, Abteilung Angewandte Geodäsie und Ingenieurgeodäsie, TU Wien, 105 pgs.

Sternberg H., W. Caspary, H. Heister, 1998. Determination of the Trajectory surveyed by the Mobile Surveying System KiSS, in: Papers presented at the Symposium Geodesy for Geotechnical and Structural Engineering, Eisenstadt, Austria, April 20-22, 1998, pp. 361-366.

Sternberg H., W. Caspary, H. Heister, 1999. Filteralgorithms for Optimal Determination of Position and Attitude of the Mobile Mapping System KiSS, in: Papers presented at the International Workshop on Mobile Mapping Technology, Bangkok, Thailand, April 21-23, 1999, pp. 2.2.1-2.2.6.

Sternberg H., 2000. Zur Bestimmung der Trajektorie von Landfahrzeugen mit einem hybriden Meßsystem, Schriftenreihe des Studiengangs Geodäsie und Geoinformation, Universität der Bundeswehr München, Heft 67, Neubiberg, Germany, 158 pgs.

Wang J. G., 1997. Filtermethoden zur fehlertoleranten kinematischen Positionsbestimmung, Schriftenreihe des Studiengangs Vermessungswesen, Universität der Bundeswehr München, Heft 52, Neubiberg, Germany, 135 pgs.

NAVIO – A Navigation and Guidance Service for Pedestrians

Günther Retscher and Michael Thienelt

Abstract

In the research project NAVIO (Pedestrian Navigation Systems in Combined Indoor/Outdoor Environements) at our University we are working on the improvement of navigation services for pedestrians. Thereby we are mainly focusing on the information aspect of location-based services, i.e., on the user's task at hand and the support of the user's decisions by information provided by such a service. Specifications will allow us to select appropriate sensor data and to integrate data when and where needed, to propose context-dependent routes fitting to partly conflicting interests and goals as well as to select appropriate communication methods in terms of supporting the user guidance by various multimedia cartography forms. These taks are addressed in the project in three different work packages, i.e., the first on "Integrated positioning", the second on "Pedestrian route modeling" and the third on "Multimedia route communication". In this paper we will concentrate on the research work and findings in the first work package. For continuous positioning of a pedestrian suitable location technologies include GNSS and indoor location techniques, cellular phone positioning, dead reckoning sensors (e.g. magnetic compass, gyro and accelerometers) for measurement of heading and distance travelled as well as barometric pressure sensors for height determination. The integration of these sensors in a modern multi-sensor system can be performed using an adapted Kalman filter. To test and to demonstrate our approach, we take a use case scenario into account, i.e., the guidance of visitors to departments of the Vienna University of Techology. The results of simulation studies and practical tests could confirm that such a service can achieve a high level of performance for the guidance of a pedestrian in urban areas and mixed indoor and outdoor environments.

1 Introduction

Pedestrian navigation services require continuous positioning and tracking of a mobile user with a certain positioning accuracy and reliability. Especially navigating in urban environments and mixed indoor and outdoor areas is a very challenging task as pedestrians move in spaces where no one of the known location methods works continuously in standalone mode. A solution of the problem can only be found if different location technologies are combined in the sense of a modern multi-sensor system. In this paper suitable location technologies for pedestrian navigation are identified and investigated. These technologies include GNSS and indoor location services as well as cellular phone positioning for absolute position determination; dead reckoning sensors (e.g. magnetic compass, gyros and accelerometers) for measurement of orientation and distance travelled from a known start position as well as barometric pressure sensors for height determination. For location determination of a pedestrian in a multi-storey building the use of WLAN (Wireless Local Area Networks) is investigated. To achieve an integrated positioning determination with other sensors and a seamless transition between indoor and outdoor areas, a multi-sensor fusion model based on an extended Kalman filter approach is employed. Finally, in a practical use case scenario the guidance of a pedestrian from public transport stops to our Department of the Vienna University of Technology is investigated. The results of this study showed that such a pedestrian navigation service can achieve a high level of performance.

2 Integrated Positioning in Navigation Services

A reliable pedestrian navigation services requires the determination of the current user’s position using different sensors that are integrated into the system design. In the work package “Integrated positioning” of the research project NAVIO (Pedestrian **Nav**igation Systems in Combined **I**ndoor/**O**utdoor Environements) the following challenging tasks are addressed:

- The capability to track the movements of a pedestrian in real-time using different suitable location sensors and to obtain an optimal estimate of the current user’s position.
- The possibility to locate the user in 3 dimensions with high precision (that includes to be able to determine the correct floor of the user in a multi-storey building).
- The capability to achieve a seamless transition for continuous positioning determination between indoor and outdoor areas.

Thereby a navigation support must be able to provide location, orientation and movement of the user as well as related geographic information matching well with the real world situation experienced by pedestrians. The integration of the sensors in a modern multi-sensor system can be performed using a Kalman filter as this algorithm is particularly suited for real-time evaluation. In the following the state-of-the-art in mobile positioning is discussed and suitable sensors for integrated positioning in a pedestrian navigation service are identified.

2.1 State-of-the-art in Mobile Positioning

Satellite-positioning technologies (GNSS) are employed most commonly for outdoor navigation. Then the achievable positioning accuracies of the navigation system are on the few meters to 10 m level in standalone mode or sub-meter to a few meter level in differential mode (e.g. DGPS). If an insufficient number of satellites is available for a short period of time due to obstructions, then in a conventional approach observations of additional sensors are employed to bridge the loss of lock of satellite signals. For pedestrian navigation, sensors such as a low-cost attitude sensor (digital compass) giving the orientation and heading of the person being navigated and a digital step counter or accelerometers for travel distance measurements can be employed. Using these sensors, however, only relative position determination from a known start position (also referred to as Dead Reckoning DR) is possible and the achievable accuracy depends on the type of movement tracking sensors used and the position prediction algorithm adopted.

For indoor positioning different techniques have been developed. They offer either absolute or relative positioning capabilities. Some of them are based on short-range or mid-range technologies using sensors such as transponders or beacons installed in the building [see e.g. Klinec and Volz, 2000; Pahlavan et al., 2002]. An example are the so-called Local Positioning Systems (LPS) that have an operation principle similar to GNSS. The LPS systems claim to achieve a distance measurement accuracy of about 0.3 to 1 m [see e.g. Werb and Lanz, 2000; Sypniewski, 2000], but no details are given on the test results and the achievable accuracy on position fixing. Other indoor positioning systems include so-called Active Badge or Active Bats Systems [Hightower and Boriello, 2001]. These systems are mainly employed for the location of people and finding things in buildings. Also WLAN (Wireless Local Area Networks) can be employed for location determination. In this case, the signal strength of the radio signals from at least one WLAN access point installed in the building is measured. The location fix is then obtained with triangulation using measurements to several access points or through comparison with in database stored signal strength values from calibrated points (this method is also referred to as fingerprinting). Further information can be found in e.g. [Bastisch et al., 2003; Beal, 2003; Imst, 2004; Retscher 2004b]. As the indoor radio channel suffers from severe multipath propagation and heavy shadow fading, the fingerprint method provides higher accuracies than triangulation. It is reported that positioning accuracies of about 1 to 3 m could be obtained in a test office building using the fingerprint WLAN positioning method (Imst, 2004). Another alternative in indoor geolocation applications is the use of ultra wideband (UWB) systems, which exploit bandwidths in excess of 1 GHz, to measure accurate time of arrival (ToA) of the received signals for estimation of distance [Pahlavan et al., 2002]. With results of propagation measurement in a typical modern office building, it has been shown that the UWB signal does not suffer multipath fading [Win and Scholtz, 1998], which is desirable for accurate ToA estimation in indoor areas. The main disadvantage, however, is the possible interference of UWB devices with the GPS system. Also Bluetooth, which has been originally developed for short range wireless communication, can be employed for locating mobile devices in a certain cell area that is represented by the range of the device which is typically less than 10 m. It can be employed for location determination using active landmarks. Locating the user on the correct floor of a multistory building is another challenging task. For more accurate determination of the user’s position in vertical dimension an improvement can be achieved employing a barometric pressure sensor or digital altimeter additionally [see Retscher and Skolaut, 2003].

As an alternative for location determination in indoor and outdoor environments, mobile positioning services using cellular phones can be employed. Apart from describing the location of the user using the cell of the wireless network, more advanced positioning methods have been developed. Most of them are based on classical terrestrial navigation methods where at least two observations are required to obtain a 2-D position fix [see e.g. Balbach, 2000; CPS, 2001; Drane et al., 1998; Hein et al., 2000; Retscher, 2002]. The achievable positioning accuracy thereby depends mainly on the location method and type of wireless network (GSM, W-CDMA, UMTS). As advanced and more accurate methods, such as the E-OTD (Enhanced Observed Time Difference) method, require modification of the network as well as installation of additional hardware in the network and reference stations which are called LMU’s (Location Measurement Units), they have not been widely deployed yet. Recent developments have therefore been concentrated on the reduction of network modification. The so-called Matrix method [see Duffett-Smith and Craig, 2004] does not need any additional hardware in the network apart from a SMLC (Serving Mobile Location Centre) where the location determination of the mobile handset is performed. Using this method positioning accuracies of 50 to 100 m at the 67 % reliability level can be achieved in the GSM network.

2.2 Suitable Sensors for Pedestrian Navigation Services

Suitable sensors and location techniques for pedestrian navigation have been identified at the start of the project NAVIO. Table 1 gives an overview about the positioning methods and the sensors that will be employed in our project. For absolute position determination primarily GNSS is employed. In the case of no GNSS availability it can be replaced by location techniques using cellular phones or indoor positioning systems (e.g. WLAN positioning). Apart from this sensors, relative DR (Dead Reckoning) sensors are employed for the observation of the distance travelled (from velocity and acceleration measurements), direction of motion or heading and height difference. The observables as well as their accuracies are summarized in Table 1.

Method	**Sensor**	**Observations**	**Accuracy**
GNSS	e.g. Garmin eTrex DGPS	y, x, z	6-10 m 1-4 m
Indoor Positioning	e.g. WLAN Positioning IMST ipos	y, x, z	1-3 m
Cellular Phone Positioning	GSM (e.g. Matrix method)	y, x	50-100 m
Dead Reckoning	e.g. PointResearch DRM-III Dead Reckoning Module	y, x z φ	20-50 m per 1 km 3 m 1°
Direction of Motion (Heading)	e.g. Honeywell Digital Compass Module HMR 3000	φ	0.5°
Acceleration	e.g. Crossbow Accelerometer CXTD02	a_{tan}, a_{rad}, a_z	> 0.03 ms^{-2}
Velocity from GNSS	e.g. Garmin eTrex	v_y, v_x v_z	~ 0,05 m^{-1} ~ 0,2 m^{-1}
Barometer	e.g. Vaisala Pressure sensor PTB220A	z	1-3 m

Tab. 1. Sensors for pedestrian navigation services with their observables and accuracies [Garmin, 2004; Imst, 2004; Duffett-Smith and Craig, 2004; PointResearch, 2004; Honeywell, 2004; Crossbow, 2004; Vaisala, 2004]
where y, x, z are the 3-D coordinates of the current position, v_y, v_x, v_z are the 3-D velocities, φ is the direction of motion (heading) in the ground plane xy, a_{tan} is the tangential acceleration and a_{rad} is the radial acceleration in the ground plane xy, a_z is the acceleration in height (z coordinate)

2.3 Integrated Positioning Using a Multi-sensor Fusion Model

An integrated position determination, using observations of all available sensors, however, is not performed in most common navigation systems. In vehicle navigation systems for instance the resulting trajectory is determined mainly based on the dead reckoning observations; GNSS is used for updating and resolving the systematic error growth of the DR observations. For guidance of a pedestrian in 3-D space and updating of his route, continuous position determination is required with positioning accuracies on the few meter level or even higher, especially for navigation in multi-storey buildings in vertical dimension (height) as the user must be located on the correct floor. The specialized research hypothesis of this work package in the project NAVIO is that a mathematical model for integrated positioning can be developed that provides the user with a continuous navigation support. Therefore appropriate location sensors have to be combined and integrated using a new multi-sensor fusion model. A Kalman filter approach is particular suited for the integration and sensor fusion in real-time. Extending basic filter concepts, a Kalman filter approach which integrates all observations from the different sensors will be developed. The model must be able to make full use of all available single observations of the sensors at a certain time to obtain an optimal estimate of the current user state (i.e., position, orientation and motion). For further information on the multi-sensor fusion model the reader is referred to Retscher and Mok [2004] and Retscher [2004b].

3 Practical Sensor Tests

Practical tests in our research project are carried out for the guidance of visitors of the Vienna University of Technology to certain offices in different buildings or to certain persons. Thereby we assume that the visitor employs a pedestrian navigation system using different sensors that perform an integrated positioning. Start points are nearby public transport stops, e.g. underground stop Karlsplatz in the center of Vienna or railway station Südbahnhof near our university. In the following, results of satellite positioning and first test measurements with the Dead Reckoning Module DRM III from Point Research are presented.

3.1 Satellite Positioning Test Results

Figure 1 shows the GPS measurements for the path from the underground stop Karlsplatz near our University to our Institute building of the Vienna University of Technology in the Gusshausstrasse located in the fourth district of the city of Vienna using two different GPS receivers, i.e., the Trimble GPS Pathfinder Pocket and the Garmin eTrex. The length of the path is approximately 500 m and it starts at the exit of underground station Karlsplatz where open skys provide free satellite visibility. Then the pedestrian walks through a park (i.e., the Resselpark) with trees where satellite signals are frequently blocked over short periods. Both GPS receivers, however, are able to determine the track of the pedestrian with a reasonable positioning accuracy. It can be seen, that the track of the Garmin eTrex receiver is much smoother as he performs some internal filtering or smoothing to estimate the receiver track compared to the Trimble GPS Pathfinder Pocket which provides the original GPS single point positions. After leaving the park, the path continues in a narrow street (i.e., Karlsgasse) onwards to our Institute building where 5-storey buildings with heights of typically 20 m cause obstructions of the satellite signals. The measurement result from the Garmin eTrex shows an increasing deviation from the true pedestrian path where the maximum deviation in the range of 13 m is reached at the intersection of Karlsgasse with Frankenberggasse. Then the position changes quite significantly as more GPS satellites become available. In the following, the positions show again a drift from the true path. As the Trimble GPS Pathfinder Pocket receiver does not apply any filtering or smoothing, the positions in the Karlsgasse are much more scattered than with the Garmin eTrex. Maximum deviations from the true path of the pedestrian of up to 25 m are reached and in some parts no position determination is possible. This gaps have to be bridged using dead reckoning observations. At the intersection of Karlsgasse with Gusshausstrasse enough satellites are visible for positioning and the path ends in front of the building where our Institute is located.

3.2 Dead Reckoning Test Results

For the measurements the Dead Reckoning Module DRM III from Point Research (PointResearch, 2004) was employed. The system is a self contained navigation unit where GPS is not required for operation. It provides independent position information based on the user’s stride and pace count, magnetic north and barometric altitude. The module is designed to self-calibrate when used in conjunction with an appropriate GPS receiver, and can produce reliable position data during GPS outages. The system consists of an integrated 12 channel GPS receiver, antenna, digital compass, pedometer and altimeter. The module is clipped onto the user’s belt in the middle of the back and the GPS antenna may be attached to a hat. Firmware converts the sensor signals to appropriate discrete parameters, calculates compass azimuth, detects footsteps, calculates altitude and performs dead reckoning position calculation. A Kalman filter algorithm is used to combine dead reckoning position with GPS position to obtain an optimum estimate for the current user’s position and track. With the dead reckoning module and GPS integrated together, a clear view of the sky is only required for obtaining the initial position fix. The fix must produce an estimated position error of 100 m or less to begin initialization. Subsequent fixes use both dead reckoning and GPS data, so obstructed satellites are not as critical as in a GPS only configuration. The Kalman filter continuously updates calibration factors for stride length and compass mounting offset. The GPS position error must be less than 30 m before GPS data will be used by the Kalman filter, and the first such fix will also initialize the module’s latitude and longitude. Subsequently, the filter will use any GPS position fix with an estimated position error of 100 m or less, adjusting stride, body offset, northing, easting, latitude and longitude continually.

First of all the Dead Reckoning Module DRM III was tested in open area with GPS satellite visibility. As test site pedestrian paths in the park of Schönbrunn Palace in Vienna have been chosen. Figure 2 shows the trajectory of the pedestrian as well as GPS and two different dead reckoning measurements. For the dead reckoning measurements the GPS positioning and the calibration of the stride length using the Kalman filter algorithm was deactivated. Without using the filter, GPS measurements are not employed to calibrate the stride length and the dead reckoning module uses the preset value of 800 mm for the stride length. The heading of the user is determined from measurements of a digital compass and a gyro. For the first dead reckoning measurement (No. 1) shown in Figure 2 both sensors are employed to obtain the heading, for the second measurement (No. 2) only the observations of the compass are employed. This results in larger deviations from the trajectory for the second dead reckoning measurements; they range from 17 m over a distance of 150 m and 29 m over 200 m. For the first dead reckoning measurement the deviations from the trajectory are in the range of 7 m over a distance of 150 m and 20 m over 200 m. It can therefore be recommended that a combination of compass and gyro measurements are employed for heading observation. An improvement of the dead reckoning measurements can only be achieved if the calibration of the stride length is employed to obtain a better estimate for the distance travelled. For comparison, GPS measurements from the internal receiver of the DRM III module are shown in Figure 2 which reach a maximum deviation of 7 m from the trajectory.

Figure 3 shows the measurement results of the DRM III dead reckoning module and GPS single point positions on a closed loop in the city of Vienna starting from the Resselpark about 160 m along Argentinerstrasse, then 200 m along Gusshaustrasse and 290 m along Karlsgasse back to the start point. The total length of the path is around 550 m. The streets are quite narrow with 5-storey buildings with an average heigth over 20 m causing frequent obstructions of the satellite signals and high GDOP values. As can be seen in Figure 3, the GPS only measurements are quite far away from the true path of the pedestrian along most parts of the track and a reliable match to the correct street would not always be possible. Using the position estimates of the dead reckoning module the resulting trajectory follows the pedestrian track along the most part of path and the deviations are only in the range of a few meters. Due to the large errors of the GPS postions, however, the calibration algorithm of the DRM III fails at the end and the resulting trajectory cannot follow the track of the pedestrian any more. Figure 4 shows the calibration of the stride length in the Kalman filter and it can be seen that the stride length gets smaller and smaller until it reaches nearly 500 mm which is not a matter of fact. In this case, it seems that the weighting of GPS positioning is too high in the Kalman filter calibration process for the stride length.

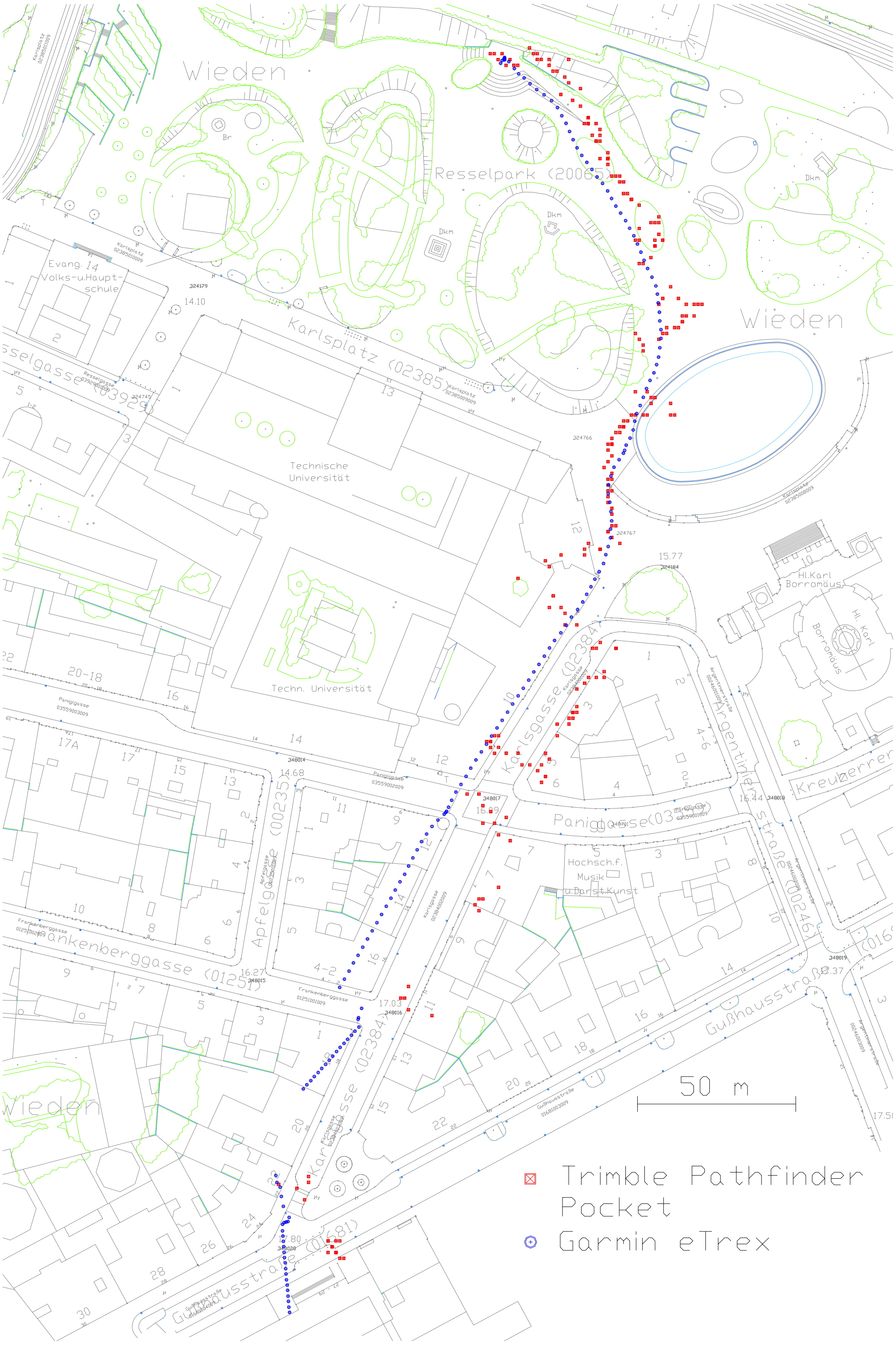

Fig. 1. GPS measurements for the pedestrian path from the underground station Karlsplatz to our office building of the Vienna University of Technology

In our project, an improvement of the current position estimate of a pedestrian using observations of different dead reckoning sensors in combination with GPS and other absolute postioning techniques (see Table 1) should be achieved using a new multi-sensor fusion model based on an extended Kalman filter approach. Further information about this approach can be found in Retscher and Mok [2004] and Retscher [2004b].

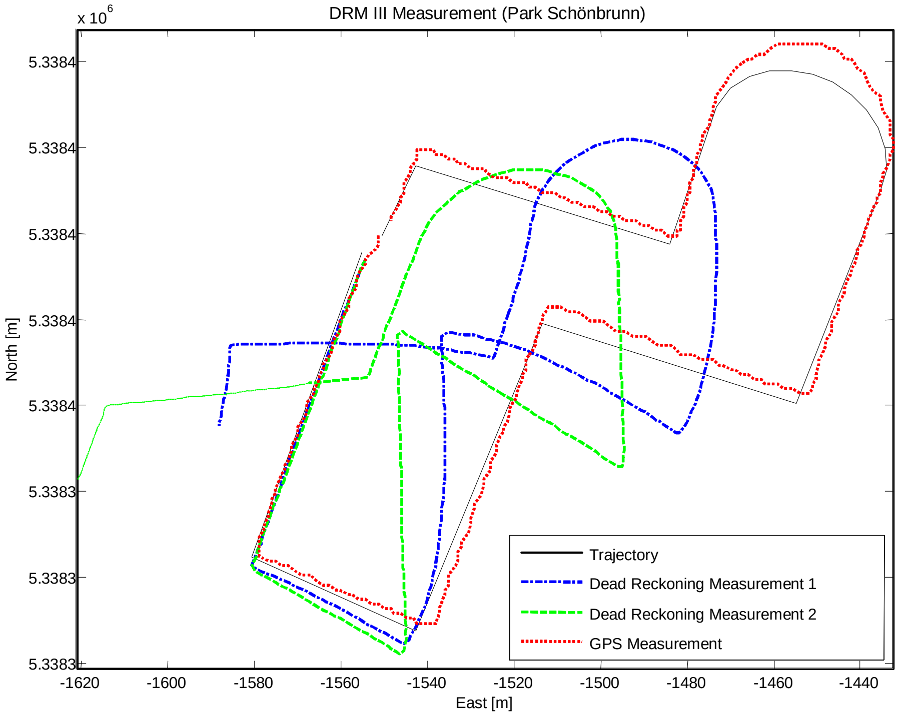

Fig. 2. Test measurements with the Dead Reckoning Module DRM III in the park of Schönbrunn Palace in Vienna

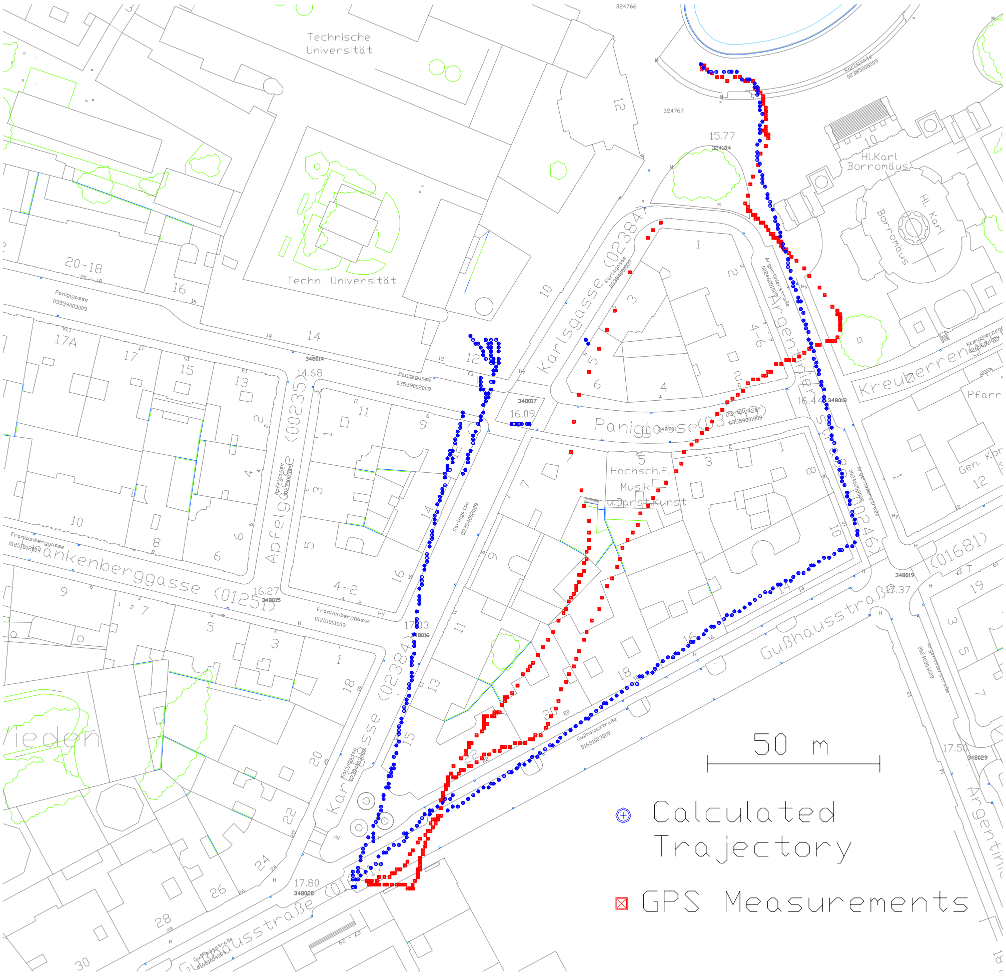

Fig. 3. Test measurements with the Dead Reckoning Module DRM III along a closed loop on narrow streets in the city Vienna

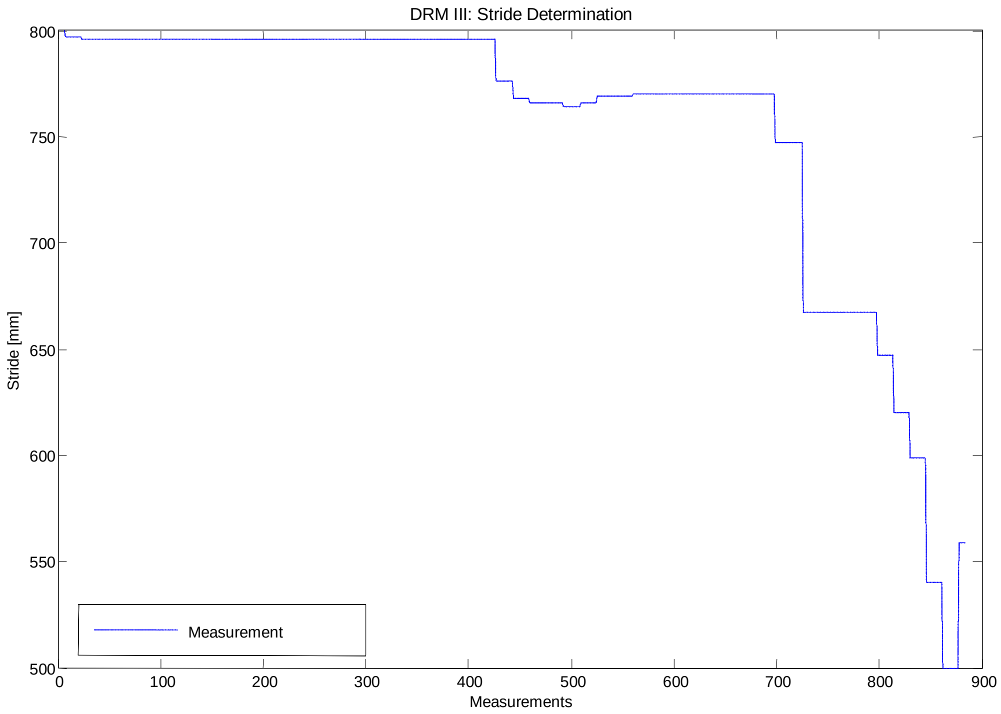

Fig. 4. Calibration of the stride length using GPS observations in the Kalman filter of the DRM III Dead Reckoning Module

4 Conclusions

In the NAVIO project major aspects being important when concepting a pedestrian navigation service are investigated, i.e., integrated positioning, multi-criteria route planning, and multimedia route communication [see Gartner et al., 2004a and b]. As a result, a specific pedestrian navigation service as use case will derive the requirements on positioning, route planning, and communication. A prototype of the service will guide visitors of the Vienna University of Technology to departments and persons. Practical tests will allow us to evaluate and demonstrate the usability of the service, and thus, prove the projects attempts.

With the work package "Integrated Positioning" of the project we will contribute to the integration of location sensors in the sense of a multi-sensor system to achieve a continuous positioning of the user of the service and a seamless transition between indoor and outdoor areas. Suitable sensors and location methods have been identified and the basic concept of a multi-sensor fusion model for integrated positioning has been developed [Retscher and Mok, 2004; Retscher 2004b]. Special emphasis has been given on the location determination and navigation of a pedestrain in a multi-storey building. Currently we are investigating the use of WLAN positioning for location determination in indoor areas.

The second work package of the project NAVIO on "Pedestrian route modeling" is dealing with the ontological modelling of navigation tasks, deriving well founded criteria and optimization strategies in route selection; and the third work package on "Multimedia route communication" is working on models for context-dependent communication modes of route information. In general, it can be said that the results of the project NAVIO will contribute to the improvement of modern (pedestrian) navigation services.

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References

Balbach O., 2000. UMTS – Competing Navigation System and Supplemental Communication System to GNSS, in: Papers presented at ION GPS Meeting 2000, Salt Lake City, Utah, U.S.A., September 19-22, 2000.

Bastisch H., S. Häfker, J. Krause, S. Wilking, B. Haje, 2003. Projekt NOM@D - Location Based Services, Presentation, Communication Networks, University Bremen, Germany, http://www.comnets.uni-bremen.de/itg/itgfg521/aktuelles/fg-treffen-230103/20030120-LBS-Allgemein-v2.pdf (Last date accessed: July 2004).

Beal J. R., 2003. Contextual Geolocation - A Specialized Application for Improving Indoor Location Awareness in Wireless Local Area Networks, in: Papers presented at the Midwest Instruction and Computing Symposium MICS2003, The College of St. Scholastica, Duluth, Minnesota, U.S.A., http://www.css.edu/depts/cis/mics_2003/MICS2003_Papers/Beal.PDF (Last date accessed: July 2004).

CGALIES, 2002. Co-ordination Group on Access to Location Information by Emergency Services, Work Package 1 Report, 2002, http://www.telematica.de/cgalies/ (Last date accessed: July 2004).

Crossbow, 2004. CXTD Digital Tilt and Acceleration Sensor, Product Information, Crossbow, U.S.A., http://www.xbow.com/Products/Product_pdf_files/Tilt_pdf/6020-0012-01_B_CXTD.pdf (Last date accessed: July 2004).

CPS (Cambridge Positioning Services Ltd.), 2001. Cursor™ Mobile Location System, Product Information at http://www.cursor-system.com/ (Last date accessed: July 2004).

Drane C., M. Macnaughtan, C. Scott, 1998. Positioning GSM Telephones, IEEE Communications Magazine, April 1998.

Duffett-Smith P. J., J. Craig, 2004. Matrix, and Enhanced Satellite Positioning, in: Papers presented at the 5th IEE International Conference on 3G Mobile Communication Technologies, Savoy Place, London, UK, 18-20 October 2004, 4 pgs.

Garmin, 2004. Garmin GPS Products, Garmin Ltd., U.S.A., http://www.garmin.com/products/ (Last date accessed: July 2004).

Gartner G., A. Frank, G. Retscher, 2004a. Pedestrian Navigation System for Mixed Indoor/Outdoor Environments, in: Gartner G. (Ed.): Geowissenschaftliche Mitteilungen, Schriftenreihe der Studienrichtung Vermessungswesen und Geoinformation, TU Wien, Heft 66, Papers presented at the 2nd Symposium on Location Based Services and Telecartography, Vienna, Austria, January 28-29, 2004, pp. 161-167.

Gartner G., A. Frank, G. Retscher, 2004b. Pedestrian Navigation System in Mixed Indoor/Outdoor Environment – The NAVIO Project, in: Schrenk M. (Ed.): CORP 2004 and Geomultimedia04. Proceedings of the CORP 2004 and Geomultimedia04 Symposium, Vienna, Austria, February 24-27, 2004, pp. 165-171, http://corp.mmp.kosnet.com/CORP_CD_2004/archiv/papers/ CORP2004_GARTNER_ FRANK_RETSCHER.PDF (Last date accessed: July 2004).

Hein G., B. Eissfeller, V. Oehler, J. O. Winkel, 2000. Synergies Between Satellite Navigation and Location Services of Terrestrial Mobile Communication, in: Papers presented at ION GPS Meeting 2000, Salt Lake City, Utah, U.S.A., September 19-22, 2000.

Hightower J., G. Borriello, 2001. Location Systems for Ubiquitous Computing, Computer, Vol. 34, No. 8, IEEE Computer Society Press, August 2001, pp. 57-66.

Honeywell, 2004. HMR 3000 Digital Compass Module, User's Guide, Honeywell International Inc., U.S.A., http://www.ssec.honeywell.com/magnetic/datasheets/hmr3000_manual.pdf (Last date accessed: July 2004).

Imst, 2004. Indoor Locating – Imst ipos, Project c21, Presentation, IMST GmbH, Carl-Friedrich-Gauß-Str. 2, D-47475 Kamp-Lintfort, Germany.

Klinec D., S. Volz, 2000. NEXUS – Positioning and Communication Environment for Spatially Aware Applications, in: Papers presented at ISPRS 2000, Amsterdam, The Netherlands, Part B2, pp. 324-330, see also: http://www.nexus.uni-stuttgart.de/ (Last date accessed: July 2004).

Pahlavan K., X. Li, J.-P. Mäkelä, 2002. Indoor Geolocation Science and Technolgy, IEEE Communications Magazine, February 2002, pp. 112-118.

PointResearch, 2004. DRM-III Dead Reckoning Module - Engineering Development Tools, PointResearch Corporataion, U.S.A., http://www.pointresearch.com/drm_eval.htm (Last date accessed: July 2004).

Retscher G., 2002. Diskussion der Leistungsmerkmale von Systemen zur Positionsbestimmung mit Mobiltelefonen als Basis für Location Based Services, in: Papers presented at the Symposium on Telekartographie, TU Wien, Austria, January 28-29, 2002, published as Geowissenschaftliche Mitteilungen, No. 58, Institute of Cartography, Vienna University of Technology, Austria, pp. 41-58.

Retscher G., G. Skolaut, 2003. Untersuchung von Messsensoren zum Einsatz in Navigationssystemen für Fußgänger, Zeitschrift für Geodäsie, Geoinformation und Landmanagement ZfV, No. 2, pp. 118-129.

Retscher G., 2004a. Multi-sensor Systems for Pedestrian Navigation and Guidance Services, in: Papers presented at the 4th Symposium on Mobile Mapping Technology, Kunming, China, March 29-31, 2004, CD-Rom Proceedings, 7 pgs.

Retscher G., 2004b. Multi-sensor Systems for Pedestrian Navigation, in: Papers presented at the ION GNSS 2004 Conference, Long Beach, California, U.S.A., September 21-24, 2004, CD-Rom Proceedings, 12 pgs.

Retscher G., 2004c. Pedestrian Navigation Systems and Location-based Services, in: Papers presented at the 5th IEE International Conference on 3G Mobile Communication Technologies, Savoy Place, London, UK, 18-20 October 2004, 5 pgs.

Retscher G., E. Mok, 2004. Sensor Fusion and Integration using an Adapted Kalman Filter Approach for Modern Navigation Systems, Survey Review, Vol. 37, No. 292 April 2004.

Sypniewski J., 2000. The DSP Algorithm for Locally Deployable RF Tracking System, in: Papers presented at International Conference on Signal Processing with Applications, Orlando, October 2000, http://www.syptech.com/publications/publications.html (Last date accessed: July 2004).

Vaisala, 2004. PTB220 Digital Barometer, Vaisala, Finland, http://www.vaisala.com/DynaGen_Attachments/Att2468/PTB220%20Brochure.pdf (Last date accessed: July 2004).

Werb J., C. Lanz, 2000. Designing a Positioning System for Finding Things and People Indoors, http://www.rftechnologies.com/pinpoint/index.htm (Last date accessed: July 2004).

Win M., R. Scholtz, 1998. On the Performance of Ultra-Wide Bandwith Signals in Dense Multipath Environment, IEEE Commun. Letters, Vol. 2, No. 2, February 1998, pp. 51-53.

Ubiquitous Positioning Technologies for Modern Intelligent Navigation Systems

Günther Retscher and Allison Kealy

Abstract

Recently new location technologies have emerged that can be employed in modern advanced navigation systems. They can be employed to augment common satellite positioning techniques (GNSS) and dead reckoning as they offer different levels of positioning accuracies and performance. An integration of other technologies is especially required in indoor and outdoor-to-indoor environments. The paper gives an overview of the newly developed ubiquitous positioning technologies and their integration in navigation systems. Furthermore two case studies are presented, i.e., the improvement of land vehicle safety using Augmented Reality (AR) technologies and pedestrian navigation services for the guidance of users to certain University offices. In the first case study the integration of map matching into a Kalman filter approach is performed (referred to as "Intelligent Vehicle Navigation") and its principle is briefly described. This approach can also be adapted for the pedestrian navigation service described in the second case study.

1 Introduction

The integration of different location technologies and sensors is viable for the performance of modern advanced navigation systems. Thereby common navigation systems rely mainly on satellite positioning (GNSS) for absolute position determination. Losses of lock of satellite signals are usually bridged using dead reckoning (DR) measurements. Due to the main limitations of the sensors (i.e., satellite availability in the case of GNSS and large drift rates in the case of DR) other positioning technologies should be integrated into the system design of a personal navigation system to augment GNSS and DR positioning. Especially navigation in urban areas is a very challenging task as the user moves in general in areas where no one of the common location techniques works continuously in standalone mode. To solve this challenging task of continuous position determination, a combination with other location techniques is required. The paper reviews current positioning technologies that can be employed in navigation systems. Useable alternative geolocation techniques include cellular phone positioning, the use of WLAN (Wireless Local Area Networks), UWB (Ultra-Wide Band), RFID (Radio Frequency Identification) and Bluetooth for location determination.

In the development of wireless geolocation techniques two basic approaches can be distinguished, i.e., one approach where the system is solely designed for positioning using certain radio signals and the second where already established wireless infrastructure (e.g. WLAN) is employed for location determination [Pahlavan et al. 2002]. Thereby the second approach has the advantage that usually no additional and costly hardware installations are required. Some of these systems have been especially developed for indoor applications, but they can also be employed in indoor-to-outdoor and urban environments. The concepts of these geolocation techniques are described in the paper.

The integration of the sensors and location techniques is usually performed using a Kalman filter approach. In vehicle navigation systems the resulting trajectory is then matched to a digital road map. Spatial information databases containing the road network are in general a standard component of many mobile navigation systems. This is directly due to their ability to provide detailed information about the location and inter-relationship of geographically defined features. The common map matching techniques traditionally use this information in an attempt to improve navigation accuracy. In a research project conducted at the University of Melbourne the integration of map matching techniques within the Kalman filter like other navigation sensors such as GPS, gyroscopes, odometers, etc. was proposed as a means of providing additional measurements that can be used to improve position and attitude determination [Kealy and Scott-Young 2004]. This approach has been termed “Intelligent Vehicle Navigation” and its principle will be described briefly in the paper.

The intelligent vehicle navigation approach has been employed in a case study for the determination of position and attitude of a vehicle for improving land vehicle safety using Augmented Reality (AR) technologies. This research has demonstrated the potential of integrated positioning systems to provide the necessary outputs of position and attitude to support real-time AR applications. AR systems have been identified in many areas as holding enormous promise to enhance human management of complex systems. Key to the effectiveness of AR systems is the performance of the integrated positioning system, as this establishes the accuracy to which virtual objects can be aligned with the real world. In the case study a multi-antenna array of dual frequency GPS receivers, a fibre optic gyro and vehicle odometer have been integrated with real-time imagery containing augmented objects to improve a driver’s ability to ‘see’ the road and surrounding vehicles despite poor visibility conditions [Kealy et al. 2004].

Furthermore in a second case study the navigation of pedestrians in combined urban and indoor environments is presented in this paper. In the research project NAVIO (Pedestrian **Nav**igation Systems in Combined **I**ndoor/**O**utdoor Environements) the guidance of visitors to departments and persons of the Vienna University of Techology is investigated [Retscher 2004]. Thereby a navigation system is employed which integrates several different sensors and location techniques, i.e., GNSS and indoor location techniques, cellular phone positioning, dead reckoning sensors (e.g. magnetic compass, gyro and accelerometers) for measurement of heading and distance travelled as well as barometric pressure sensors for height determination. The results of simulation studies and practical tests could confirm that such a service can achieve a high level of performance for the guidance of a pedestrian in urban areas and mixed indoor and outdoor environments [Retscher and Thienelt 2004].

2 Review of Positioning Technologies Used in Navigation

For location determination of cellular phones or other mobile devices advanced positioning methods have been developed based on measurements using the signals of the wireless network. Most of them are based on classical terrestrial navigation methods where at least two observations to different base transmitting stations (BTS) are required to obtain a 2-D position fix [see e.g. Balbach 2000, Drane et al. 1998, Hein et al. 2000, Retscher 2002]. The achievable positioning accuracy thereby depends mainly on the location method and type of wireless network (GSM, W-CDMA, UMTS). Thereby the most accurate location method is the so-called Enhanced Observed Time Difference (E-OTD) method where the position fix is obtained from the measurements of time differences of signals sent from at least three BTS at the mobile station (MS) and a reference station in the network which is referred to as Location Measurement Unit (LMU). Using E-OTD the achievable positioning accuracy ranges between 50 to 150 m for urban areas. As advanced and more accurate methods, such as E-OTD, however, require modification of the network as well as installation of additional hardware and one LMU for every 3 to 5 serving BTS's, they have not been widely deployed yet in wireless networks around the world. Useable location-based services therefore rely mostly on cell positioning (i.e., Cell ID) which provides only positioning accuracies on the 150 m to 1 km level in urban areas and up to 35 km in rural areas. Recent developments have therefore been concentrated on the reduction of network modification for advanced positioning. The so-called Matrix method [Duffett-Smith and Craig 2004] does not need any additional hardware in the network apart from a SMLC (Serving Mobile Location Centre) where the location determination of the mobile handset is performed. The standard matrix method is based on E-OTD that does not require any LMU's. In this case a software upgrade is installed in the MS and the terminal measures the relative receive times of the signals from surrounding network transmitters (BTS). These timings are occasionally requested by the matrix SMLC from "anonymous" terminals and are used to calculate and maintain a list of network transmission offsets (the so-called network timings). When a position request for a specified MS is generated by an application, the terminal responds with its timing measurements which the matrix locator then uses in conjunction with the network timings to calculate the position of the MS. Standard matrix systems have been tested around the world in different wireless networks and achieve a positioning accuracy of 50 to 100 m at the 67 % reliability level in the GSM network. The positioning can also be performed using only one MS as the measurements for obtaining the network timings need not to be simultaneous. Measurements at different times of one moving MS can be used instead of measurements from anonymous terminals. These are used to maintain the network timing model and the current measurement is used to calculate that location. In fact, the previous and current measurements can also be used in a single calculation to calculate all locations and hence to obtain the track of the moving MS. This method is also referred to as Solo Matrix and if it is embedded into the MS and combined with satellite positioning (GPS) the term Enhanced GPS (E-GPS) is used. Then the solo matrix can provide assistance data such as initial position and reference time for the GPS positioning as in the case of Assisted GPS (A-GPS).

Apart from cellular networks, wireless LAN have become popular in recent years. WLAN uses radio signals and is based on a standard defined by the Institute of Electrical and Electronics Engineers (IEEE) (IEEE 802.11 2004). Thereby a WLAN network consists of so-called access points (or hotspots) and for location determination the signal strengths of the radio signals from at least one of these access points are measured. The location fix is then obtained with trilateration using measurements to several access points or through fingerprinting where the measured signal strength values are compared with in a database stored signal strength values from calibrated points [Beal 2003, Imst 2004, Retscher 2004]. As the indoor radio channel suffers from severe multipath propagation and heavy shadow fading, the fingerprint method achieves higher positioning accuracies than trilateration. Positioning accuracies of about 1 to 3 m could be obtained in a test office building using the fingerprint WLAN positioning system ipos of the German company Imst [2004]. The positioning system ipos makes use of a standard WLAN infrastructure and no modification of the hardware is required. The location determination of the mobile users is performed on a server in the network where the database of the signal strength values of the calibrated points is accessible. The database of the signal strength values has to be obtained using calibration measurements everywhere in the building (e.g. inside every room of the building). The calibration has to be done at least once in the beginning before the system can be used for positioning. Then the location of the user is calculated using a Kalman filter approach. Further postprocessing can be employed, e.g. sliding window averaging.

Multiple mobile devices can be simultaneously tracked who have access to at least one access point.

Ultra wideband (UWB) systems, which exploit bandwidths in excess of 1 GHz, are developed for high speed data transmission that has been standardized in IEEE 802.15.3a. They can be employed for measuring accurate time of arrival (ToA) used for estimation of distance or time difference of arrival (TDoA) used for distance difference estimation of the received signals from several base stations for indoor geolocation applications [Pahlavan et al. 2002, Kong et al. 2004]. With results of propagation measurement in a typical modern office building, it has been shown that the UWB signal does not suffer multipath fading [Win and Scholtz 1998], which is desirable for accurate ToA or TDoA estimation in indoor areas. Kong et al. [2004] achieved positioning accuracies in the range of 0.2 to 1 m at a 67% reliability level for indoor position determination using up to 8 base stations installed in a building.

Radio Frequency Identification, or RFID for short, is employed in the consumer goods industry for the contactless transmission of information for product identification. Uninterrupted traceability of the merchandize within the supply chain, optimization of order management as well as enhanced product availability are but a few advantages of this new technology [Metro Group 2004]. In future, RFID will replace the barcode for product identification. RFID consist of three components, i.e., tags (computer chips) which are in fact n-bit transponders, and readers with antennas. The reader is able to read the stored information of the tag in close proximity where the range is usually up to 6 m in the case of short-range tags with batteries. For the underlying technology the reader is referred to e.g. Finkenzeller [2002]. To employ RFID for positioning, one approach would be to install RFID tags along roads (especially in areas without GPS visibility, e.g. in tunnels, under bridges, etc.) and have a reader and antenna installed in the vehicle. When the vehicle passes the tag the RFID reader retrieves its ID and other information (e.g. the location). Such an approach is described by Chon et al. [2004] and they have shown that the tag can be read at vehicle speeds up to 150 km/h. Another possible application would be to install RFID tags at specific landmarks (or points of interest) and if the user passes by he can retrieve the tag information with its location. This would lead to the concept of active landmarks where the user of a navigation system is positioned using location information retrieved from the surrounding smart environment.

Also Bluetooth, which has been originally developed for short range wireless communication, can be employed for locating mobile devices in a certain cell area that is represented by the range of the device which is typically less than 10 m. It can also be employed for location determination using active landmarks.

Apart from the location techniques described above, other methods haven been developed for indoor location. Some of them are based on short-range or mid-range technologies using sensors such as transponders or beacons installed in the building. Also visual or optical tracking systems have been developed that employ specific markers that are installed around the building and used to detect the users current location [see e.g. Newman et al. 2004]. In the area of satellite positioning, further development is carried out for so-called high sensitive GPS (HSGPS) systems that can also work indoors (e.g. in a wooden building, sport complex, etc.). The number of satellites available and their geometry, however, limit the performance of these systems and the major error source is the multipath. Performance tests reported by Lachapelle [2004] showed much lower positioning accuracies for indoor satellite positioning than that achieved in open space without obstructions. Locating of a user on the correct floor of a multistory building is another challenging task. For more accurate determination of the user's height an improvement is achieved employing a barometric pressure sensor or digital altimeter additionally [Retscher 2004].

Table 1 summarizes the possible positioning techniques as well as their observables and their corresponding accuracies. The table contains also specifications of relative sensors such as a digital compass, gyro, acceleration sensors for dead reckoning as well as inertial measurement systems (INS) that measure the heading, pitch, roll and the distance travelled of user from a known start position. Future information about the dead reckoning sensors can be found in Retscher [2004] as well as Retscher and Thienelt [2004].

Positioning Method		**Observations**	**Accuracy**
GNSS	GPS	y, x, z	± 6 – 10 m
	DGPS		± 1 – 4 m
Velocity from GNSS		v_y, v_x v_z	~ ± 0,05 m^{-1} ~ ± 0,2 m^{-1}
Cellular Phone Positioning (GSM)	Cell ID	y, x	± 150 m – 35 km
	Solo Matrix		± 50 – 100 m
WLAN Positioning	IMST ipos	y, x, z	± 1 – 3 m
UWB Positioning (TDoA)		y, x, z	± 0.2 – 1 m
RFID Positioning (active landmarks)		y, x, z	± 6 m
Bluetooth (active landmarks)		y, x, z	± 10 m
Inertial Navigation Systems (INS)	Crossbow IMU700CA-200 Inertial Measurement Unit	a_x, a_y, a_z φ, ψ, θ	< ± 0.08 m s^{-2} < ± 0.03 °/s
Dead Reckoning	PointResearch DRM-III Dead Reckoning Module	y, x z φ	± 20 – 50 m per 1 km ± 3 m ± 1°
Heading	Honeywell Compass Module HMR 3000	φ	± 0.5°
Acceleration	Crossbow Accelerometer CXTD02	a_{tan}, a_{rad}, a_z	> ± 0.03 ms^{-2}
Barometer	Vaisala Pressure sensor PTB220A	z	± 1-3 m

Tab. 1. Positioning technologies for navigation services with their corresponding observables and accuracies [Duffett-Smith and Craig 2004, Imst 2004, Kong et al. 2004, Chon et al. 2004, Crossbow 2004a, PointResearch 2004, Honeywell 2004, Crossbow 2004b, Vaisala 2004] where y, x, z are the 3-D coordinates of the current position, v_y, v_x, v_z are the 3-D velocities, a_x, a_y, a_z are the 3-D accelerations, a_{tan} is the tangential acceleration and a_{rad} is the radial acceleration in the ground plane xy, φ is the direction of motion (heading) in the ground plane xy, ψ is the pitch and θ is the roll

3 Intelligent Vehicle Navigation

Augmented reality (AR) technologies enable digitally stored information (virtual objects) to be overlaid on views of the real world. To increase safety in driving under poor visibility conditions, for example the road boundaries and other safety features (e.g. traffic signs) as well as other vehicles on the road can be overlaid an image of the real world. Thereby the AR systems rely on position and attitude parameters to register augmented objects with the real world environment. The accuracy with which these parameters can be determined, as well as the availabilty of the solution, can have significant effect on the success of the AR system as a whole. To determine accurate and continuous outputs of position and attitude parameters (i.e., heading, pitch and roll), an array of three RTK GPS receivers, a fibre optic gyro and an odomter have been employed [Kealy and Scott-Young 2004]. The integration of the observations of these sensors in combination with map matching is performed using a Kalman filter approach which is referred to as "Intelligent Vehicle Navigation" (IVN).

The IVN algorithm developed is modelled on the simple rules of navigation that humans use on a day-to-day basis, and in doing so incorporates both geometric and topological map matching techniques. This algorithm has several advantages that are:

- It consists of a simple, yet effective set of four rules (closest road, bearing matching, access only and distance in direction).
- It relies on the short term precision of the navigation sensors (in particular DR when GPS is unavailable).
- It no longer assumes that the vehicle is on the road centerline, but instead it is 'following' the road network.

The closest road rule of IVN makes the assumption that the vehicle is travelling along a road (which is typically the case). This constraint can be included in the location solution, thus improving the accuracy of the computed position of the vehicle. This algorithm is most effective when the nearest road is in fact the road being travelled. However, when approaching intersections or when two roads are close to each other, the nearest road may not be the road being travelled. In such cases, constraining the solution to fall on the nearest road actually downgrades the calculated position. To avoid such errors, the bearing matching rule is required. This rule requires that the nearest road to which the vehicle's position is corrected must have a bearing similar to the measured direction of travel. This corrects the problem previously described. The threshold of similarity between the vehicle's bearing and the bearing of the surrounding roads may be adjusted to suit the accuracy of the navigation sensors. However, the larger the threshold, the more likely it becomes that roads will be incorrectly matched as having the same bearing as that of the vehicle. Figure 1(b) shows a case where application of the closest road and bearing matching rules incorrectly position the vehicle. The access only rule is designed to identify and prevent this error from occurring. Take, for example, a vehicle travelling along road A in the road layout diagram shown in Figure 2. Assuming the only route to road C is via road B, logic dictates that for the vehicle to be travelling along road C it must previously have travelled along road B. By logging previously travelled roads, the navigation system can prevent the vehicle from being located on a road that it could not possibly be on. The fourth rule, i.e., the distance in direction rule, reduces the accumulation of distance error by calculating the distance travelled by the vehicle in the direction of the road rather than the direction measured by the heading sensor. This is particularly important when heading sensors of low accuracy are employed. For example, if a vehicle travels 1000 metres along a road of bearing 60 degrees while measuring the road to have a bearing of 65 degrees (i.e. 5 degrees in error), an error in distance of 4 metres will occur (Figure 3). Although this may seem insignificant, over several kilometres, or with lower accuracy navigation instruments, larger errors can accumulate. This error is avoided by calculating the distance travelled independently from the bearing of the vehicle and then applying this distance in the direction of the road being travelled.

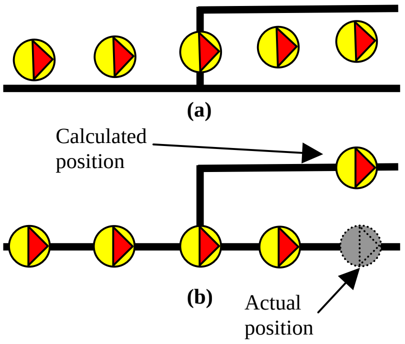

Fig. 1. Correcting to the nearest road taking road bearing into account: (a) Navigation without correction (b) Navigation with correction [after Kealy et al., 2004]

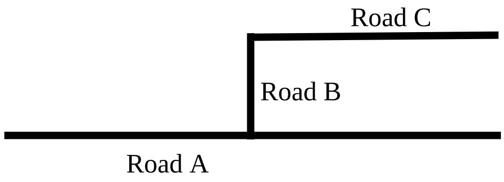

Fig. 2. Road layout scenario [after Kealy et al., 2004]

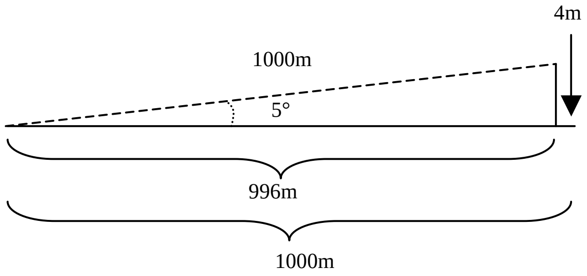

Fig. 3. Distance error propagated from bearing measurement error [after Kealy et al., 2004]

Incorporating IVN into the Kalman filter requires the development of observation equations from the IVN rules. The IVN observation equations are derived from the IVN estimate of the vehicle's 'corrected' position (which lies on a road segment) and an estimate of the vehicle's heading (i.e., the heading of the road segment at the IVN 'corrected' position). This procedure also allows for additional parameters to be estimated by the filter such as the offset from the centreline which is described by the Euclidean distance of the vehicle from the centreline. The process for including IVN information and the updated parameters for the state of the Kalamn filter is shown in Figure 4. Using data from GPS and DR sensors, the position and attitude of the vehicle are estimated. This information provides input for the IVN algorithms. The results from IVN are then combined with the GPS/DR measurements and filtered to provide an optimal solution using all available information. There is only one Kalman filter that has to be run twice where the first run provides the input for the IVN algorithms and secund run computes the optimal state of the mobile platform using all available measurements (i.e., GPS, DR and IVN). Further details about the algorithm can be found in Scott-Young [2004] as well as Kealy and Scott-Young [2004].

For the evaluation of the developed integration algorithm an AR prototype, i.e., ***i*ARM** (**I**ntelligent **A**ugmented **R**eality **M**apper), was constructed. Apart from the navigation sensors described previously, the ***i*ARM** consists of a digital video camera and a database containing 3-D objects used for augmentation. The system was installed on a typical land mobile vehicle. Figure 5a shows the augmented road boundaries on the real world image captured by the digital video camera. The results presented in the figure are typical of the visual registration accuracy of augmented data and the real world images. Figure 5b shows simulated poor visibility conditions. Despite these conditions the Intelligent Navigation Aid is able to highlight the road boundaries, clearly marking the edges of the road. If other vehicles are also positioned and their current location is transmitted to the system, then they can also be augmented to the digital image and the driver can 'see' them despite the poor visibility conditions.

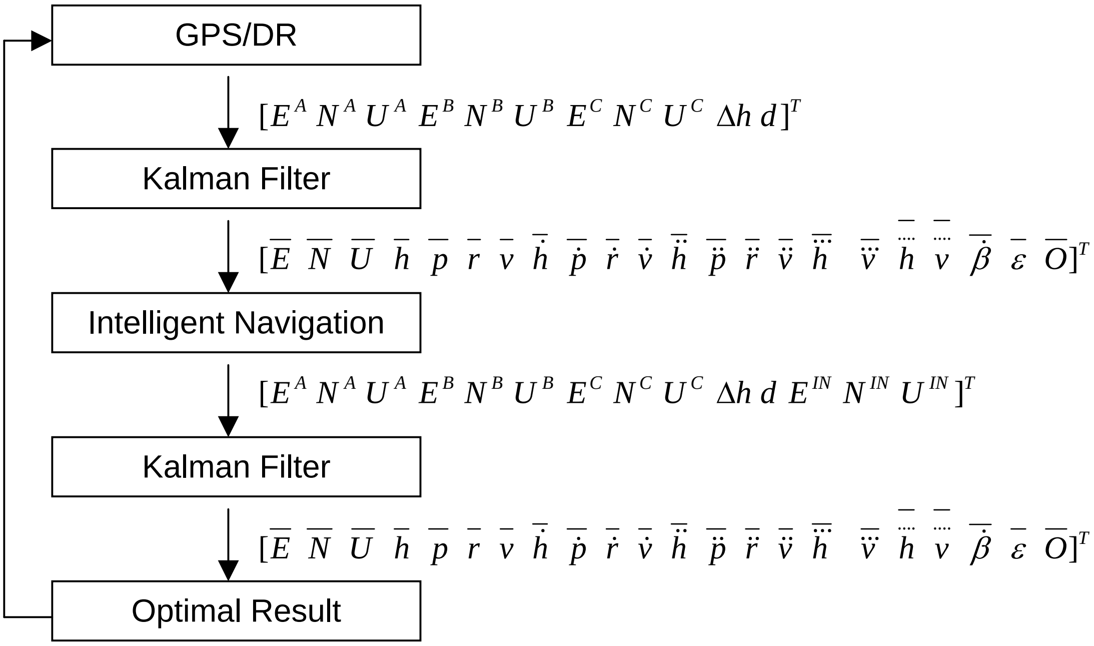

Fig. 4. Kalman filter process with Intelligent Vehicle Navigation [after Scott-Young, 2004] where E^A, E^B, E^C are the Eastings of the three GPS antennas A, B, and C in the platform reference frame, N^A, N^B, N^C are the Northings, U^A, U^B, U^C are the Up coordinates respectively, Δh is the measured change in heading, d is the measured distance travelled, $\bar{E}$ is the estimated Easting coordinate, $\bar{N}$ is the Northing coordinate, $\bar{U}$ is the Up coordinate, $\bar{h}$ is the heading, $\bar{p}$ is the pitch, $\bar{r}$ is the roll, $\bar{v}$ is the velocity, $\bar{\dot{h}}$ is the change in heading, $\bar{\dot{p}}$ is the change in pitch, $\bar{\dot{r}}$ is the change in roll, $\bar{\dot{v}}$ is the change in velocity or acceleration, $\bar{\ddot{h}}$ is the change in $\bar{\dot{h}}$, $\bar{\ddot{p}}$ is the change in $\bar{\dot{p}}$, $\bar{\ddot{r}}$ is the change in $\bar{\dot{r}}$, $\bar{\ddot{v}}$ is the change in acceleration or jerk, $\bar{\dddot{h}}$ is the change in $\bar{\ddot{h}}$, $\bar{\dddot{v}}$ is the change in jerk, $\bar{\ddddot{h}}$ is the change in $\bar{\dddot{h}}$, $\bar{\ddddot{v}}$ is the change in $\bar{\dddot{v}}$, $\bar{\dot{\beta}}$ is the gyro drift rate error, $\bar{\varepsilon}$ is the odometer scale factor error, $\bar{O}$ is the Euclidean distance from the road centreline, E^{IN} is the Easting coordinate as measured from the road database, N^{IN} is the Northing coordinate, U^{IN} is the Up coordinate respectively.

(a) (b)

Fig. 5. Augmented images using the *i*ARM (Intelligent Augmented Reality Mapper) [after Scott-Young, 2004]

4 Pedestrian Navigation Services

A reliable pedestrian navigation service requires the determination of the current user's position using different sensors that are integrated into the system design. In the work package "Integrated positioning" of the research project NAVIO (Pedestrian **Nav**igation Systems in Combined **I**ndoor/**O**utdoor Environements) the following challenging tasks are addressed [Retscher and Thienelt, 2004]:

- The capability to track the movements of a pedestrian in real-time using different suitable location sensors and to obtain an optimal estimate of the current user's position.
- The possibility to locate the user in 3 dimensions with high precision (that includes to be able to determine the correct floor of the user in a multi-storey building).
- The capability to achieve a seamless transition for continuous positioning determination between indoor and outdoor areas.

Thereby a navigation support must be able to provide location, orientation and movement of the user as well as related geographic information matching well with the real world situation experienced by pedestrians (Gartner et al. 2004a and b). The useable sensors and location techniques are summarizedin Table 1. A Kalman filter approach is particular suited for the integration and sensor fusion in real-time. For further information on the employed multi-sensor fusion model the reader is referred to Retscher and Mok [2004] and Retscher [2005].

Practical tests in the NAVIO project are carried out for the guidance of visitors of the Vienna University of Technology to certain offices in different buildings or to certain persons. Thereby we assume that the visitor employs a pedestrian navigation system using different sensors that perform an integrated positioning. In the following, first test measurements with the Dead Reckoning Module DRM III from PointResearch [2004] are presented. Figure 6 shows the dead reckoning observations as well as the GPS measurements along a 475 m long track in the park of Schönbrunn Palace in Vienna. In the dead reckoning module, measurements of accelerometers are employed to count the steps of the walking pedestrian and the distance travelled is obtained using a predefined value for the stride length. Using GPS observations the stride length can be calibrated. Furthermore a compass and a gyro are employed for measurement of the heading or direction of motion. The dead reckoning observations shown in Figure 6 have been obtained without using the GPS calibration. They reach deviations in the range of 7 m over a distance of 150 m and 20 m over 200 m from the given track. The GPS measurements have a maximum deviation of 7 m. Figure 6 shows also the resulting trajectory from the internal Kalman filter of the DRM III module calculated from a combination of GPS and DR observations. It can be seen that the large drift rate of the DR observations can be reduced. Using the DR observations, GPS outages (i.e., when GPS is unavailable) up to 150 to 200 m can be bridged with a reasonable positioning accuracy. For longer GPS outages, however, other location technologies have to be employed providing an absolute position estimate or IVN rules have to be integrated within the Kalman filter to correct for the DR drift.

5 Conclusions and Future Work

Newly developed ubiquitous location technologies can be integrated in modern advanced navigation systems to augment common satellite positioning (GNSS) and dead reckoning. Due to their integration the performance, usability as well as reliability and integrity of the

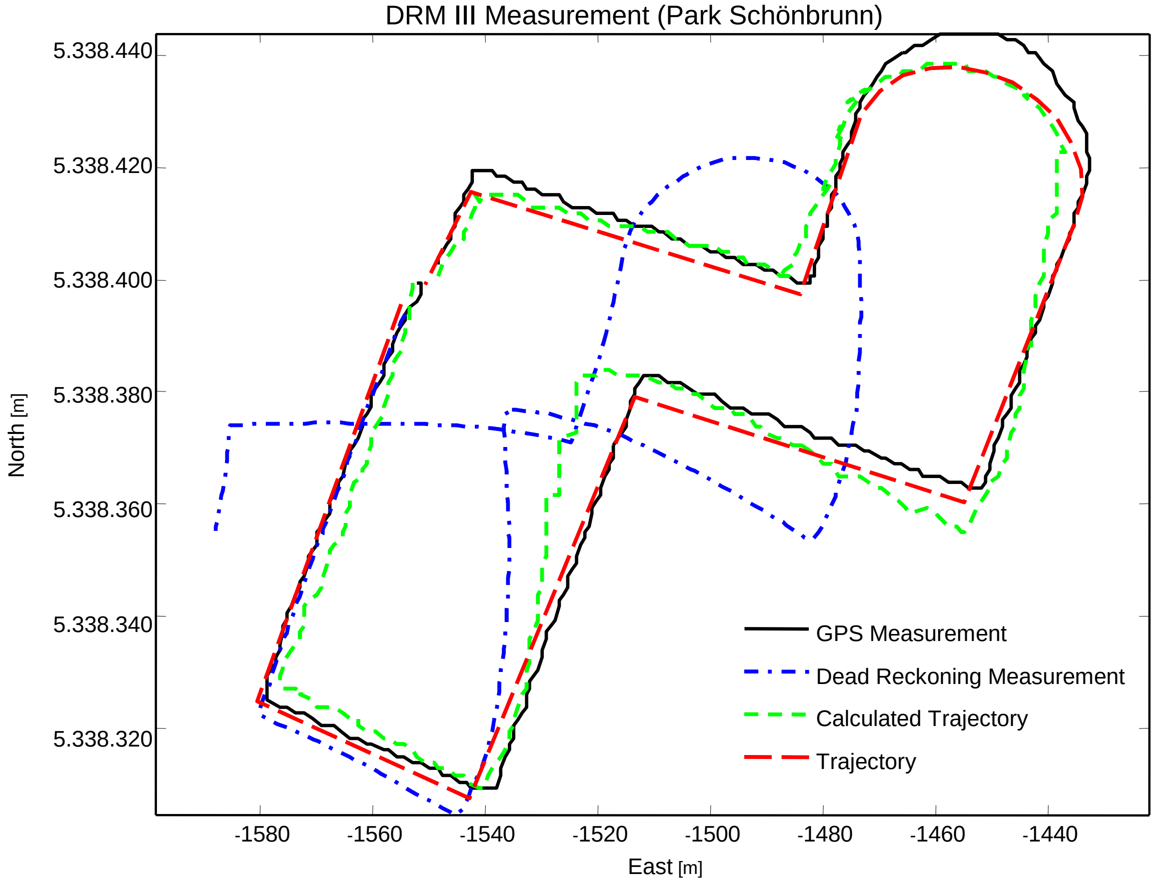

Fig. 6. Test measurements with the Dead Reckoning Module DRM III in the park of Schönbrunn Palace in Vienna

navigation service can be significantly increased. Nowadays also new low cost sensors (e.g. MEMS Inertial Measurement Units) can be employed for dead reckoning. Their performance was investigated in two different case studies. The aim of the first case study was to investigate the performance of an integrated position and attitude determination system to support AR applications in outdoor unprepared environments. Therefore multiple sensors and data sources were integrated in combination with map matching within a Kalman filter. Due to the integration of Intelligent Vehicle Navigation (IVN) rules into the filter a significant improvement to position and attitude determination during GPS outages could be achieved. In the case study the visualization of road boundaries and surrounding vehicles under poor visibility conditions for land vehicle navigation using an AR prototype was investigated. This has direct impact on safety aspects of driving. The second case study analyzed the use of multiple sensors and location techniques for pedestrian navigation services where the integration of the sensors is performed using a multi-sensor fusion model based on an adapted Kalman filter approach. First test measurement results using a dead reckoning module incorporating GPS are presented. A further refinement of the approach can be achieved by the integration of other ubiquitous location technologies (e.g. for indoor positioning) into the navigation service and the use of IVN rules based on map matching.

Acknowledgements

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References

Balbach O., 2000. UMTS – Competing Navigation System and Supplemental Communication System to GNSS, in: Papers presented at ION GPS Meeting 2000, Salt Lake City, Utah, U.S.A., September 19-22, 2000.

Beal J. R., 2003. Contextual Geolocation - A Specialized Application for Improving Indoor Location Awareness in Wireless Local Area Networks, in: Papers presented at the Midwest Instruction and Computing Symposium MICS2003, The College of St. Scholastica, Duluth, Minnesota, USA, http://www.css.edu/depts/cis/ mics_2003/MICS2003_Papers/Beal.PDF (Last date accessed: July 2004).

Chon H. D., S. Jun, H. Jung, S. W. An, 2004. Using RFID for Accurate Positioning, in: Papers presented at the 2004 International Symposium on GNSS, Sydney, Australia, 6-8 December, 2004, 10 pgs.

Crossbow, 2004a. IMU700CA – Fiber Optic Gyro Based IMU, Product Information, Crossbow, U.S.A., http://www.xbow.com/Products/Product_pdf_files/Inertial_pdf/6020-0037-01_B_IMU700CA.pdf (Last date accessed: December 2004).

Crossbow, 2004b. CXTD Digital Tilt and Acceleration Sensor, Product Information, Crossbow, U.S.A., http://www.xbow.com/Products/Product_pdf_files/Tilt_pdf/6020-0012-01_B_CXTD.pdf (Last date accessed: December 2004).

Drane C., M. Macnaughtan, C. Scott, 1998. Positioning GSM Telephones, IEEE Communications Magazine, April 1998.

Duffett-Smith P. J., J. Craig, 2004. Matrix, and Enhanced Satellite Positioning, in: Papers presented at the 5th IEE International Conference on 3G Mobile Communication Technologies, Savoy Place, London, UK, 18-20 October 2004, 4 pgs.

Finkenzeller K., 2002. RFID Handbook: Fundamentals and Application in Contactless Smart Cards and Identification, Carl Hanser Verlag, Munich, Germany.

Gartner G., A. Frank, G. Retscher, 2004a. Pedestrian Navigation System for Mixed Indoor/Outdoor Environments, in: Gartner G. (Ed.): Geowissenschaftliche Mitteilungen, Schriftenreihe der Studienrichtung Vermessungswesen und Geoinformation, TU Wien, Heft 66, Papers presented at the 2nd Symposium on Location Based Services and Telecartography, Vienna, Austria, January 28-29, 2004, pp. 161-167.

Gartner G., A. Frank, G. Retscher, 2004b. Pedestrian Navigation System in Mixed Indoor/Outdoor Environment – The NAVIO Project, in: Schrenk M. (Ed.): CORP 2004 and Geomultimedia04. Proceedings of the CORP 2004 and Geomultimedia04 Symposium, Vienna, Austria, February 24-27, 2004, pp. 165-171, http://corp.mmp.kosnet.com/CORP_CD_2004/ archiv/papers/CORP2004_GARTNER_FRANK_RETSCHER.PDF (Last date accessed: December 2004).

Hein G., B. Eissfeller, V. Oehler, J. O. Winkel, 2000. Synergies Between Satellite Navigation and Location Services of Terrestrial Mobile Communication, in: Papers presented at ION GPS Meeting 2000, Salt Lake City, Utah, U.S.A., September 19-22, 2000.

Honeywell, 2004. HMR 3000 Digital Compass Module, User's Guide, Honeywell International Inc., USA, http://www.ssec.honeywell.com/magnetic/datasheets/hmr3000_manual.pdf (Last date accessed: December 2004).

IEEE 802.11, 2004. IEEE 802.11TM Wireless Local Area Networks - The Working Group for WLAN Standards, http://grouper.ieee.org/groups/802/11/ (Last date accessed: December 2004).

Imst, 2004. Indoor Locating – Imst ipos, Project c21, Presentation, IMST GmbH, Carl-Friedrich-Gauß-Str. 2, D-47475 Kamp-Lintfort, Germany.

Kealy A. N., S. Scott-Young, P. Collier, I. Bishop, 2004. Improving Land Vehicle Safety Using Augmented Reality Technologies, in: Papers presented at the 4th Symposium on Mobile Mapping Technology, Kunming, China, March 29-31, 2004, CD-Rom Proceedings, 7 pgs.

Kealy, A. N., S. Scott-Young, 2004. An Integrated Position and Attitude Determination System to Support Real-Time, Mobile, Augmented Reality Applications, in: Papers presented at the 2004 International Symposium on GNSS, Sydney, Australia, 6-8 December, 2004, 17 pgs.

Kong H., Y. Kwon, T. Sung, 2004. Comparisons of TDOA Triangulation Solutions for Indoor Positioning, in: Papers presented at the 2004 International Symposium on GNSS, Sydney, Australia, 6-8 December, 2004, 11 pgs.

Lachapelle G., 2004. GNSS Indoor Location Technologies, in: Papers presented at the 2004 International Symposium on GNSS, Sydney, Australia, 6-8 December, 2004, 15 pgs.

Metro Group, 2004. Welcome to the Future Store – A Successful Start in the Future of Retailing, Product information, http://www.future-store.org/ (Last date accessed: December 2004).

Newman J., M. Wagner, M. Bauer, A. Mac Williams, T. Pintaric, D. Beyer, D. Pustka, F. Strasser, D. Schmalstieg, G. Klinker, 2004. Ubiquitous Tracking for Augmented Reality, Technical Report, Vienna University of Technology, http://www.ims.tuwien.ac.at/media/ documents/publications/ ubitrackismar04.pdf (Last date accessed: December 2004).

Pahlavan K., X. Li, J.-P. Mäkelä, 2002. Indoor Geolocation Science and Technolgy, IEEE Communications Magazine, February 2002, pp. 112-118.

PointResearch, 2004. DRM-III Dead Reckoning Module - Engineering Development Tools, PointResearch Corporataion, U.S.A., http://www.pointresearch.com/drm_eval.htm (Last date accessed: December 2004).

Retscher G., E. Mok, 2001. Integration of Mobile Phone Location Services into Intelligent GPS Vehicle Navigation Systems, in: Papers presented at the 3rd Workshop on Mobile Mapping Technology, Cairo, Egypt, January 3-5, 2001.

Retscher G., 2002. Diskussion der Leistungsmerkmale von Systemen zur Positionsbestimmung mit Mobiltelefonen als Basis für Location Based Services. in: Papers presented at the Symposium on Telekartographie, TU Wien, Austria, January 28-29, 2002, published as Geowissenschaftliche Mitteilungen, No. 58, Institute of Cartography, Vienna University of Technology, Austria, pp. 41-58.

Retscher G., 2004. Multi-sensor Systems for Pedestrian Navigation, in: Papers presented at the ION GNSS 2004 Conference, Long Beach, California, U.S.A., September 21-24, 2004, CD-Rom Proceedings, 12 pgs.

Retscher G., E. Mok, 2004. Sensor Fusion and Integration using an Adapted Kalman Filter Approach for Modern Navigation Systems, Survey Review, Vol. 37, No. 292 April 2004, pp. 439-447.

Retscher G., M. Thienelt, 2004. NAVIO – A Navigation and Guidance Service for Pedestrians, in: Papers presented at the 2004 International Symposium on GNSS, Sydney, Australia, 6-8 December, 2004, 12 pgs.

Retscher G., 2005. A Knowledge-based Kalman Filter Approach for an Intelligent Pedestrian Navigation System. in: Papers presented at the ION GNSS 2005 Conference, Long Beach, California, U.S.A., September 13-16, 2005, CD-Rom Proceedings, 11 pgs.

Scott-Young S., 2004. Integrated Position and Attitude Determination for Augmented Reality Systems, PhD Dissertation, The University of Melbourne, Australia, 247 pgs.

Vaisala, 2004. PTB220 Digital Barometer, Vaisala, Finland, http://www.vaisala.com/ DynaGen_Attachments/ Att2468/PTB220%20Brochure.pdf (Last date accessed: December 2004).

Win M., R. Scholtz, 1998. On the Performance of Ultra-Wide Bandwith Signals in Dense Multipath Environment, IEEE Commun. Letters, Vol. 2, No. 2, February 1998, pp. 51-53.

Performance and Accuracy Test of a WiFi Indoor Positioning System

Günther Retscher, Eva Moser, Dennis Vredeveld, Dirk Heberling and Jörg Pamp

Abstract

Location based-services and personal navigation require the location determination of a user not only in outdoor environments but also indoor. For indoor location already established wireless infrastructure such as WiFi (Wireless Fidelity) or WLAN (Wireless Local Area Networks) can be employed. This approach has the advantage that no costly hardware installations are necessary inside a building if WiFi is already available. The IMST GmbH has developed a software framework called "ipos" for indoor positioning technologies. The principle of the developed platform and the performance of the location determination using WiFi in a localization testbed of IMST GmbH are presented in this paper.

1 Introduction

WiFi has won growing interest and users in the last years. In particular the comfortable and mobile access to the internet were here the driving factors. Access points can nowadays be found in our daily environment, e.g. in many office buildings, public spaces and in urban areas. Parallel to this development there is meanwhile substantial interest in offering the user information which refers to the current location of the user (so-called Location-based Services LBS). Such LBS, however, will be accepted by the user only if the cost performance ratio is satisfactory. Thus if existing infrastructure such as WiFi without additional hardware installation can be used for location determination, then the realization costs are small and the service can be offered under attractive conditions.

A common approach for the localization of a handheld terminal or mobile device by means of WiFi is based on measurements of received signal strengths of the WiFi radio signals from the surrounding access points at the terminal [see e.g. Heberling, 2005; Teuber and Eissfeller, 2006]. This information is available due to the beacon broadcast multiple times a second by every access points. An estimate of the location of the terminal is then obtained on the basis of these measurements and a signal propagation model inside the building. The propagation model can be obtained using simulations or with prior calibration measurements at certain locations. In the second case, the measured signal strength values at a certain location in the building are compared with the signal strength values of calibrated points stored in a database. This technique is also referred to as fingerprinting.

The IMST GmbH has developed a software platform as a basis for the realization of LBS applications. It consists of an efficient, freely parameterizable framework, which is suitable for multiple application architectures. Thereby signal strength measurements are performed on user terminals, while evaluations and visualizations can take place if necessary on user terminals. The developed positioning system "ipos" makes use of a standard WiFi infrastructure and no modification of the hardware is required.

In a study the performance and the achievable positioning accuracies of the positioning system “ipos” have been tested. This study was conducted in cooperation between the Vienna University of Technology and IMST GmbH. The tests were performed in a localization testbed in an office building of IMST. Currently, the testbed is based on WiFi and uses standard IEEE802.11x WiFi hardware. With seven access points an area of over 1500 m^2 is covered (see Figure 3) where the tests have been performed in an area half of the total covered size. The results of this study are presented in this paper. It is possible to localize a user in the testbed with an accuracy of better than 3 metres at a 90 % significance level. Of course, the original WiFi services are also still available.

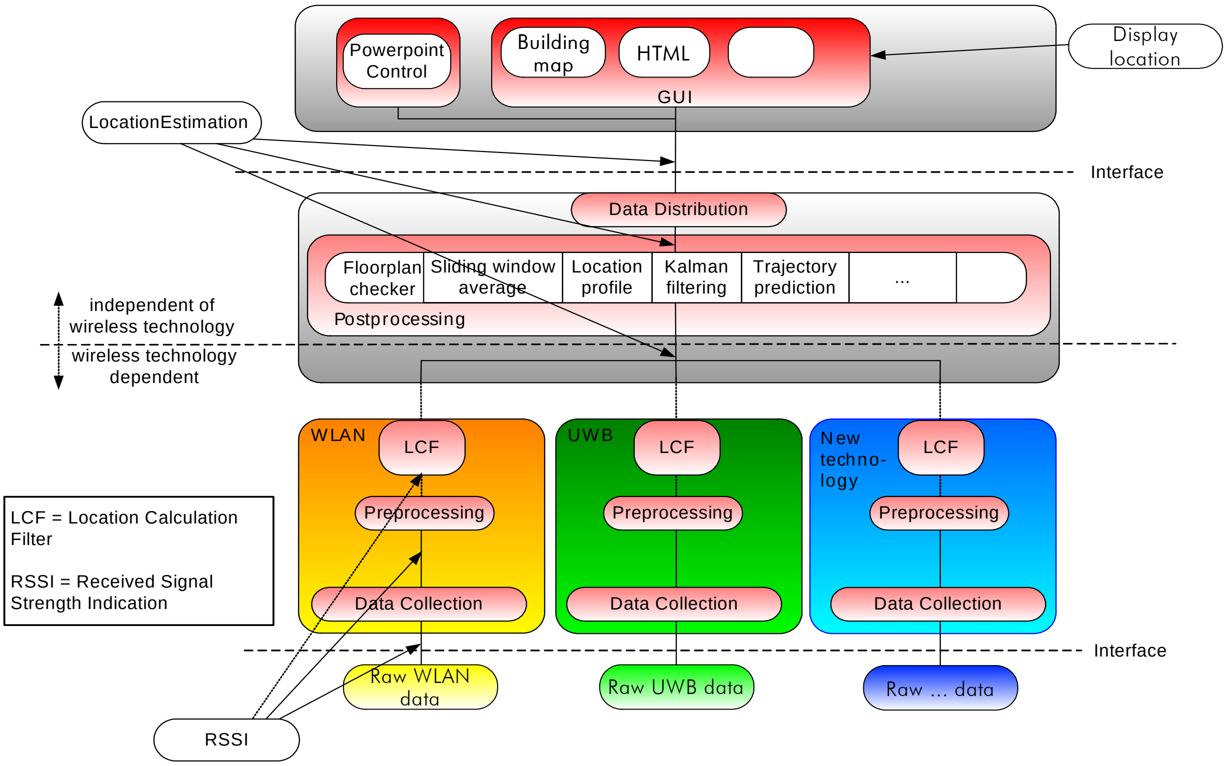

Fig. 1. The IMST *ipos* software framework

Extensions of the testbed to include other localization technologies, e.g. ultra-wideband (UWB) or GPS localization, are currently under development. Figure 1 shows the “ipos” system design and the software framework. The software framework supports multiple localization techniques. For example, in the WiFi (or WLAN) case, the user terminal measures signal strengths, while calculations and visualizations can be performed within the network or at the user terminal. This raw data is then transmitted to the framework and received at the WLAN data collector block. It is then processed bottom-up until it reaches a data distribution filter. The next (optional) step after received raw data involves pre-processing the data. This can include averaging or (in case of WiFi) filtering on MAC address of the access points. The next step (LCF) is mandatory and converts the received raw data into a position. The position represents the estimated location of the user that has sent the raw data. The next step is postprocessing. Once this step is reached, all data is independent of its underlying wireless technology. Using different processing steps, the estimation can be adapted to the application’s needs. One of the possible postprocessing steps is the sliding window average, which will be explained in more detail in section 3.3. Data fusion, finally, allows then for a seamless handover between multiple localization techniques.

2 Principle of WiFi Fingerprinting

The principle of WiFi positioning is based on the fact that the perceived signal strength of WiFi access points in the user's surroundings is a function of his position [Bahl and Padmanabhan, 1999]. This location dependant information can be acquired from the WiFi device driver. A device driver may support two ways to obtain information that is relevant for our purposes: active probing and RF monitoring. During RF monitoring, which is also known as passive scanning, the WiFi device listens for beacon messages on assigned channels. These beacon messages are broadcasted periodically by an access point in order for a client to find potential access points in range to associate to. This is, for instance, necessary if the signal-to-noise ratio (SNR) of the signal from the client's current access point degrades and connectivity may be lost. The beacon messages received can then be used to initiate a hand-off to an access point with a better SNR. During active probing, which is also known as active scanning, the driver uses probe request frames on each channel where it is able to detect wireless activity. Every access point receiving this probe request will respond with a probe response frame. Both beacon and probe response packets contain the MAC addresses of visible[23] access points. The corresponding signal strength can be obtained through the services provided by the WiFi MAC-layer, see IEEE [1999] for details. Once the scan command is completed, it results in a list of all visible access points with their current radio signal strength indicator (RSSI) for the current position. As the RSSI value is an indication on the relative position with respect to the corresponding access point, it is the main parameter the location calculation is based upon.

2.1 Location Calculation

The calculation of the location of a user takes place in two phases: an offline and an online phase. During the offline phase, which has to be executed only once for each building, a so-called *radiomap* will be composed. This radiomap can be considered to be a collection of calibration points at different locations in the building, each with a list of RSSI values for visible access points at that particular location. This process is also known as *fingerprinting*. During the online phase, the calibration points are being used to calculate the most probable location of the user, whose actual location is unknown.

2.1.1 Offline Phase

As mentioned before, the offline phase can be seen as a calibration. A certain amount of locations will be chosen, depending on the size and layout of the building. At each of these locations, a number of calibration measurements will be performed. This is due to the fact that the orientation of the user affects the RSSI value measured by the WiFi device. For example, if the user's physical location is between the access point and the mobile device, the measured signal strength will probably be smaller compared to the situation where the user positions itself on the opposite side of the device. This is due to the fact that the signal is attenuated by the human body. The difference between two orientations has been reported to be as much as 5 dB (compare Figure 5) [Bahl and Padmanabhan, 2000; Ladd et al., 2002].

The goal of a single measurement is to determine the received signal strength of every visible access point at this location with this orientation. Due to the fact that the received signal strength is being influenced by many factors, a number of sequential measurements

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[23] In this context, visible means that the signal strength of this access points is larger than the noise level. The noise level is considered to be –97 dBm by default.

will be taken in order to collect statistically more reliable information on what average signal strength can be expected. Every measurement consists of a list of visible access points. For each access point, the received signal strength is measured. Once the measurements have been performed, a histogram is made with the measured data (see Figure 2). Each access point yields a separate histogram. These histograms are stored in the system database.

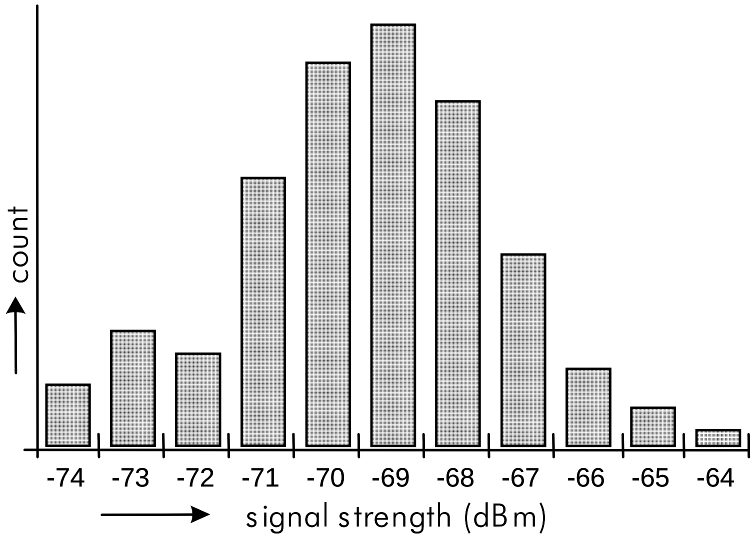

Fig. 2. Histogram of the measured signal strength values for one access point

2.1.2 Online Phase

As mentioned before, the online phase is the phase where the calculation software periodically receives measurements from one or more mobile devices. This information is compared against the values obtained from the offline phase, which yields a calculated position for each device. Once the received measurement has been parsed and found to be correct, it will be used as input for the calculation algorithm. The calculation is the central part of the *ipos* (Indoor Positioning) software framework, which will be explained in more detail in the following section. Details regarding the algorithms used can be found in Heberling [2005].

2.2 Software Framework

The methods described above have been integrated into a powerful software framework for indoor positioning technologies (see Figure 1). It represents a configurable, scalable, and open architecture for easy integration into third party applications on the one hand and adding more wireless localization technologies on the other hand. Running on Windows XP, Windows Mobile 2003, and Linux it supports a wide range of applications. The framework can be divided horizontally and vertically. Horizontally, the different processing steps are displayed, while vertically different wireless technologies can be distinguished, e.g. WiFi and UWB. However, once a location has been calculated, there is no longer a difference between the wireless technologies and the vertical division no longer applies.

The different processing steps are organized as follows:

1. Data collection: this comprises the retrieval of the measured data from the device that is to be localized. In case of WiFi, this is a list of MAC addresses of access points with their respective RSSI values;
2. Preprocessing: contains any sort of preprocessing steps on the raw data obtained in the first step;
3. Location calculation (LCF): calculates the estimated location. The format of this location estimation is common to all localization technologies;
4. Postprocessing: contains any possible operation that may be performed on one (or more) calculated locations obtained from the previous step, e.g. a sliding average, trajectory prediction, etc;
5. Data distribution: receives the calculation locations and makes them available to client applications by means of a socket server.

For the test measurements that will be discussed in the following chapter, in general no pre- or postprocessing filters were used (except in one case where a sliding window average postprocessing filter was used in Figure 8 (b) in section 3.3), as the aim of these measurements was to identify the accuracy of the location calculation as such.

3 Test Measurements

The WiFi positioning system “ipos” was tested in the localization testbed in the office building of IMST GmbH. Figure 3 shows the first floor of the building where 7 access points (● in Figure 3) are located that cover an area of approximately 1500 m^2. For the tests 7 office rooms (A, B, C, G, H, I and J in Figure 3) with an average space of around 25 m^2 each, two connecting corridors with about 15 m^2 each and a foyer with 100 m^2 (area D, E, F in Figure 3) were selected.

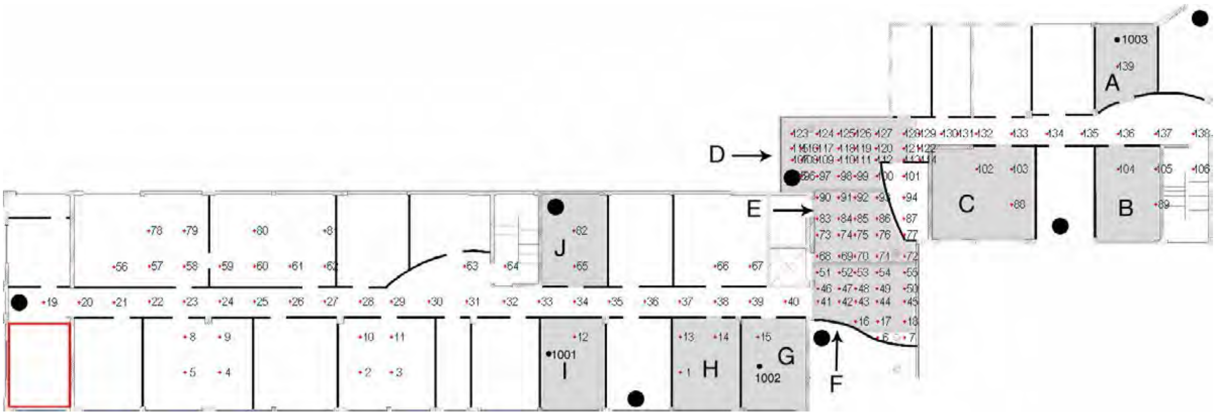

Fig. 3. Localization testbed in the office building of IMST GmbH

In the test bed standard IEEE802.11x WiFi hardware is used. For the measurements a tablet PC with a WIFI card was employed. The PC was put on a built trolley and was moved from each measurement to the next either in stop-and-go or kinematic mode. Figure 4 shows the measurements on a point in the corridor during the calibration of the system.

3.1 Calibration Measurements (Offline phase)

To use WiFi fingerprinting the signal strength values to all used access points have to be determined at certain locations in the building. These values are obtained during calibration measurements in the beginning and are stored in a database (see section 2.1.1).

Thereby the result of the measurements depends on the orientation of the user (see Figure 5). Usually the calibration measurements are performed in four directions (e.g. parallel or orthogonal to the main axis of the building). As can be seen in Figure 5 the signal strength varies quite significantly for the four different orientations. The maximum value of the received signal strength is in the range of -32,9 to -43,9 dBm.

Fig. 4. Measurement set up in the offline phase

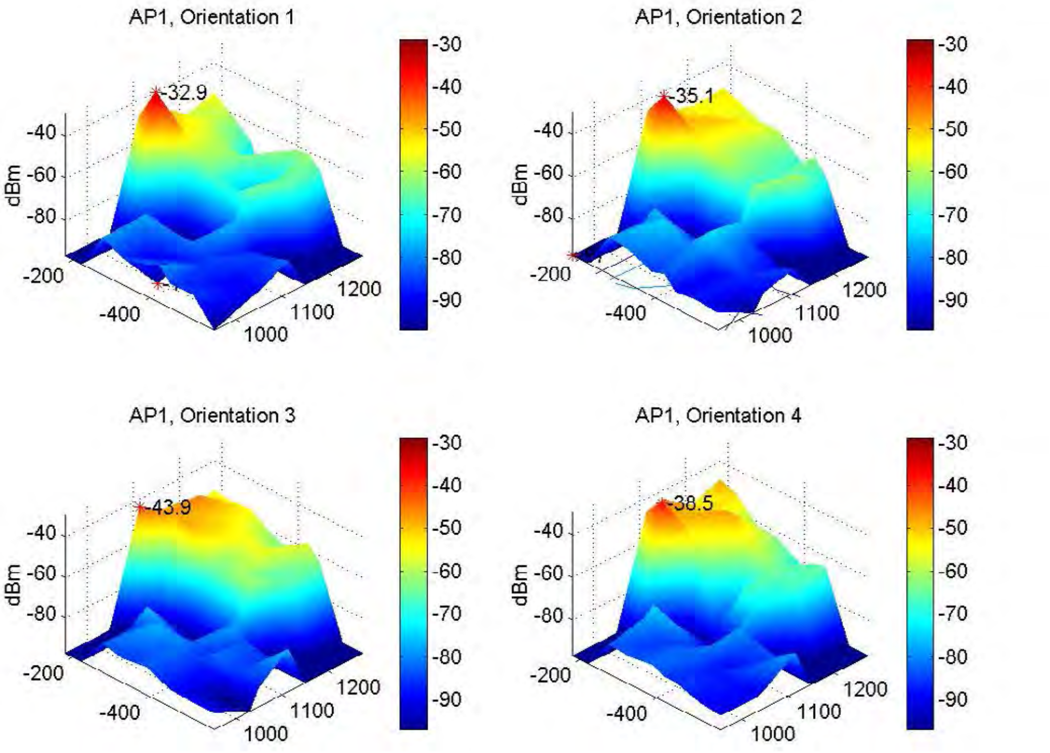

Fig. 5. Signal strength observations to one access point at four different orientations

In tests it was also investigated if more than four orientations would yield to better results. Therefore a fifth orientation to the access point with the strongest signal strength values was observed. The tests have shown, however, that there are only marginal differences between the use of 4 or 5 directions during the calibration. Further information regarding this test can be found in Retscher et al. [2006]. From the analysis of the test it can be concluded that the use of 4 directions in the calibration measurements is sufficient as the fifth direction does not improve the overall system performance but would require more time in the data acquisition. Furthermore different observation times on the points have been tested. For this purpose points in office rooms and the foyer were selected and observation times from 10 seconds up to 2 minutes were used. As there were no significant differences for observations using 50 s and up to 1 min 20 s, usually an observation duration of 50 s was employed for the calibration measurements. In genreal, it must be noted that the obtained database in the calbriation is only valid for the current environment inside the building and the number of access points used. If the environment changes and additional access points become available a recalibration would be required.

3.2 Location Determination of a User in an Office Building

In several tests the accuracy performance of the location determination of a user of the WiFi positioning system “ipos” was analyzed. In the following some tests results for the location determination of a user in an office room are presented. As the office rooms in the testbed have similar sizes apart from the foyer (i.e., 100 m^2), the foyer was divided into three areas (i.e., area D, E, F in Figure 3) of similar size to a standard office room. In the office rooms usually one or two calibration points are located. For the tests also a continuously moving user and a standing user were investigated. Exemplary Figure 6 shows the position fixes of a moving user in room A (for the location of the room see Figure 3) where in Figure 6 (a) the position fixes using one calibration point and in Figure 6 (b) the position fixes using two calibration points inside the room are shown. In both cases the majority of the observed points lies inside the room (86% in the case of 2 calibration points and 69% in the case of 1 calibration point). In addition, around the room a tolerance zone of double the room size was drawn. In this tolerance zone 98% of the position fixes are located if two calibration points are used and 82% if one calibration point is used.

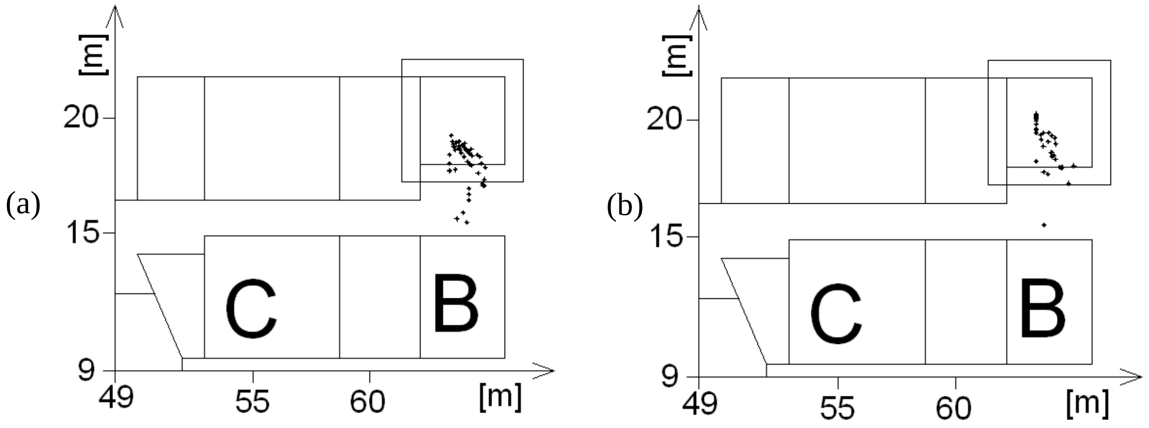

Fig. 6. Position fixes of a moving user in room A using one (a) or two (b) calibration points inside the room

Figure 7 summarizes all test results in the 7 office rooms and the 3 areas in the foyer (area A to J in Figure 3). Figure 7 shows the number of position fixes in % if one or two calibration points are used inside the room or defined area (Figure 7 (a)) or inside the tolerance zone (Figure 7 (b)). As can be seen from the diagrams, the probability that a position fix is located inside the room is higher if two calibration points are used. Thereby in 8 areas (out of 10) more than 50% of all position fixes are inside the room. If only one calibration point was used then only in half of the tested rooms more than 50% of all position fixes are inside. In room B and C only 10% of the position fixes were inside and in room I none of them. If the tolerance zone is considered the performance of the observations using only one calibration point is improved. The performance improvement is in average 22% (apart from room B). On the other hand, the performance improvement is in average 13% if two calibration points were used. It can therefore be recommended that two calibration points should be located in every room to have the majority of position fixes located inside the room. The tests have also shown that there is no significant difference between the observations in the standard office rooms and the foyer.

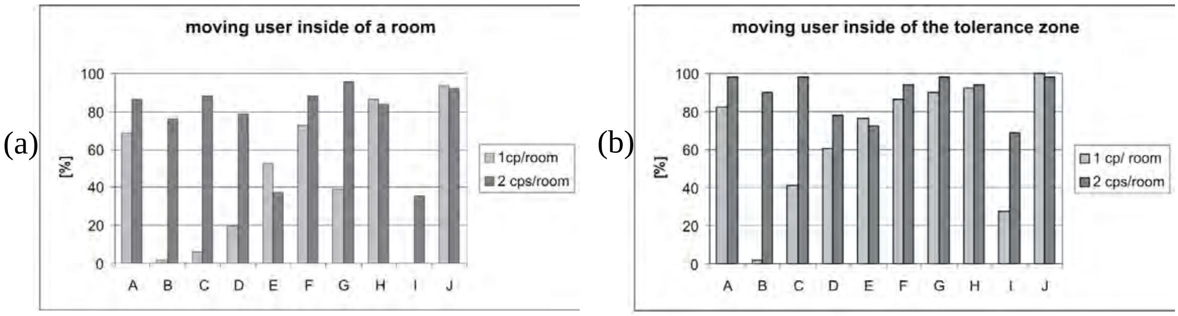

Fig. 7. Position fixes of a moving user inside a room (a) or tolerance zone (b) where one or two calibration points (cps) are used

3.3 Navigation Scenario

A typical use case is also the navigation and guidance from one office room to another. Figure 8 shows such a use case scenario where the user has to be positioned along the corridor as he walks from one office room (e.g. room A or B in Figure 8) to another room (e.g. room I or J in Figure 8). The top Figure 8 (a) shows the position fixes obtained from the ipos software. The track of the user can be clearly seen. The maximum deviations from the true path are less than 4 m in most cases. The bottom Figure 8 (b) shows the position fixes which have been smoothed using a sliding window average postprocessing filter. In this case, the maximum deviations from the true path are less than 2 m and 90% of all observations are within 1 m from the true path.

The sliding window average filter stores the last M positions it received. For every inserted new position, the oldest stored position is removed. The output of the filter is the weighted average of the M stored positions. All of the stored positions have equal weights of 1/M. See Figure 9 for details. Increasing the value of M makes the filter output smoother but also increases its latency.

4. Concluding Remarks and Outlook

For certain applications, an offline phase may be undesirable and/or more accurate positioning information may be required. Inherently, the radio channel between a transmitter (TX) and receiver (RX) contains information on the location of the one with respect to the other, which allows us to serve just these needs. To probe the channel, the TX has to radiate a pulse, such that the RX is able to measure the channel's response and obtain information on the radio channel and thus relative location. Typically, the radio channel consists of many multipath components, but the line-of-sight component contains the most localization information. However, to isolate the LOS component from the rest, the pulse duration must be shorter than the typical delay difference between the LOS component and the first arriving multipath component. In indoor environments, the so-called rms-delay spread is typically (very) small, meaning that the delay introduced by individual radio path differs only slightly. As a result, pulse duration needs to be in the

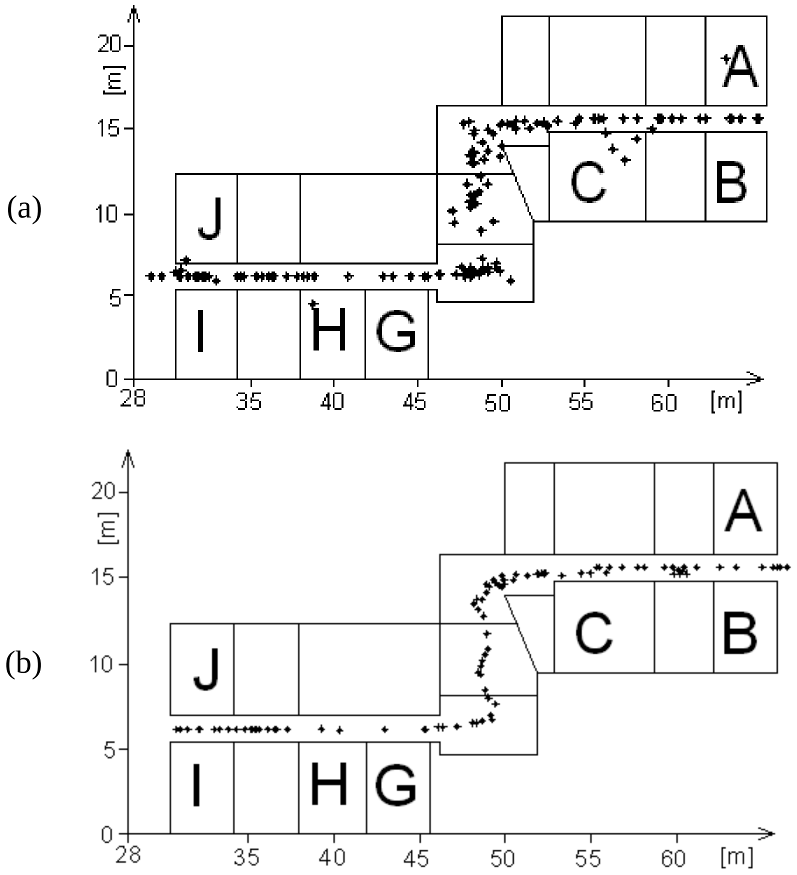

Fig. 8. Position fixes in a navigation scenario along the corridor for unfiltered observations (a) and using a sliding window average filter (b)

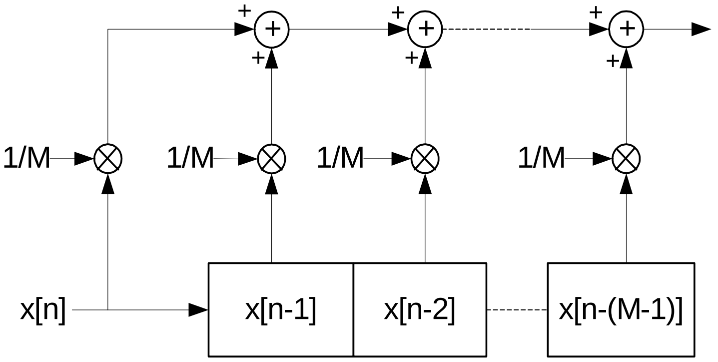

Fig. 9. Working principle of a sliding window average filter with size M

order of nanoseconds or smaller to avoid pulse overlapping[24]. The usage of short pulses inherently means that the bandwidth of the radio signal will be very large, i.e., in the order of several Gigahertz. In the past, no system was allowed to use such a large bandwidth, but after the legislation of UWB by the FCC in 2002 (FCC, 2002), and in the light of the upcoming legislation of UWB in Europe, industry and the scientific community quickly realized that accurate indoor localization can become reality, opening up a whole new application range.

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[24] In the case of WiFi, pulse-overlapping does occur, resulting in the distinct fading pattern as function of space, allowing us to do fingerprinting.

To gather experience and to prepare for future developments, IMST initiated the project Puls-On in August 2004, using a co-funding of the province of North-Rhine Westphalia. The goal of the project was to design an ultra wide-band localization system, able to localize in indoor environments. Furthermore, a fully functional demonstrator needed to be built using commercial-off-the-shelf (COTS) components.

To localize a single object or person, the Puls-On system uses three entities, mobile stations (MSs), base-stations (BSs) and a control station (CS). Each object or person to be localized has to carry such a MS, which periodically sends wideband radio beacons, which are used for both low rate but robust data communication and for localization. The base-station's function is to determine the angle of arrival (AoA) of the incoming radio beacons and to relay it to the CS.

To determine the AoA, the BS uses two patch antennas, separated by half a wavelength. The output of these antennas is processed by the modem to a) find the LOS component and b) to determine the related angle of arrival. Due to the large system bandwidth, the modem is able to distinguish individual radio paths. The CS is responsible for combining the AoA information in such a way that the location of all mobile-stations can be determined; and be visualised in a user-friendly form. For the computation of the location, the CS must receive the measured AoA from at least two base stations and needs to know the position and orientation of each BS. The usage of more BSs will inherently improve the accuracy/robustness of the localization.

The project was successfully completed in the summer of 2005, but the system is still under investigation and improvement. The system has recently been integrated with the ipos architecture, allowing the re-use of existing postprocessing and data-distribution filters, as well all of the location display applications.

References

Bahl P., V.N. Padmanabhan, 1999. User Location and Tracking in an In-building Radio Network, Microsoft Technical Report MSR-TR-99-12.

Bahl P., V.N. Padmanabhan, 2000. RADAR: An In-building RF-based User Location and Tracking System, Proc. IEEE Infocom.,

F.C.C., 2002. First Report and Order 02-48, Feb. 2002.

Heberling D., 2005. Indoor Positioning Using WLAN, in Conference Proceedings Wireless Congress 2005: Systems & Applications, Munich, Germany, November 2005.

IEEE, 1999. The Institute of Electrical and Electronics Engineers, Inc., Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications, IEEE Standard 802.11.

IMST GmbH, 2006. Indoor Positioning – Imst ipos, Project c21, IMST GmbH, http://www.centrum21.de/ (Last date accessed: January 2007).

Ladd, A. M., et al., 2002. Robotics-based Location Sensing Using Wireless Ethernet, Technical Report TR02-393, Department of Computer Science, Rice University.

Moser E., 2006. Genauigkeits- und Leistungstest eines WLAN Indoor Positionierungssystems, Diploma Thesis, Institute of Geodesy and Geophysics, Vienna University of Technology.

Retscher G., 2004. Multi-sensor Systems for Pedestrian Navigation, in Proceedings of ION GNSS 2004 Conference, Long Beach, California, U.S.A., September 21-24, 2004, unpaginated CD-Rom Proceedings, 12 pgs.

Retscher G., 2004. Allgegenwärtige Positionierungsmethoden für Moderne und Intelligente Navigationssysteme und –dienste, Österreichische Zeitschrift für Vermessung und Geoinformation VGI, 3-4, pp. 136-144.

Retscher G., A. Kealy, 2006. Ubiquitous Positioning Technologies for Modern Intelligent Navigation Systems, The Journal of Navigation, 59/1, pp. 91-103.

Retscher G., E. Moser, D. Vredeveld, D. Heberling, 2006. Performance and Accuracy Test of the WLAN Positioning System ipos, in Proceedings of the 3rd Workshop on Positioning, Navigation and Communication WPNC 2006, University of Hannover, Germany, March 16, 2006, Hannoversche Beiträge zur Nachrichtentechnik, Band 0.3, Shaker Verlag, 7-15, see also http://www.wpnc.net/years/wpnc06/programm06.htm (Last date accessed: January 2007).

Romme J., B. Kull, 2005. A Low-datarate and Localization System, in Proceeding of UWB4SN 2005: Workshop on UWB for Sensor Networks, Lausanne, Switzerland, November 2005, http://icawww1.epfl.ch/uwb4sn/slides/RommeUWB4SN041105.pdf (Last date accessed: January 2007).

Teuber A., B. Eissfeller, 2006. WLAN Indoor Positioning Based on Euclidian Distances and Fuzzy Logic, in Proceedings of the 3rd Workshop on Positioning, Navigation and Communication WPNC 2006, University of Hannover, Germany, March 16, 2006, Hannoversche Beiträge zur Nachrichtentechnik, Band 0.3, Shaker Verlag, 159-168, see also http://www.wpnc.net/years/wpnc06/programm06.htm (Last date accessed: January 2007).

Augmentation of Indoor Positioning Systems with a Barometric Pressure Sensor for Direct Altitude Determination in a Multi-storey Building

Günther Retscher

Abstract

A challenging task is to determine the correct floor of a user in a multi-storey building using pedestrian navigation and guidance services as most common indoor location techniques provide only 2-D position determination. Therefore it can be recommended to augment the position determination system with a barometric pressure sensor for direct observation of height differences. In the research project NAVIO (Pedestrian **Nav**igation Systems in Combined **I**ndoor/**O**utdoor Environments) tests with a barometric pressure sensor have been performed and their results are presented in the paper. The tests show that it is possible to determine the correct floor of a user using a barometric pressure sensor as the standard deviation of the estimation of the height differences is better than ± 0.5 m.

1 Introduction

In recent years new technologies and methods for positioning in indoor environments have been developed. Useable geolocation techniques include cellular phone positioning, the use of WiFi or WLAN (wireless local area networks), UWB (ultra-wide band), RFID (radio frequency identification), Bluetooth and other systems using infrared, ultrasonic and radio signals [see e.g. Retscher, 2005b]. In this paper a brief overview of some of these technologies that can be employed for personal navigation systems is given. Most of the systems, however, are able to locate the user only in two dimensions and the altitude or height of the user is not determined. To be able to locate a user on the correct floor of a multi-storey building, however, the height has to be observed using an additional sensor. In the research project NAVIO [Gartner et al., 2004] the use of a barometric pressure sensor for the direct observation of height differences is suggested. Test measurements have been performed in a 5-storey office building and are presented in the paper.

2 Overview of Indoor Positioning Systems

For indoor positioning different location techniques have been developed which use signals such as infrared, ultrasonic, radio signals or visible light [Retscher and Kistenich, 2006]. Methods for position determination include Cell of Origin (CoO) where the location of the user is described in a certain cell area around the transmitter, measurement of Time of Arrival (ToA) where the travel time of a signal between a transmitter and receiver is obtained, measurement of Time Difference of Arrival (TDoA) where the time difference of signals sent from a transmitter is determined at two receiving stations, signal strength measurements for location determination using fingerprinting (e.g. WiFi fingerprinting [see Retscher, 2004]) where the signal strength values are compared with previously stored values in a database and the location of the user is obtained using a matching approach, and location determination using digital images [Retscher and Kistenich, 2006]. Table 1 gives an overview about different indoor location techniques.

System name	Signal	Method	Positioning	Tracking	Geometrical	Symbolic	Range	Costs	Positioning Accuracy [m]
Active Badge	IR	CoO		✓		✓	inside room	low	room
WIPS	IR	CoO	✓			✓	inside room	low	room
Active Bat	US	ToA		✓	✓		inside room	high	0,1
Cricket	US	ToA	✓			✓	inside room	low	1,2
Cellphones (GSM/CDMA)	RS	TDoA/ AoA		✓	✓		few km	low	50-100
A-GPS	RS	ToA	✓		✓		where GPS available	high	20-25
Locata	RS	ToA	✓		✓		several km	high	0,1-1
Paric P^3	RS	TDoA		✓	✓		20 m	high	0,1-1
Radar	RS	SS	✓	✓	✓		50-100m	high	3-4
IMST ipos	RS	SS	✓	✓	✓		50-100m	high	1-3
Ekahau	RS	SS	✓		✓		50-100m	high	1-3
WhereNet	RS	SS	N/A	N/A	✓		50-100m	N/A	N/A
UWB	RS	ToA/ TDoA	✓		✓		50-100m	high	0,2
Bluetooth	RS	CoO	✓	✓	✓		10 m	average	10
SpotON	RS	SS	✓	✓	✓		N/A	average	1 m^3
RFID	RS	CoO	✓	✓		✓	0.01-100m	low	1-100
CyberCode	VL	DI	✓			✓	inside room	average	variable
Ubitrack	VL	DI		✓	✓		inside room	N/A	N/A
EasyLiving	VL	DI		✓	✓		inside room	high	variable

Tab. 1: Comparison of some indoor location techniques

The following abbreviations are used in Table 1:

Signals:
IR....... Infrared
US...... Ultrasonic
RS...... Radio signals
VL...... Visible light

Postioning Methods:
CoO.... Cell of Origin
ToA.... Time of Arrival
TDoA.. Time Difference of Arrival
AoA.... Angle of Arrival
SS…... Signal strength measurement
DI…… Digital images

N/A..... not available

The systems Active Badge [Want et al., 1992] and WIPS [Roth, 2004] employ infrared signals for location determination, Active Bat [Hightower und Boriello, 2001] and Cricket [Roth, 2004] use ultrasonic signals. Apart from CoO, for the location of cellular phones ToA or TDoA measurements can be performed [Retscher, 2002]. Satellite or similar signals are also employed for the location of cellular phones using Assisted GPS (A-GPS) or for the Australian system Locata [Barnes et al., 2003] which makes use of standard RTK positioning with L-band signals similar to GPS and the NZ system Paric P³ (Partial Pulse Positioning) [Paric, 2006] which is an inverse GPS concept. For indoor positioning the use of WiFi has become popular and the systems Radar [Bahl and Padmanabhan, 2000], IMST ipos [Imst, 2004], Ekahau [Ekahau, 2005] and WhereNet [WhereNet, 2005] are using WiFi signals from surrounding access points. Apart from WiFi also Ultra Wide Band (UWB) signals and Bluetooth [Hallberg et al., 2003] can be employed. SpotON employs also radio signals and perfoms signal strength measurements [Hightower et al., 2000]. Table 1 also contains three systems using digital images for location determination, i.e., CyberCode [Rekimoto and Ayatsuka, 2000], Ubitrack [Newman et al., 2004] and EasyLiving [Brumitt et al., 2000]. Apart from these also digital TV signals might be employed in the future for indoor positioning [see e.g. Do et al., 2006]. For a further description of the systems see Retscher and Kistenich [2006].

For navigation and wayfinding in smart environments the use of RFID (Radio Frequency Identification) for ubiquitous positioning is also a promissing solution. RFID is a method of remotely storing and retrieving data using devices called RFID tags. An RFID tag is a small object, such as an adhesive sticker, that can be attached to or incorporated into a product. RFID tags contain antennas to enable them to receive and respond to radio-frequency queries from an RFID transceiver. For location determination RFID tags can be placed on active landmarks or on known locations in the surrounding environment. If the user passes by with an RFID reader the tag ID and additional information (e.g. the 3-D coordinates of the tag) are retrieved. Thereby the range between the tag and reader in which a connection between the two devices can be established depends on the type of tag. RFID tags can be either active or passive. Passive RFID tags do not have their own power supply and the read range is less than for active tags. They have practical read ranges that vary from about 10 mm up to about 5 m. Active RFID tags, on the other hand, must have a power source, and may have longer ranges and larger memories than passive tags, as well as the ability to store additional information sent by the transceiver. At present, the smallest active tags are about the size of a coin. Many active tags have practical ranges of tens of metres, and a battery life of up to several years. The location method is Cell of Origin (CoO) and the size of the cell is defined by the range of the tags. Therefore the positioning accuracy of active RFID tags ranges between a few metres up to tens of metres and with passive tags up to about 5 m. Although this positioning accuracy can be low for some applications, RFID positioning can be very useful in combination with other sensors. A concept for indoor location determination using RFID has been developed and is presented in Retscher et al. [2006].

3 Principle of Location Determination of the User on the Correct Floor in a Multi-storey Building

The 2-D location of a person which should be located in a building can be determined using an indoor location system such as WiFi fingerprinting or RFID. In addition, the altitude of the person is obtained using the Vaisala pressure sensor PTB220A. The sensor can be employed for the determination of height differences from changes of the air pressure. The PTB220A is designed for measurements in a wide environmental pressure and temperature range with an extremely high accuracy [Vaisala, 2005]. Starting from a given height the pressure changes can be converted to changes in height using the following equation:

$$\Delta H = H_2 - H_1 = 18464 \cdot (1 + 0{,}0037 \cdot T_m) \cdot (\lg p_1 - \lg p_2) \tag{1}$$

where ΔH is the height difference in [m] between two stations 1 and 2, p_1 and p_2 are the pressure observations in [hPa] at station 1 and 2 and T_m is the mean value of the temperature in [°C] of both stations. It must be notetd that this equation is an approximation formula that is valid for central Europe only [Kahmen, 1997]. Tests showed that there is no significant difference between the results using the approximation formula and an equation derived from Jordan which is also valid for other parts in the world and takes into account the geographic location of the two stations.

4 Performance Tests of the Barometric Pressure Sensor for the Altitude Determination

Extensive testing has been carried out in a 5-storey office building of the Vienna University of Technology. The main results of this study are presented in the following. Figure 1 shows the test area. The trajectory leads from the main entrance of the building via two staircases to our Institute which is located on the third floor of the 5-storey building.

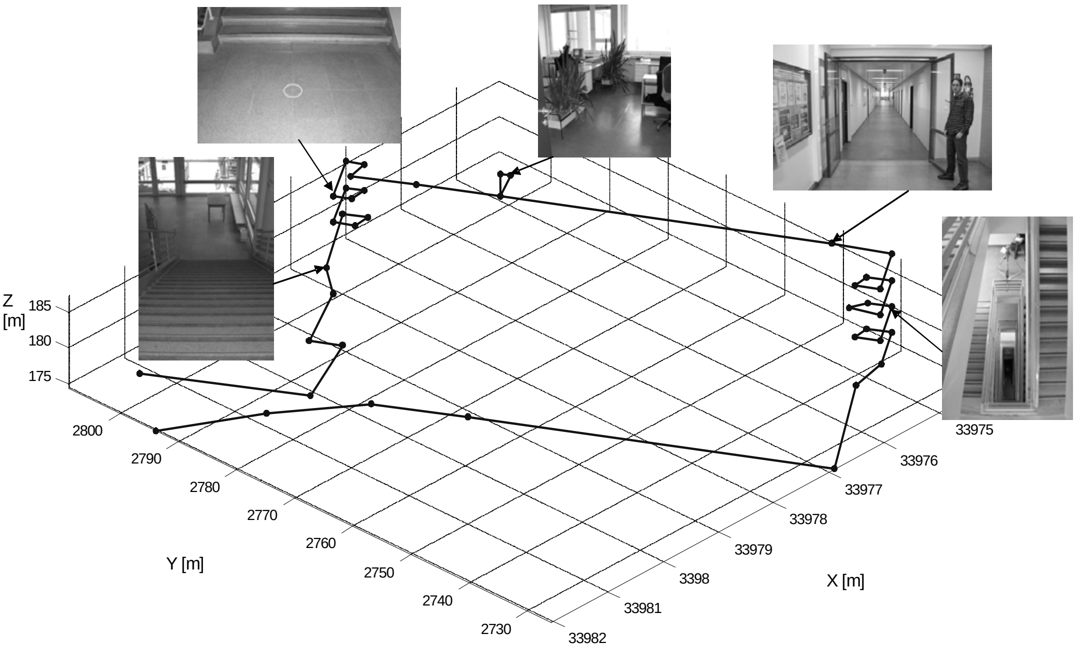

Fig. 1. Indoor trajectory in our office building of the Vienna University of Technology from the main entrance to the third floor of the building

4.1 Determination of the Sensor Drift

First of all the drift of the sensor was analyzed in several long-term tests. Figure 2 shows an observation of the sensor over a period of two hours performed on a benchmark located on the roof of the building. The height of the benchmark is 200.05 m. The sampling rate of the observations was one second. The temperature dropped from 16.5° C to 15.8° C during the two-hour observation period. The maximum deviation from the given height reached values of + 0.42 m and – 0.64 m in the first half hour. Thereby the observations can vary randomly within this range of about 1.06 m. Some discontinuous variations are also caused by the wind during the observation period. In summary, it can be concluded that no significant drift rates could be seen during several long-term tests. The influence of wind, temperature changes and the air conditioning system inside the building, however, can be clearly seen in the observations. For the first half hour of operation variations of the air pressure in the range of ± 0.15 hPa could be seen. Considering the resolution of the sensor, which is 0.01 hPa, the sensor can be regarded as stable and no drift rate will be considered in the following. Over longer observation periods than half an hour, the drift of the sensor can be calibrated using an update from an absolute altitude determination (e.g. using height observations from GPS or returning to points in the building with known altitude).

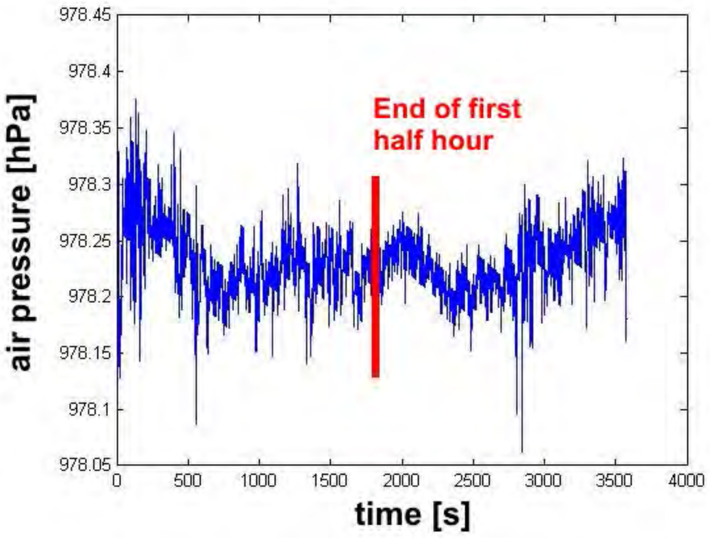

Fig. 2. Long term sensor observations with the Vaisala pressure sensor PTB220A on benchmark No. 11 on the roof of the building

4.2 Determination of a Characteristic Curve for the Barometric Pressure Sensor

It was also investigated if a functional connection between the observed pressure differences and the height differences can be derived. This connection can be described using characteristic curves which describe the functional connection between the observed pressure differences and the height differences. If such a curve exists and the functional connection is linear then the pressure differences can be converted into height differences. For this purpose observations in the building have been carried out during different times of the day and different absolute air pressures. Figure 3 shows six observations in the morning of one day and the resulting linear characteristic curve. The start point of three of these observations was on the ground floor and for the other three on the roof of the building. The resulting characteristic curve is given by the following equation:

$$\Delta H = 8.769 \cdot \Delta p \tag{2}$$

where ΔH is the height difference in [m] and Δp is the difference in air pressure in [hPa].

As can be seen from Figure 3 the measurement series show a good agreement with the resulting characteristic curve. There is also no difference if the observations start either on the ground floor or on the roof of the building. Further characteristic curves have been obtained from different measurement series at different absolute air pressures and are discussed in Kistenich [2005]. It could be seen that we are able to calculate a linear characteristic curve which describes a linear functional connection between the air pressure observations and the changes in height.

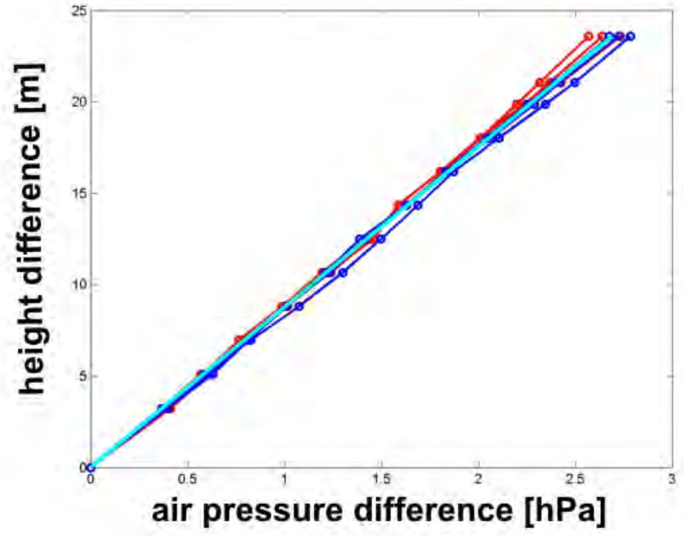

Fig. 3. Linear characteristic curve of six measurement series in the office building between the ground floor and the roof (6th floor)

4.3 Determination of the Height in the Building

Finally the accuracy of the height determination was analyzed. Figure 4 shows observations with the Vaisala pressure sensor PTB220A in the office building starting from the main entrance up to the third floor of the building. It can be clearly seen that the sensor is able to determine the correct floor of the user with a high precision relatively to a given start altitude determined outside the building (e.g. from GPS observations). The standard deviation of the pressure observation is in the range of ± 0.2 hPa and the maximum deviation of the determined height is less than 1.0 m for 91 % of the observations. Thereby the deviations depend also on the time of day; higher deviations are obtained during noon where usually more people are inside the building and larger variations of the air pressure occur caused by higher air circulation due to frequent opening of doors and windows. The maximum outlier during noon reaches about 1.4 m. In summary, it can be concluded that the sensor is able to locate the user on the correct floor.

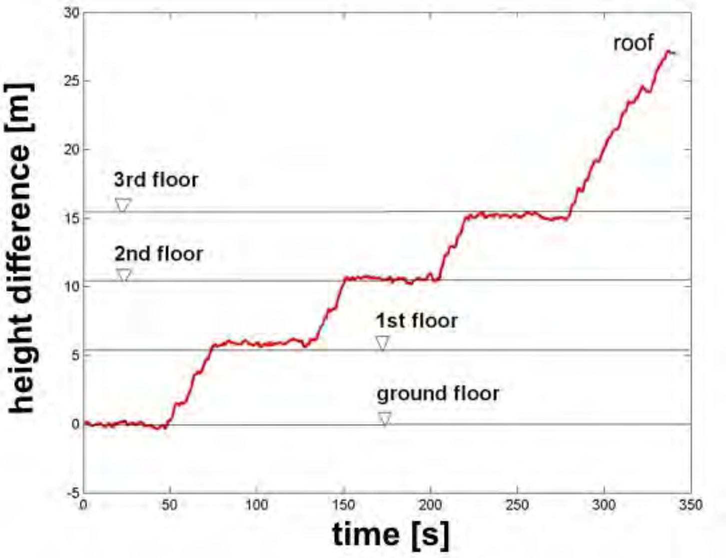

Fig. 4. Test measurements with the Vaisala pressure sensor PTB220A in an office building of the Vienna University of Technology

5 Conclusions and Outlook

For the location determination of persons and objects in buildings a variety of systems have been developed in recent years. In this paper an overview about their principle of operation and their performance is given. They provide mostly only 2-D location determination of the user and the determination of the correct floor is a very challenging task. Therefore in our research the augmentation of indoor location systems using a barometric pressure sensor for direct observations of the altitude was investigated. From the presented sensor tests it can be seen that a high precision and relability for the location of a pedestrian on the correct floor of a multi-storey building can be achieved if a barometric pressure sensor is employed. Then in combination with other indoor location techniques and dead reckoning sensors a continouous 3-D position determination in indoor environments is possible. The observations of all sensors have to be combined and an integrated position solution has to be obtained. A new multi-sensor fusion model has been developed for the integration and is described in Retscher (2005a) and Thienelt et al. (2005). Due to the development of new advanced sensors it can be expected that multi-sensor solutions including a barometric pressure sensor which provide 3-D location capabilities in outdoor and indoor environments will be deployed in pedestrian navigation services in the near future. We believe that these services will play an important role in the field of location-based services. Typical applications can include personal navigation and guidance services in multi-storey office buildings and tourist guides in complex urban and indoor environments.

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References

Bahl P., V. Padmanabhan, 2000. Radar: An In-Building RF-based User Location and Tracking System, Proceedings of IEEE Infocom, Tel-Aviv, March, pp. 775-784.

Barnes J., C. Rizos, J. Wang, 2003. Locata: A New Positioning Technology for High Precision Indoor and Outdoor Positioning, in: Papers presented at the ION GPS/GNSS 2003 Conference, Portland, Oregon, U.S.A., September 9-12, 2004, unpaginated CD-Rom Proceedings.

Brumitt B., B. Meyers, J. Krumm, A. Kern, S. Shafer, 2000. EasyLiving: Technologies for Intelligent Environments, Microsoft Corporation.

Do J-Y., M. Rabinowitz, P. Enge, 2006. Performance of Hybrid Positioning System Combining GPS and Television Signals, in: Papers presented at the IEEE/ION PLANS 2006 Conference, San Diego, California, U.S.A., April 25-27, 2006, CD-Rom Proceedings, pp. 556-564.

Ekahau, 2005. Ekahau Homepage, Finland, http://www.ekahau.com (Last date accessed: February 2007).

Gartner G., A. Frank, G. Retscher, 2004. Pedestrian Navigation System for Mixed Indoor/Outdoor Environments. in: Gartner G. (Ed.): Geowissenschaftliche Mitteilungen, Schriftenreihe der Studienrichtung Vermessungswesen und Geoinformation, TU Wien, Heft 66, Papers presented at the 2nd Symposium on Location Based Services and Telecartography, Vienna, Austria, January 28-29, 2004, pp. 161-167.

Hallberg J., M. Nilsson, K. Synnes, 2003. Bluetooth Positioning, Proceddings of the 10th International Conference on Telecommunications (ICT), Tahiti, February 23 – March 1, 2003.

Hightower J., R. Want, G. Boriello, 2000. SpotON: An Indoor 3D Location Sensing Technology Based on RF Signal Strength. University of Washington, Department of Computer Science and Engineering.

Hightower J., G. Boriello, 2001. A Survey and Taxonomy of Location Systems for Ubiquitous Computing, Technical Report, University of Washington, Department of Computer Science and Engineering.

Imst, 2004. Indoor Locating – Imst ipos, Project c21, Presentation, IMST GmbH, Carl-Friedrich-Gauß-Str. 2, D-47475 Kamp-Lintfort, Germany, see also http://www.centrum21.de/ (Last date accessed: February 2007).

Kahmen H., 1997. Vermessungskunde. 19. Auflage, Walter de Gruyter, Berlin, New York, pp. 475-482.

Kistenich M., 2005. Indoor Positioning: Vergleich von Systemen zur Positionsbestimmung und Navigation in Gebäuden, Diploma thesis, Institute of Geodesy and Geophysics, Research Group Engineering Geodesy, Vienna University of Technology.

Newman J., M. Wagner, M. Bauer, A. Mac Williams, T. Pintaric, D. Beyer, D. Pustka, F. Strasser, D. Schmalstieg, G. Klinker, 2004. Ubiquitous Tracking for Augmented Reality, Technical Report, Vienna University of Technology, http://www.ims.tuwien.ac.at/media/documents/publications/ubitrackismar04.pdf (Last date accessed: February 2007).

Paric, 2006. Partial Pulse Positioning (P³), Paric Measurement Homepage, New Zealand, http://www.paric.co.nz/ (Last date accessed: February 2007)

Rekimoto J., Y. Ayatsuka, 2000. CyberCode: Designing Augmented Reality Environments with Visual Tags, Proceedings of DARE 2000, Elsinore, pp. 1-10.

Retscher G., 2002. Diskussion der Leistungsmerkmale von Systemen zur Positionsbestimmung mit Mobiltelefonen als Basis für Location Based Services (LBS), in: Kelnhofer, F., Lechthaler, M., Brunner, K. (Eds.): Geowissenschaftliche Mitteilungen, Schriftenreihe der Studienrichtung Vermessungswesen und Geoinformation, TU Wien, Heft 58, pp. 41-58.

Retscher G., 2004. Multi-sensor Systems for Pedestrian Navigation, in: Papers presented at the ION GNSS 2004 Conference, Long Beach, California, U.S.A., September 21-24, 2004, unpaginated CD-Rom Proceedings, 12 pgs.

Retscher G., 2005a. A Knowledge-based Klaman Filter Approach for an Intelligent Pedestrian Navigation System, in: Papers presented at the ION GNSS 2005 Conference, Long Beach, California, U.S.A., September 13-16, 2005, unpaginated CD-Rom Proceedings, 11 pgs.

Retscher G., 2005b. Indoor Positioning Technologies for Personal Navigation Systems, in Grün A., H. Kahmen (Eds.): Optical 3-D Measurement Techniques VII, Papers presented at the 7th Conference on Optical 3-D Measurement Techniques, Vienna, Austria, October 3-5, 2005.

Retscher G., M.Kistenich, 2005. Höhenbestimmung in einem Gebäude mit einem digitalen Barometer für die Navigation von Fußgängern, Allgemeine Vermessungsnachrichten (AVN), 10/2005, pp. 348-354.

Retscher G., M.Kistenich, 2006. Vergleich von Systemen zur Positionsbestimmung und Navigation in Gebäuden. Zeitschrift für Geodäsie, Geoinformation und Landmanagement (ZfV), 131. Jahrgang, Heft 1/2006, pp. 25-35.

Retscher G., K. Zhang, S. Zhang, Y. Wang, 2006. RFID and GNSS for Indoor and Outdoor Positioning - Two Different Case Studies. European Journal of Navigation, Vol. 4, No. 5, November 2006, pp. 49-54.

Roth J., 2004. Data Collection, in: Schiller, J. and Voisard A. (Eds.): Location-Based Services, Morgan Kaufmann Publishers, U.S.A., pp. 175-205.

Thienelt M., A. Eichhorn, A. Reiterer, 2005. WiKaF – A Knowledge-based Kalman-Filter for Pedestrian Positioning, in: Gartner G. (Ed.): Geowissenschaftliche Mitteilungen, Schriftenreihe der Studienrichtung Vermessungswesen und Geoinformation, TU Wien, No. 74, Papers presented at the 3rd Symposium on Location Based Services and Telecartography, Vienna, Austria, November 28-30, 2005, pp. 99-103.

Vaisala, 2005. PTB220 Digital Barometer, User's guide, Vaisala, Finland, http://www.vaisala.com/businessareas/instruments/servicesupport/userguides/barometricpressure/PTB220%20User%20Guide%20in%20English.pdf (Last date accessed: February 2007).

Want R., A. Hopper, V. Falcao, J. Gibbson, 1992. The Active Badge Location System, ACM Transactions on Information Systems, 10(1), pp. 91-102.

WhereNet, 2005. WhereNet Homepage, USA, http://www.wherenet.com (Last date accessed: February 2007).

A Knowledge-based Kalman Filter for an Intelligent Pedestrian Navigation System

Günther Retscher

Abstract

Continuous and reliable position determination is very important in any navigation application. Therefore a combination and integration of different location techniques and positioning sensors is required. In most navigation applications this integration is performed using a Kalman filter approach. In this paper a new approach which makes use of knowledge-based systems for preprocessing the sensor observations is presented. In the preprocessing step the quality and reliability of the sensor observations is tested and gross errors and outliers are detected and eliminated. Furthermore the preprocessing step is used to determine the weightings of the sensor observations in the stochastic model of the following central Kalman filter. The weightings of the sensor observations can then be adjusted in the filter depending on their availability and quality. This approach is developed in a research project at our University for a pedestrian navigation and guidance service. In this project different location techniques such as GNSS and indoor positioning are combined with dead reckoning sensors (e.g. digital compass for heading determination, accelerometers for measurement of distance travelled, barometric pressure sensor for altitude determination) for continuous position determination of a pedestrian user. The project takes a use case into account, i.e., the navigation and guidance of visitors of our university to certain offices and persons. Selected results of field tests using different sensors are also presented in the paper. From the tests it could be seen that such a service can achieve a high accuracy and reliability for continuous position determination of a pedestrian user. It can also be expected that the performance of the system can be increased using the new intelligent knowledge-based Kalman filter approach for the integration of all available sensor observations.

1 Introduction

In the research project NAVIO (Pedestrian **Nav**igation Systems in Combined **I**ndoor/**O**utdoor Environements) we are working on the development of modern intelligent navigation systems and services for pedestrian navigation and guidance. The project is mainly focusing on the information aspect of location-based services, i.e., on the user's task at hand and the support of the user's decisions by information provided by such a service. Specifications will allow us to select appropriate sensor data and to integrate data when and where needed, to propose context-dependent routes fitting to partly conflicting interests and goals as well as to select appropriate communication methods in terms of supporting the user guiding by various multimedia cartography forms. These taks are addressed in the project in three different work packages, i.e., the first on 'Integrated positioning', the second on 'Pedestrian route modeling' and the third on 'Multimedia route communication'. To test and to demonstrate our approach and results, the project takes a use case scenario into account, i.e., the guidance of visitors to departments of the Vienna University of Techology [Gartner et al., 2004].

In this paper we will concentrate on the research work and findings in the first work package. Challenging tasks that are dealt with here are:

- the capability to track the movements of a pedestrian in real-time using different suitable location sensors and to obtain an optimal estimate of the current user's position,
- the possibility to locate the user in 3 dimensions with high precision (that includes to be able to determine the correct floor of a user in a multi-storey building), and
- the capability to achieve a seamless transition for continuous positioning determination between indoor and outdoor areas.

For that purpose the navigation support must be able to provide location, orientation and movement of the user as well as related geographic information matching well with the real world situation experienced by pedestrians. Usable location sensors have been classified and the most suitable ones for guidance and navigation services were selected. For pedestrian navigation systems suitable location technologies include GPS/GNSS and indoor location techniques, cellular phone positioning, dead reckoning sensors (e.g. magnetic compass, gyros and accelerometers) for measurement of heading and distance travelled as well as barometric pressure sensors for altitude determination [Retscher, 2004].

Our proposal and a part of our future research work is focused on the development of modern and advanced intelligent mobile multi-sensor systems that can be employed for any personal navigation application especially in the field of location-based services. Due to the fact that satellite positioning with GNSS (Galileo, GPS, etc.) does not work under any environmental condition (e.g. in urban 'canyons' with no satellite visibility and indoor) a combination and integration with other sensors (e.g. dead reckoning sensors, inertial navigation systems (INS), cellular phone positioning, etc.) is essential. In our approach a loose coupling of the employed sensors in the sense of a hybrid multi-sensor system should be achieved. Therefore it is proposed to develop a multi-sensor fusion model which makes use of knowledge-based systems. As far as we can see now knowledge-based systems can be especially useful. Thereby the decision which sensors should be used to obtain an optimal estimate of the current user's position and the weightings of the observations shall be based on knowledge-based systems. The new algorithm would be of great benefit for the integration of different sensors as the performance of the service would be significantly improved. The main development will be focused on the deduction of a multi-sensor fusion model based on knowledge-based systems. In this paper the basic principle of the new approach will be described.

2 Concept of an Intelligent Multi-Sensor Fusion Model

The integration of different sensors and location methods shall be based on an intelligent multi-sensor fusion model in the project NAVIO. In this approach the current position of a user is estimated using a Kalman filter approach which makes use of knowledge-based systems. Figure 1 shows a process flow of the intelligent multi-sensor fusion model. Firstly the observations of each sensor and location technique of the multi-sensor system are analyzed in a knowledge-based preprocessing filter. In this step the plausibility of the observations is tested as well as gross errors and outliers are detected and eliminated. The analyzed and corrected observations are then used in the following central Kalman filter for the optimal estimation of the current user's position and its velocity and direction of movement. In this processing step all suitable sensor observations as identified before are employed and the stochastic filter model is adapted using the knowledge of the preprocessing step. For example, the weightings of the GPS observations can be reduced in the case if the current GPS positioning accuracy is low due to a high GDOP value (i.e., bad satellite-receiver geometry). Then the optimal estimate of the user's position should be more based on the observations of other sensors (e.g. dead reckoning observations).

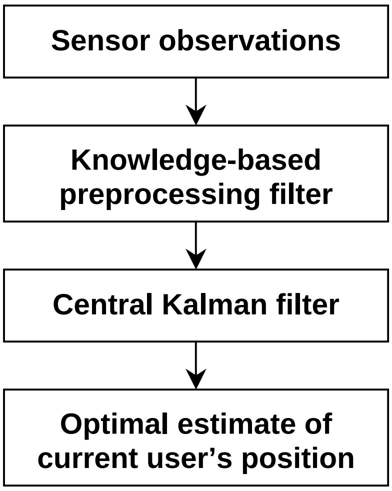

Fig. 1. Process flow of the intelligent multi-sensor fusion model
[after Thienelt et al., 2005]

In the following the principle of the knowledge-based preprocessing filter will be discussed in more detail.

3 Principle of Knowledge-Based Systems

To provide an automated preprocessing of the sensor observations, a knowledge-based approach has been choosen. In the following, the basics underlying knowledge-based systems are described.

Programs which emulate human expertise in well defined problem domains are called knowledge-based systems [Stefik, 1998] and they are the results of research in the area of artificial intelligence. Their main advantages in comparison with conventional programming languages (such as Delphi, Fortran and C++) are [Reiterer et al., 2003]:

- the knowledge about the problem domain is seperated from general problem-solving knowledge which makes it easier for the knowledge engineer to manipulate this knowledge;
- not only 'hard' knowledge can be represented, but also 'loose' knowledge (which is useful and potentially very profitable);
- experts knowledge that exists very often in form of rules can be captured in this form without converting into forests of data definitions and procedures.

Another advantage of a knowledge-based approach is that some tools make it very simple to deal with uncertainty. An uncertainty occurs if one is not absolutely certain about a piece of information. The uncertainty can be represented by a crisp numerical value (from 0 to 1), where on the one hand a factor of 1 indicates that the user/system is very certain that the information is true, and on the other hand a factor of 0 indicates that it is very uncertain that the information is true.

There exist various schemes for knowledge representation, e.g. rules, frames, semantic nets and others. Each has its peculiar strengths and weaknesses. The structure of a rule-based approach is very similar to the way how people solve problems. Thereby human experts find it convenient to express their knowledge in form of rules (i.e., situation – action pairs). Furthermore rules are a way to represent knowledge without complex programming constructs [Reiterer et al., 2003].

For the implementation of a knowledge-based system in practice different approaches can be selected, e.g. procedural methods, object oriented methods, logical based methods, etc. In practice also combinations of the different methods are employed. For the implementation of the knowledge-based preprocessing filter a rule-based object oriented approach was selected [Thienelt et al., 2005].

The rule-based system consists of two components, i.e., a working memory (WM) and a set of rules or the so-called rule memory [Brownston et al., 1985]. The WM is a collection of working memory elements which itself are representations of a working memory type (WMT). WMT's can be considered as record declarations in PASCAL or so-called struct declarations in C. The second component of a rule-based system are the rules. The rule base is divided into three groups of rules, i.e.,

- rules for the choice of suitable algorithms,
- rules for the predefinition of necessary parameters, and
- rules to define the order of the algorithms.

A rule is divided into two parts, namely the lefthand side (LHS) and the righthand side (RHS). In the LHS the preconditions of the rule are formulated, whereas in the RHS the actions are formulated. A rule can be applied (or 'fired') if all its preconditions on the LHS are satisfied. Then the actions specified in the RHS are executed. Rules can be seen as so-called IF-THEN statements, e.g.

$$\text{IF (condition 1 AND condition 2) THEN (action).} \tag{1}$$

There are algorithms for the so-called matching phase, i.e., the phase where all rules are checked against all working memory elements which are efficient in practice. The result of the matching phase is the 'conflict set' which includes all rule instances 'ready to be fired'. A conflict resolution strategy selects one rule instance which is actually fired [Reiterer et al., 2003].

The coding of the rule is performed in the chosen programming language. For the knowledge-based preprocessing filter an implementation based on CLIPS [2005] or wxCLIPS [2005] will be performed [Thienelt et al., 2005].

The processing of the rules is performed as described above. In the case under consideration this process is performed in a forward-reasoning following the recognize-act-cycle. In forward-reasoning a specific rule is selceted from an existing database which fulfills the preconditions of the database and then its action part is applied (or fired) where the action changes the existing database. This proces is repeated as long as no rule can be applied anymore [Puppe, 1991]. The recognize-act-cycle consists of the following three steps, i.e.,

- the examination where all rules are tested about their feasibility,
- the selection of the rule where a specific rule from the preselection is selected, and
- the action where the selected rule or its action part is applied.

This cycle is run as long as no rule can be executed anymore or if a stop signal is given.

4 Central Kalman Filter

After the preprocessing filter, an optimal estimation of the current user's position and its velocity and direction of movement is performed in a central Kalman filter using all suitable observations from the sensors and location techniques. Using this recursive approach the state of the movement of the pedestrian can be estimated based on the use of theoretical assumptions about the user's movement behavior and current observations. As usual the user's movement behavior is formulated in the system equations and the observations are introduced in the measurement equation of the filter. The Kalman filter provides then an exact solution to the linear Gaussian filtering problem and the problem is characterized completely by its state vector and covariance matrix. The filtering process is reduced to the prediction and updating of these two statistical parameters. In this paper, the fundamentals of the Kalman filter will not be described as they can be found in several publications [e.g. Gelb, 1986; Schrick, 1977].

For the system equations of the filter a 3-D kinematic motion model is employed which enables the prediction of the state of the movement of the pedestrian (e.g. the current position, velocity and heading) from one epoch to the next. Depending on the type of the model different parameters can be included in the state vector $\vec{x}(k)$. The following parameters can be used to describe the state of the system [see Retscher and Mok, 2004; Retscher, 2004]:

- 3-D coordinates of the current position y, x, z of the user,
- 3-D velocities v_y, v_x, v_z,
- 3-D accelerations a_y, a_x, a_z,
- direction of motion (heading) φ in the ground plane xy,
- velocity v in the ground plane xy,
- radial acceleration a_{rad} in the ground plane xy.

If the state vector $\vec{x}(k)$ includes only 6 parameters, i.e., the 3-D coordinates of the current position y, x, z and the velocities v_y, v_x, v_z, the kinematic model describes a constant linear movement. A constant accelerated movement is described with 9 parameters in the state vector where in addition to the previous model also the 3-D accelerations a_y, a_x, a_z are included in the kinematic model. A constant radial movement can be described by different parameters in the state vector, i.e., the 3-D coordinates of the current position y, x, z, the heading φ, the velocity v and the radial acceleration a_{rad} in the ground plane xy and the velocity v_z in z-direction. Using these models the filter predicts different the movement of the user where in the first model compared to the second no accelerations are used and in the third model a radial movement without tangential accelerations a_{tan} is employed. Simulations have shown that the third model gives a good approximation to describe the movement behavior of a pedestrian [Retscher and Mok, 2004].

Figure 2 shows the architecture of the central Kalman filter. It consists of four different modules which describe either the current environment of the pedestrian (outdoor or indoor area) or the movement of the pedestrian (pedestrian moves or does not move) or takes into account a possible failure of the filter. Thereby of great importance is the detection of bad GPS quality in outdoor environements due to e.g. bad satellite-receiver geometry (high GDOP value) or multipath. From the results of the knowledge-based preprocessing filter an additional statistical evaluation of the deviations between the kinematic motion model and the GPS observations (e.g. using tests of the innovation, i.e., the difference between the real observations and the predicted measurements, in the Kalman filter) and an adequate weighting of the GPS observations in the stochastic filter model is performed. In the indoor environment the filter estimate is mainly based on the oberservations of the dead reckoning sensors. This is the case if no other indoor location system is employed that provides absolute coordinates of the user (e.g. WLAN or WiFi fingerprinting; see [Retscher, 2004]). The dead reckoning observations depend thereby mainly on the output of the heading sensor (i.e., digital compass). Similar to the analysis of the GPS observations in the outdoor environment, the observations of the digital compass are analyzed for gross errors or outliers and their weight for the Kalman filter is derived. In the case if the pedestrain does not move the observations are not used to determine a new position estimate but the previous determined state is kept. If a failure of the filter occurs a reinitialization is required [Thienelt et al., 2005].

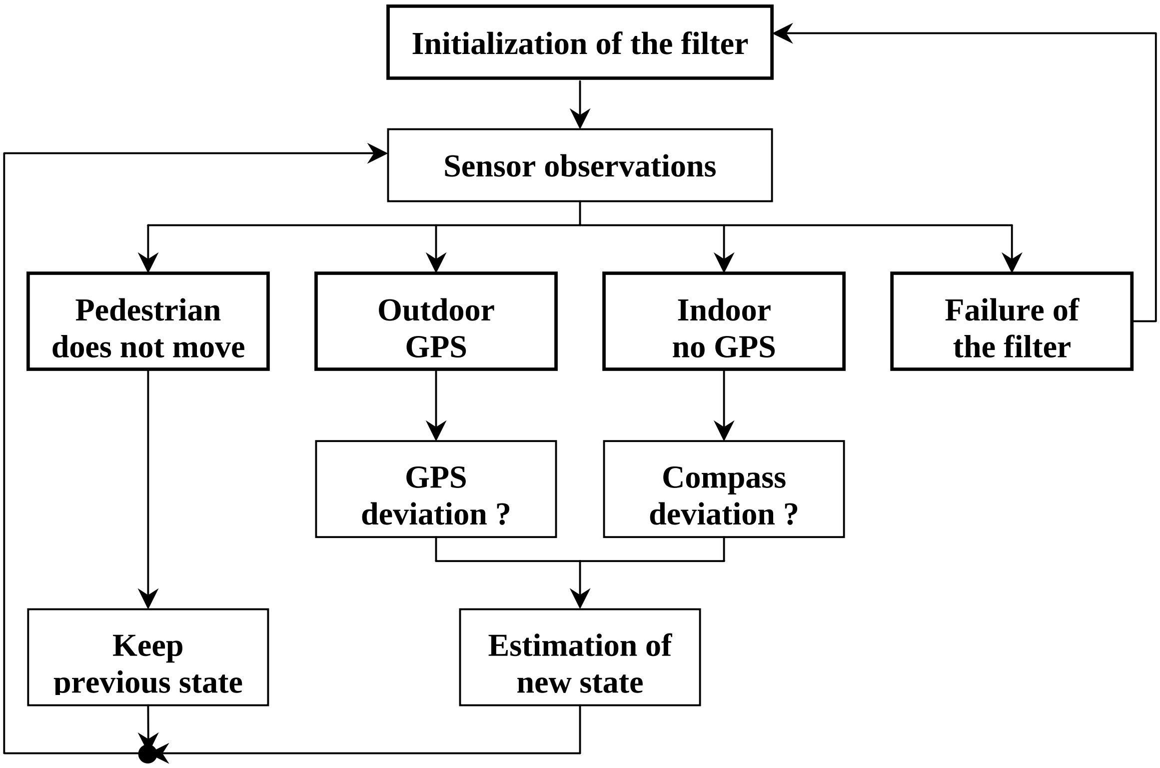

Fig. 2. Architecture of the central Kalman filter [after Thienelt et al., 2005]

The proposed filter model is developed in a way that it is open for the integration of future developed sensors. Furthermore an improvement of the accuracy and reliability for position determination is achieved in the model by integrating all single sensor observations available at a certain time (epoch). It is suggested to derive an extended filter model capable to calculate the user state from all available measurement data, also in the case, if only incomplete observations from a single sensor are available (e.g. if insufficient numbers of satellites for GPS/GNSS positioning are available due to obstructions). Any single observation can then contribute to improve the previous state of a tracked user by updating the prediction in the filter model. This approach would provide the advantage to estimate the user state recursively also, if an individual positioning method would fail by refining the estimate of the solution using single observations (e.g. GPS pseudoranges, attitude parameters, distance travelled, velocity or acceleration and height difference) together with the observations of other sensors (e.g. in the case of availability range measurements to pseudolits, transponders, beacons or base transmitter stations of cellular phone networks).

5 Suitable Sensors for Pedestrian Navigation

The integration of different location technologies and sensors is essential for the performance of modern advanced navigation systems. Common navigation systems rely mainly on satellite positioning (GNSS) for absolute position determination. Losses of lock of satellite signals are usually bridged using dead reckoning (DR) observations. Due to the main limitations of the sensors (i.e., satellite availability in the case of GNSS and large drift rates in the case of DR) other positioning technologies should be integrated into the system design of a personal navigation system to augment GNSS and DR positioning.

Other radio positioning systems and wireless geolocation technologies have been developed and can be employed in personal navigation systems. Following Pahlavan et al. [2002] two basic approaches can be distinguished in the development of wireless geolocation techniques, i.e., one approach where the system is solely designed for positioning using certain radio signals and the second where already established wireless infrastructure (e.g. WLAN/WiFi or UWB) is employed for location determination. The second approach has the advantage that usually no additional and costly hardware installations are required. Some of these systems have been especially developed for indoor applications, but they can also be employed in indoor-to-outdoor and urban environments [Retscher and Kealy, 2006]. One approach is the use of WLAN (or WiFi) signals for position determination. The basic principle of this approach has been analyzed and can be found in [Retscher, 2004]. In a study the performance of a WLAN fingerprint method has been recently tested and it can be summarized that positioning accuracies in the range of 1 to 3 m can be achieved.

6 Dead Reckoning Sensors Employed in the Project NAVIO

For the pedestrian navigation service in the project NAVIO the following dead reckoning (DR) sensors are employed:

- dead reckoning module DRM III from PointResearch,
- Honeywell digital compass module HMR 3000,
- Crossbow accelerometer CXTD02, and
- Vaisala pressure sensor PTB220A.

The dead reckoning module DRM III from PointResearch [2005] is a self contained navigation unit where GPS is not required for operation. It provides independent position information based on the user’s stride and pace count, magnetic north and barometric altitude. The module is designed to self-calibrate when used in conjunction with an appropriate GPS receiver, and can produce reliable position data during GPS outages. The system consists of an integrated 12 channel GPS receiver, antenna, digital compass, pedometer and altimeter (see Figure 3). The module is clipped onto the user’s belt in the middle of the back and the GPS antenna may be attached to a hat. Firmware converts the sensor signals to appropriate discrete parameters, calculates compass azimuth, detects footsteps, calculates altitude and performs dead reckoning position calculation. An internal Kalman filter algorithm is used to combine dead reckoning position with GPS position to obtain an optimum estimate for the current user’s position and track. With the dead reckoning module and GPS integrated together, a clear view of the sky is only required for obtaining the initial position fix. The fix must produce an estimated position error of 100 m or less to begin initialization. Subsequent fixes use both dead reckoning and GPS data, so obstructed satellites are not as critical as in a GPS only configuration. The internal Kalman filter continuously updates calibration factors for stride length and compass mounting offset. The GPS position error must be less than 30 m before GPS data will be used by the Kalman filter, and the first such fix will also initialize the module's latitude and longitude. Subsequently, the filter will use any GPS position fix with an estimated position error of 100 m or less, adjusting stride, body offset, northing, easting, latitude and longitude continually.

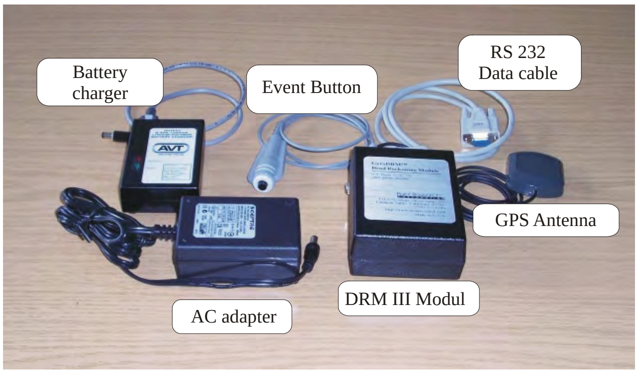

Fig. 3. Components of the PointResearch dead reckoning module DRM III

The Honeywell digital compass module HMR 3000 is employed in the project NAVIO for precise heading determination of the pedestrian. The HMR 3000 consists of a magnetic sensor and a two-axis tilt sensor [Honeywell, 2005]. The low power, small device is housed in a non-magnetic metallic enclosure that can be easily installed on any platform. A sophisticated auto compass calibration routines will correct for the magnetic effects of the platform. Wide dynamic range of the magnetometer allows the HMR 3000 to be useful in applications with large local magnetic fields. The influence of magnetic disturbances on the sensor has been tested and is presented in [Retscher and Thienelt, 2005]. It could be seen that deviations of only 2 to 3 degrees occurred if the source of disturbance (e.g. a notebook computer or a metallic lighter) is put in a distance of about 30 cm from the sensor. Higher deviations occur, however, at shorter distances to the sensor. As a consequence the sensor should be kept away from mobile phones, coins, metallic lighters and keys.

For measurement of the accelerations of the pedestrian the Crossbow accelerometer CXTD02 should be employed. The CXTD02 is a tilt and acceleration sensor and measures tilt and acceleration using a triaxial MEMS accelerometer [Crossbow, 2005]. It provides high performance in more demanding measurement applications where high accuracy must be maintained over a wide temperature range. The low noise floor and true DC response guarantees a long-term stability. It should be analyzed in detail how the sensor can employed for the determination of the distance travelled, pitch and roll of the sensor platform.

In addition, the Vaisala pressure sensor PTB220A is employed in the project for determination of height differences from changes of the air pressure. The PTB220A is designed for measurements in a wide environmental pressure and temperature range with an extremly high accuracy [Vaisala, 2005]. Starting from a given height the pressure changes can be converted in changes in height using the following equation:

$$\Delta H = H_2 - H_1 = 18464 \cdot \left(1 + 0{,}0037 \cdot t_m\right) \cdot \left(\lg B_1 - \lg B_2\right) \tag{2}$$

where ΔH is the height difference between two stations 1 and 2, B_1 and B_2 are the pressure observations at station 1 and 2 and t_m is the mean value of the temperature of both stations. It must be notetd that this equation is an approximation formula that is valid for central Europe only [Kahmen, 1997].

7 Sensor Tests

Practical tests in the NAVIO project are carried out for the guidance of visitors of the Vienna University of Technology to certain offices in different buildings or to certain persons. Thereby we assume that the visitor employs a pedestrian navigation system using different sensors that perform an integrated positioning. Start points are nearby public transport stops, e.g. underground station Karlsplatz in the center of Vienna. A simulation study for this application was presented in [Retscher and Mok, 2004]. In the same area tests with two different GPS receivers have been carried out and their results are presented in [Retscher and Thienelt, 2004]. Because of obstructions caused by the surrounding four to five storey buildings it frequently happens that GPS signals are lost so that large parts of the route of the pedestrian must be bridged by dead reckoning. Only in the park at the exit of the underground station and on isolated road crossings it is possible to receive GPS signals with sufficient quality. This area is therefore suitable for testing the combination of absolute and relative DR location sensors. Further sensor tests are schedulded to be performed in the next months in this area.

Test measurements with the dead reckoning module DRM III from PointResearch [2005] have been carried out in another test area in the park of Schönbrunn Palace in Vienna (see Figure 4). This test site has been chosen as it provides free satellite visibility. Figure 5 shows the dead reckoning observations as well as the GPS measurements along a 540 m long track in the park of Schönbrunn Palace. In the dead reckoning module, measurements of accelerometers are employed to count the steps of the walking pedestrian and the distance travelled is obtained using a predefined value for the stride length. Using GPS observations the stride length can be calibrated. Furthermore a compass and a gyro are employed for measurement of the heading or direction of motion. The dead reckoning observations shown in Figure 5 have been filtered using the internal Kalman filter of the DRM III module. Apart from the beginning where a precise start position is missing, the DR measurements reach deviations of up to 5.5 m for the first measurement series (DR measurements 1 in Figure 5) and up to 25.9 m for the second measurement series (DR measurements 2 in Figure 5) from the known path. The GPS measurements show a maximum deviation of 3.5 m in the first measurement series and 15.6 m in the second measurement series. As can be seen from Figure 5 the second measurement series shows an absolute shift of approximately 20 m from the known path. This error can be eliminated if a local transformation is applied. Using the internal Kalman filter of the DRM III module the large drift rates of the DR observations can be reduced and GPS outages (i.e., when GPS is unavailable) of up to 150 to 200 m can be bridged with a reasonable positioning accuracy. For longer GPS outages, however, other location technologies have to be employed providing an absolute position estimate to correct for the DR drift.

Figure 6 shows test observations with the Vaisala pressure sensor PTB220A in our office building of the Vienna University of Technology. This building has 5 storeys and our department is located in the 3rd floor. It can be clearly seen in Figure 6 that the sensor is able to determine the correct floor of the user with a high precision. The standard deviation of the pressure observation is in the range of ± 0.2 hPa and the maximum deviation of the determined height is less than ± 1 m for 90 % of the observations.

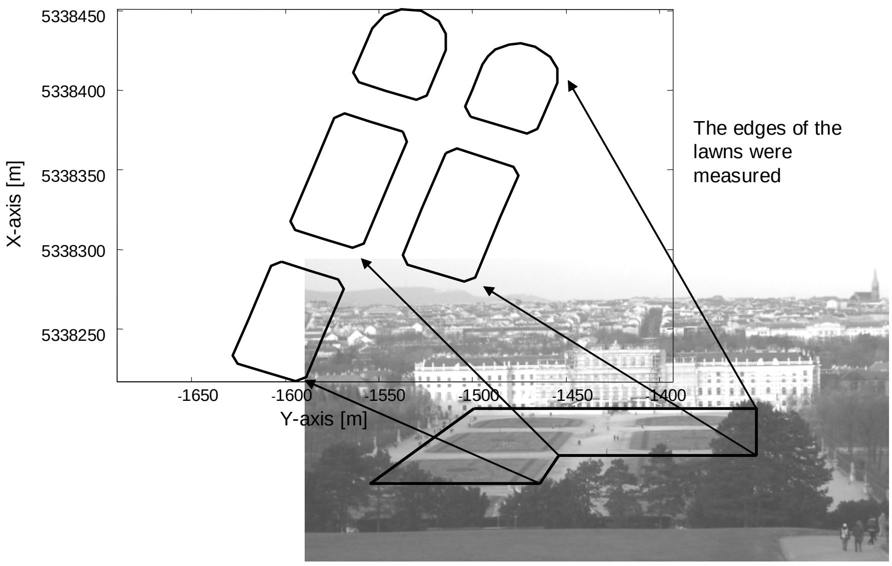

Fig. 4. Field test site in the park of Schönbrunn Palace in the city of Vienna

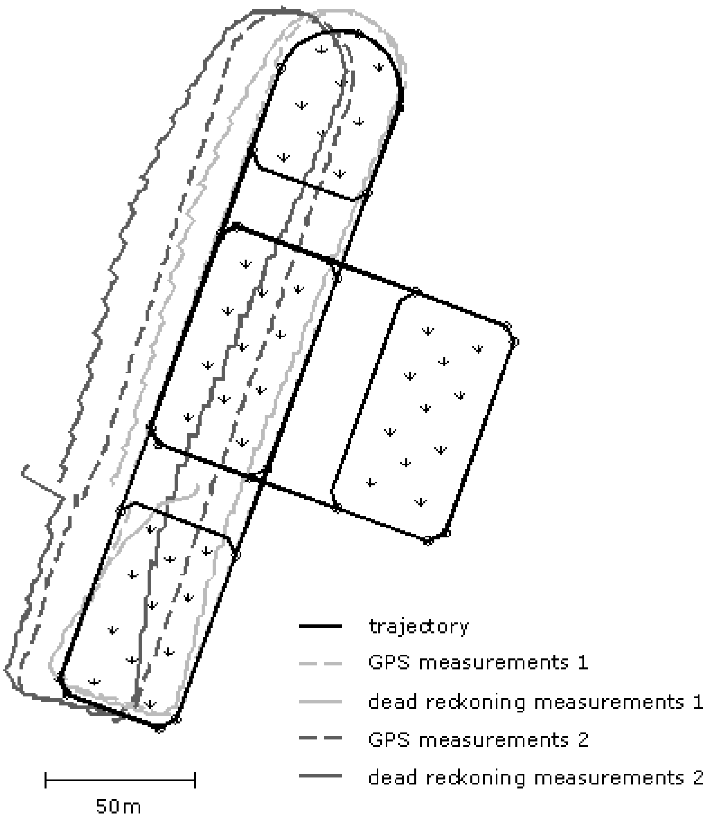

Fig. 5. Test measurements with the dead reckoning module DRM III in the park of Schönbrunn Palace in Vienna

The results of the different tests could confirm that a pedestrian navigation service can achieve a high level of performance for the guidance of a user in an urban area and mixed indoor and outdoor environments. Standard deviations in the range of few metres can be acchieved for 3-D positioning in urban areas although obstructions cause frequent loss of lock for satellite positioning. If GPS outages occur they can be bridged using dead reckoning observations over a distance of up to 150 m with the required positioning

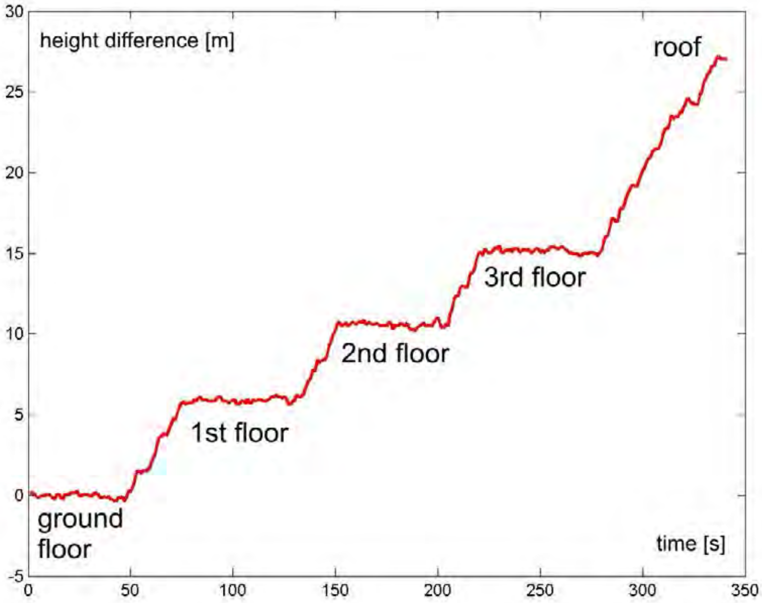

Fig. 6. Test measurements with the Vaisala pressure sensor PTB220A in our office building of the Vienna University of Technology

accuracy. For indoor areas satellite positioning can be replaced by indoor positioning systems (e.g. WLAN/WiFi fingerprint; see [Retscher, 2004]) and the altitude of the user can be observed using a barometric pressure sensor. The achievable positioning accuracies in the range of a few metres are satisfactory for continuous and reliable location determination in a pedestrian navigation and guidance service.

8 Concluding Remarks

From the presented sensor tests can be seen that a high precision and relability for the position determination of a pedestrian can be achieved if different location techniques and dead reckoning sensors are employed and combined. For the integration of all observations a new multi-sensor fusion model based on an extended Kalman filter which makes use of a knowledge-based preprocessing of the sensor observations can be applied. The principle of this new approach is presented in the paper. The knowledge-based preprocessing filter represents an extension of common multi-sensor fusion models in a way that the data based system analysis and modeling is supplemented by a knowledge-based component and therefore not directly quantifiable information is implemented through formulation and application of rules. This rules are tested in the preprocessing step and if they are fulfilled certain actions are executed. Due to the knowledge-based analysis of the sensor observations gross errors and outliers can be detected and eliminated in this processing step. In addition, the preprocessing filter supplies input values for the stochastic model of the central Kalman filter. Therefore the weightings of the sensor observations can be adjusted in the Kalman filter depending on the availability and quality of the current observations. This integration approach will be implemented and further sensor tests will be carried out to test and analyze this approach. Due to the development of advanced sensors it can be expected that such multi-sensor solutions will be deployed in pedestrians navigation services in the near future. We believe that these services will play an important role in the field of location-based services as a rapid development has already started which is driven by their possible applications.

Acknowledgments

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References

Brownston L., R. Farrell, E. Kant, N. Martin, 1985. Programming Expert Systems in OPS5: An Introduction to Rule-based Programming. Addison-Wesley Longman Publishing Co.

CLIPS, 2005. CLIPS – A Tool for Building Expert Systems. http://www.ghg.net/clips/CLIPS.html (Last date accessed: March 2006).

Crossbow, 2005. CXTD Digital Tilt and Acceleration Sensor, Product Information, Crossbow, U.S.A., http://www.xbow.com/Products/Product_pdf_files/Tilt_pdf/6020-0012-01_B_CXTD.pdf (Last date accessed: March 2006).

Gartner G., A. Frank, G. Retscher, 2004: Pedestrian Navigation System in Mixed Indoor/Outdoor Environment – The NAVIO Project. in: Schrenk M. (ed.): CORP 2004 and Geomultimedia04. Proceedings of the CORP 2004 and Geomultimedia04 Symposium, Vienna, Austria, February 24-27, 2004, pp. 165-171, http://corp.mmp.kosnet.com/CORP_CD_2004/archiv/papers/CORP2004_GARTNER_FRANK_RETSCHER.PDF, (Last date accessed: March 2006).

Gelb A. (ed.), 1986. Applied Optimal Estimation. The MIT Press, Cambridge, Massachusetts and London, England, 9th print, 374 pgs.

Honeywell, 2005. HMR 3000 Digital Compass Module, User's Guide, Honeywell International Inc., U.S.A., http://www.ssec.honeywell.com/magnetic/datasheets/hmr3000_manual.pdf (Last date accessed: March 2006).

Kahmen H., 1997. Vermessungskunde. 19. Auflage, Walter de Gruyter, Belin, New York, pp. 475-482.

Pahlavan K., X. Li, J.-P. Mäkelä, 2002. Indoor Geolocation Science and Technolgy. IEEE Communications Magazine, February 2002, pp. 112-118.

PointResearch, 2005. DRM-III Dead Reckoning Module - Engineering Development Tools, PointResearch Corporataion, U.S.A., http://www.pointresearch.com/datasheets/gyrodrm.pdf (Last date accessed: March 2006).

Puppe F., 1991. Einführung in Expertensysteme. 2nd edition, Springer Verlag, Berlin, Heidelberg, New York.

Reiterer, A., Kahmen, H., Egly, U., Eiter, T., 2003. Knowledge-based Image Preprocessing for a Theodolite Measurement System. in: Gruen, A., H. Kahmen (eds.). Optical 3-D Measurement Techniques VI, Zurich, September 22-25, 2003, Vol. II, pp. 183-190.

Retscher G., E. Mok, 2004. Sensor Fusion and Integration using an Adapted Kalman Filter Approach for Modern Navigation Systems. Survey Review, Vol. 37, No. 292, April 2004, pp. 439-447.

Retscher G., 2004. Multi-sensor Systems for Pedestrian Navigation, in: Papers presented at the ION GNSS Meeting, Long Beach, California, U.S.A., 21-24 September, 2004 (Institute of Navigation, Fairfax, Virginia), unpaginated CD-ROM.

Retscher G., M. Thienelt, 2004. NAVIO – A Navigation and Guidance Service for Pedestrians. Journal of Global Positioning Systems, CPGPS, Vol. 3, No. 1-2, pp. 208-217, see http://www.gmat.unsw.edu.au/wang/jgps/v3n12/v3n12p26.pdf (Last date accessed: March 2006).

Retscher G., A. Kealy, 2006. Ubiquitous Positioning Technologies for Modern Intelligent Navigation Systems. The Journal of Navigation, Vol. 59, No. 1, January 2006, pp. 91-103.

Retscher G., M. Thienelt, 2005. Evaluation and Test of a Digital Compass Module Employed for Heading Determination in a Pedestrian Navigation System. in Grün A., H. Kahmen (eds.): Optical 3-D Measurement Techniques VII, Papers presented at the 7th Conference on Optical 3-D Measurement Techniques, Vienna, Austria, October 3-5, 2005.

Schrick K.-W., 1977. Anwendungen der Kalman-Filter-Technik. Methoden der Regelungstechnik, R. Oldenbourg Verlag, München, Wien.

Stefik M., 1998. Introduction to Knowledge Systems. 2nd edition, Kaufmann, San Francisco.

Thienelt M., A. Eichhorn, A. Reiterer, 2005. Konzept eines wissensbasierten Kalman-Filters für die Fußgängerortung (WiKaF). VGI, Österreichische Zeitschrift für Vermessung und Geoinformation, Vol. 93, No. 2, pp. 96-104.

Vaisala, 2005. PTB220 Digital Barometer, User's guide, Vaisala, Finland, http://www.vaisala.com/businessareas/instruments/servicesupport/userguides/barometricpressure/PTB220%20User%20Guide%20in%20English.pdf (Last date accessed: March 2006).

WxCLIPS, 2005. wxCLIPS. http://www.anthemion.co.uk/wxclips/ (Last date accessed: March 2006).

Test and Integration of Location Sensors for a Multi-sensor Personal Navigator

Günther Retscher

Abstract

In the work package "Integrated Positioning" of the research project NAVIO (Pedestrian Navigation Systems in Combined Indoor/Outdoor Environements) we are dealing with the navigation and guidance of visitors of our University. The start points are the public transport stops in the surroundings of the Vienna University of Technology and the system user should be guided to certain office rooms or persons. For the user's position determination different location sensors are employed, i.e., for outdoor positioning GPS and dead reckoning sensors, such as a digital compass and gyro for heading determination, accelerometers for the determination of the distance travelled, a barometric pressure sensor for altitude determination and, for indoor areas, location determination using WiFi fingerprinting. All sensors and positioning methods are combined and integrated using a Kalman filter approach. An optimal estimate of the current location of the user is obtained using the filter. To perform an adequate weighting of the senors in the stochastic filter model, the sensor characteristics and performance were investigated in several tests. The tests were performed in different environments either with free satellite visibility, in urban canyons or inside buildings. The tests have shown that it is possible to determine the user's location continuously with the required precision and that the selcted sensors provide a good performance and high reliability. Selected tests results and our approach will be presented in the paper.

Keywords: Integrated Positioning, Indoor location, Sensor fusion, Kalman filter

1 Introduction

The acceptance of mobile personal navigation systems has growen in recent years. Many applications require nowadays the location determination and tracking of persons or objects in combined indoor and outdoor environements. Most personal navigation systems rely on location determination using GNSS in combination with map matching. In general, these systems show a high performance for availability and positioning accuracy. However, the continuous position determination in urban areas where satellite signals are frequently blocked is very challenging. In the NAVIO project [Gartner et al., 2004] the navigation of a pedestrian in combined indoor/outdoor environments is investigated and a system developed. One of the main challenges investigated was the usage of dead reckoning sensors for the continuous position determination of a pedestrian. For this purpose different sensors were tested and integrated into a system. The reliability of the location determination was improved in our system by the use of new multi-sensor fusion model based on a Kalman filter. As more sensors than the minimal number required have been integrated, statements can be derived about the quality of each sensor for an optimal estimate of the current user's position and its usability in the system design. In the following the sensors employed in NAVIO are described and their integration is discussed. Finally a test of the sensors is presented.

2 The NAVIO System Design

Figure 1 shows the employed sensors in the NAVIO system developed at the Vienna University of Technology. The following sensors are integrated:

- Garmin eTrex Summit GPS receiver,
- Dead Reckoning Module DRM III from PointResearch,
- Honywell digital compass HMR 3000, and
- Vaisala PTB 220 barometric pressure sensor.

In the system the GPS is employed for absolute position determination and the other three sensors are used as dead reckoning sensors for relative position determination from a given start position. Using this sensors the distance travelled, the direction of motion and the changes in altitude can be determined. For the data acquisition a software module has been developed using Matlab [Retscher and Thienelt, 2006]. An optimal estimate of the current user's position, its velocity and direction of motion is then obtained using a Kalman filter approach. For this purpose a new algorithm has been developed and was implemented using Matlab.

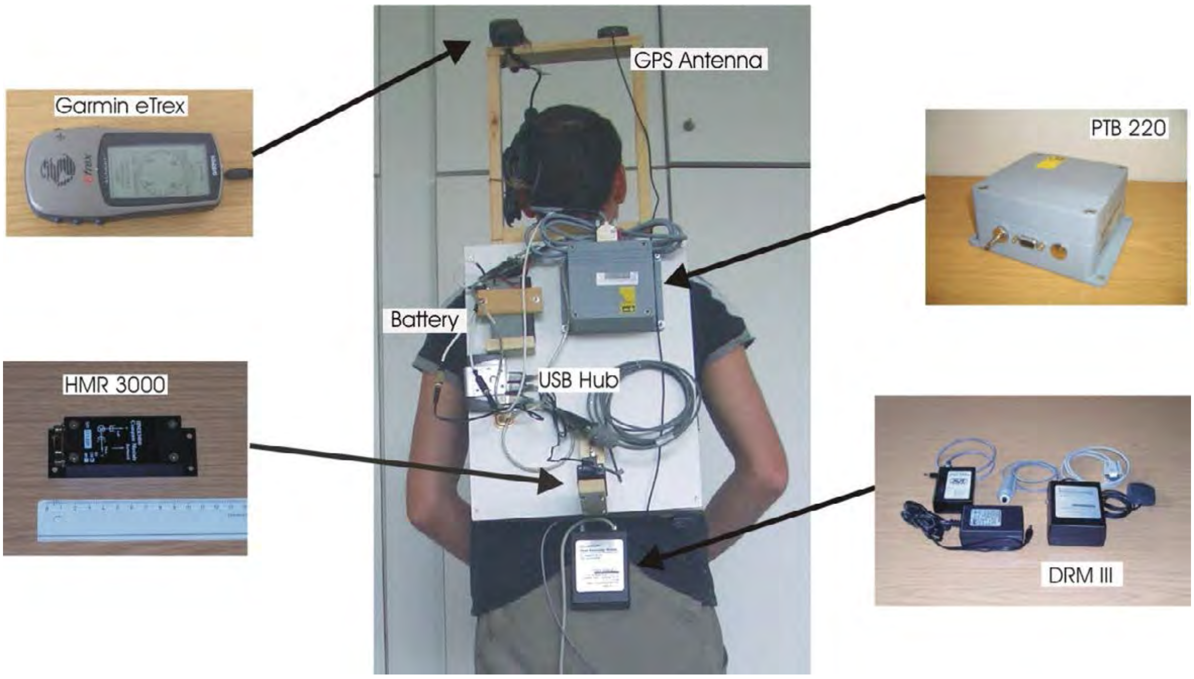

Fig. 1. Sensors of the NAVIO system

3 Sensor Integration Using a new Multi-sensor Fusion Model

For the integration of the different location sensors a multi-sensor fusion model based on an extend Kalman filter that makes use of a knowledged-based preprocessing of the available sensor observations has been developed. The concept of the new algorithm was presented in [Retscher, 2007] and Figure 2 shows the necessary steps of the operation. In the first step the observations of each sensor of the multi-sensor system are analyzed in a knowledge-based preprocessing filter. In this step the plausibility of the observations is tested and the gross errors and outliers detected and eliminated. The analyzed and corrected observations are then used in the following central Kalman filter for the optimal estimation of the current user's position and its velocity and direction of movement. In this processing step all suitable sensor observations are employed and the stochastic filter model is adapted using the knowledge of the preprocessing step. For example, the weightings of the GPS observations can be reduced if the current GPS positioning accuracy is low due to a high GDOP value (i.e., bad satellite-receiver geometry) or other error sources (e.g. multipath). The optimal estimate of the user's position is then based more on the observations of the dead reckoning sensors. This approach leads to an optimal estimate of the current user's position, the direction of motion and velocity.

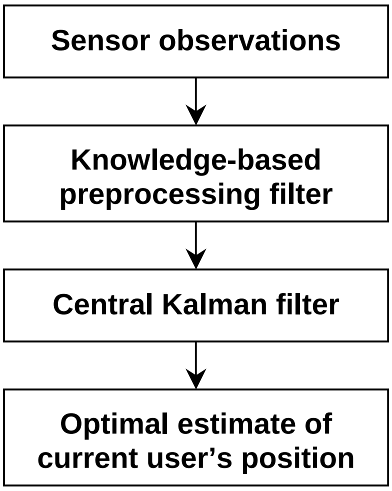

Fig. 2. Process flow of the intelligent multi-sensor fusion model [Retscher, 2007]

In the Kalman filter two different kinematic filter models which describe a linear radial movement behaviour of the pedestrian were tested. Then the accelerations were taken into account in the stochastic disturbance vector of the Kalman filter. In the first model a kinematic formulation of the movement of the pedestrian was performed [see Wang, 1997]; in the second model sudden changes in the pedestrian's direction of motion were also taken into account [see Retscher and Thienelt, 2006].

In the first kinematic filter model the following system equations are used:

$$Y(k+1) = Y(k) + v_t(k)\sin(\alpha(k))\,(t_{k+1} - t_k) + \frac{1}{2}a_r(k)\cos(\alpha(k))\,(t_{k+1_1} - t_k)^2 \tag{1}$$

$$X(k+1) = X(k) + v_t(k)\cos(\alpha(k))\,(t_{k+1} - t_k) - \frac{1}{2}a_r(k)\cos(\alpha(k))\,(t_{k+1} - t_k)^2 \tag{2}$$

$$\alpha(k+1) = \alpha(k) + \frac{a_r(k)}{v_t(k)}\,(t_{k+1} - t_k) \tag{3}$$

$$v_t(k+1) = v_t(k) \tag{4}$$

$$a_r(k+1) = a_r(k) \tag{5}$$

where $X(k)$ and $Y(k)$ are the 2-D coordinates, $\alpha(k)$ is the azimuth, $v_t(k)$ is the tangential velocity and $a_r(k)$ is the radial acceleration.

Disturbances to the system are caused by a scalar tangential acceleration $a_t(k)$ and in radial direction by the derivative of the radial acceleration $\dot{a}_r(k)$ (i.e., the so-called radial jerk). Due to the selceted time interval the impact of the disturbances is reduced to a minimum. Therfore we can assume for the expectation value $E\{a_t\} = 0$ und $E\{\dot{a}_r\} = 0$. Over one epoch of the filter the two disturbance values can also be considered as constant.

4 Location Sensor Testing

The performance and the accuracy of these sensors was tested in different test areas representing a real world situation for the system. The first test area was in the park of Schönbrunn palace with unhindered satellite visibility, the second in the urban environment surrounding our University building and the third, indoor in our office building. The sensor tests also provided very important information for the deduction of the stochastic Kalman filter model for the integration of the sensor observations.

4.1 GPS Sensor Tests

Two different GPS sensors are available, i.e., the Garmin eTrex and the in-built GPS sensor of the dead reckoning module DRM III of the company PointReseearch. The availability and reliability of this sensors in urban areas were tested and the observations compared with a surveyed reference trajectory. For the Garmin eTrex a RMSE for the absolute coordinates of ± 3 m and relative positioning accuracies on the dm-level could be obtained. For the DRM III, however, the absolute positioning accuracy is the range of ± 5 to 8 m and relative positioning accuracies on the m-level. Also the availability and reliability of the Garmin eTrex in urban canyons is higher than the DRM III receiver.

4.2 Heading Sensor Tests

To analyze the performance of the heading sensors long term laboratory observations for determination of the sensor drift and test observations in the real world situation were performed. The manufacturers specifications were checked from the long term observations and the sensor drift rate analysed. In the tests of the Honeywell HMR 3000 heading sensor no significant drift rate could be seen and an average standard deviation of ± 0.22° with maximum deviations of 1.2° obtained. For the heading sensor of the PointResearch DRM III a standard deviation of ± 0.85° with maximum deviations of 3.6° was observed. In addition, the influence of magnetic disturbances on the heading observations was tested. The results were presented in Retscher and Thienelt [2005]. As an example Figure 3 shows the influence of street lamps along the route of the pedestrian. Large deviations occurred if the source of disturbance was very close to the sensor. The influence of other system components, i.e., the notebook computer, barometric pressure sensor Vaisala PTB 220 and a metallic lighter were also tested. Here deviations of 2 to 3° occurred if the source of disturbance was within about 30 cm of the sensor. Higher deviations occured at shorter distances to the sensor. As a consequence the sensor should be kept away from any likely sources that could cause disturbances such as mobile phones, coins, metallic lighters and keys.

When the sensors were employed for the heading determination of a pedestrian in the real world, larger standard deviations than those in the laboratory tests were seen. The main reason for this was that the movement of a pedestrian depends very much on the surface (e.g. paved road, uneven surfaces, etc.) and the pedestrian's walking behaviour (i.e., walking, running, etc.). On asphalt surfaces standard deviations of ± 2 to 3.5° were obtained for the DRM III sensor and ± 3.5 to 4.5° for the HRM 3000. As the limiting factor is the movement behaviour of the pedestrian and the walking surface, we can conclude that the use of such low cost sensors for the heading determination fulfills our system requirements.

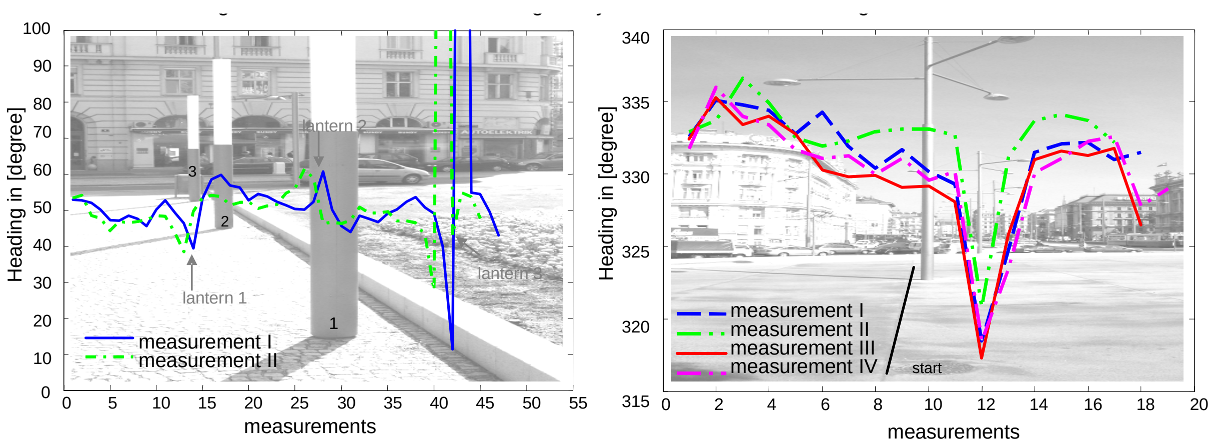

Fig. 3. Magnetic influences of street lamps on the Honeywell HMR 3000

4.3 Barometric Pressure Sensor

Direct altitude determination is particularly necessary in indoor environments where the use of a barometric pressure sensor could locate the user to the correct floor of a multi-storey building. Two different sensors were analyzed, i.e., the internal barometer of the PointResearch DRM III module and the Vaisala pressure sensor PTB 220. First of all the accuracy and the drift rate of both sensors were investigated in long term laboratory tests. In these tests we found that the standard deviation for the altitude determination of the PTB 220 is in the range of ± 0.11 to 0.33 m and for the DRM III in the range of ± 1 m. Maximum deviations of ± 0.60 m were obtained for the PTB 220 and ± 3 m for the DRM III.

Further tests were conducted in the office building of the Vienna University of Technology for location determination of a user on the correct floor. Figure 4 shows the observations with the PTB 220 and DRM III inside the building. As can be seen, the PTB 220 was able to determine the floor of the user very precisely (Figure 4 left) whereas the deviations of the barometer in the DRM III were much larger (Figure 4 right). Use of the DRM III could locate the user on the wrong floor of the building as the standard deviations was larger than the height difference between floors (i.e., 3.7 m). To conclude we can therefore recommend that a more precise and expensive barometric pressure sensor such as the Vaisala PTB 220 should be integrated into a pedestrian navigation system if the user has to be located in indoor environments.

4.4 Measurement of Distance Travelled

The measurement of the distance travelled was performed using the acceleration sensors of the PointResearch DRM III. The DRM III module was clipped to the user’s belt and the observations of the acceleration sensors used to detect and count the number of the steps. In several tests the quality of the stride detection was tested to determine the dependance of the pedestrian’s walking behaviour. For that purpose the user made a manual count of the number of steps and the result was compared with the DRM III measurements. Over a distance of about 70 m differences in the number of steps of 1 to 2 steps occurred which would result in an error in distance of about 1.5 m. The error, however, is larger if the pedestrian changes speed quickly between walking and running as only an average value for the stride length is taken into acount.

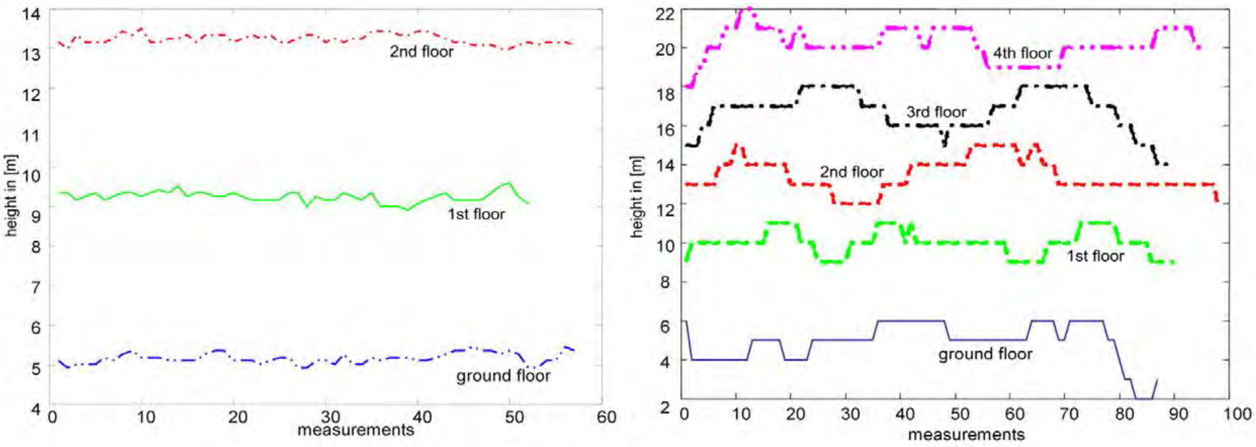

Fig. 4. Indoor observations with the PTB 220 (left) and barometer of the DRM III (right) for determination of the correct floor of the user

4.5 General Remarks

Apart from determining standard deviations for each sensor, the main observation from the sensor tests was that it is very challenging to determine the correct distance travelled and the direction of motion of the user. The determination of the user's direction of motion depends not only on the quality of the heading observations using the digital compass as the limiting factor but it was also apparent that the movement behaviour of the walking pedestrian is very critical.

5 Sensor Integration Performance Test

A main goal in the development of the new sensor fusion model was the reliability improvement of positional information in urban environments. Our approach was to test the system in the surroundings of our University. Figure 5 shows the test area in the 4th district of Vienna where typically 5 to 6-storey buildings are located along narrow streets. In the north of the selected area the trajectory starts in the Resselpark, continues along Argentinerstrasse and Gusshausstrasse to Karlsgasse and returns to the start point. Our office building is located at the intersection of Gusshausstrasse and Karlsgasse. Figure 5 (left) shows the positioning result of the PointResearch DRM III module and Figure 5 (right) the result of all suitable sensor observations of the NAVIO system. The red line in Figure 5 (left) shows the GPS positions of the DRM III module. Due to bad satellite reception along the Karlsgasse and the large positioning errors of the GPS receiver, the DRM III system was not able to perform a continuous position determination from the start point to the end point in the Resselpark; the drift of the dead reckoning sensors was to large in the Karlsgasse and no useable update from GPS was available. Figure 5 (right) shows the result of our calculated trajectory using the new multi-sensor fusion approach. As can bee seen from Figure 5 (right), a continuous postion determination is possible using all suitable sensor observations. Also the positioning accuracy of the determined trajectory is much higher. The larger errors in the range of 7.5 m from the reference trajectory occurred only along Gusshausstrasse and at the intersection of the Gusshausstrasse and Karlsgasse. A further improvement at sharp turns is expected using the improved filter approach which takes also sudden changes in the direction of motion of the pedestrian into account (compare section 3).

Fig. 5. Urban test area in the 4th district of Vienna with DRM III Trajectory (left) and NAVIO multi-sensor system trajectory (right)

6 Indoor Location Determination

Further research in the NAVIO project was carried out for the investigation of indoor location techniques. As most systems provide only location capability in two dimensions, the augmentation of an indoor location system with a barometric pressure sensor for direct observation of the altitude of the user was investigated. As shown in section 4.3, we were able to determine the correct floor of a user in a multi-storey building using the Vaisala PTB 220 pressure sensor. Testing was performed in our office building of the Vienna University of Technology. For the absolute position determination inside the building the use of Wireless LAN or WiFi was tested [Retscher et al., 2006]. This approach had the advantage that already available infrastructure in our office building could be employed. For this purpose the German company IMST GmbH cooperated and provided the indoor location system ‘ipos’. The ‘ipos’ system uses standard WiFi hardware and the location determination of a mobile user is performed on a mobile terminal or a server in the network. First of all a calibration of the system in an offline phase was required. Signal strength measurements were performed at known locations and stored in a database. This enabled a mobile user to be located during the online phase. The accuracy and performance of the system was tested in a diploma thesis in the localization testbed of IMST GmbH in Germany. The system is now available in our office building of the Vienna University of Technology and can be employed in combination with the dead reckoning sensors. Figure 6 (top) shows the location of the calibration points for a first system test on the 3rd floor of our office building and Figure 6 (bottom) the location test performed by students in our practical course on location-based services moving along the corridor. Due to the small number of calibration points and the location of the access points the trajectory of the moving user could be obtained with a standard deviation of about ± 3 m. Using the knowledge of the building model the trajectory can be matched to the corridor.

Fig. 6. Indoor location determination using WiFi fingerprinting with the system 'ipos' on the 3rd floor of an office building (on the top the location of the calibration points is shown and on the bottom the trajectory of a moving user along the corridor)

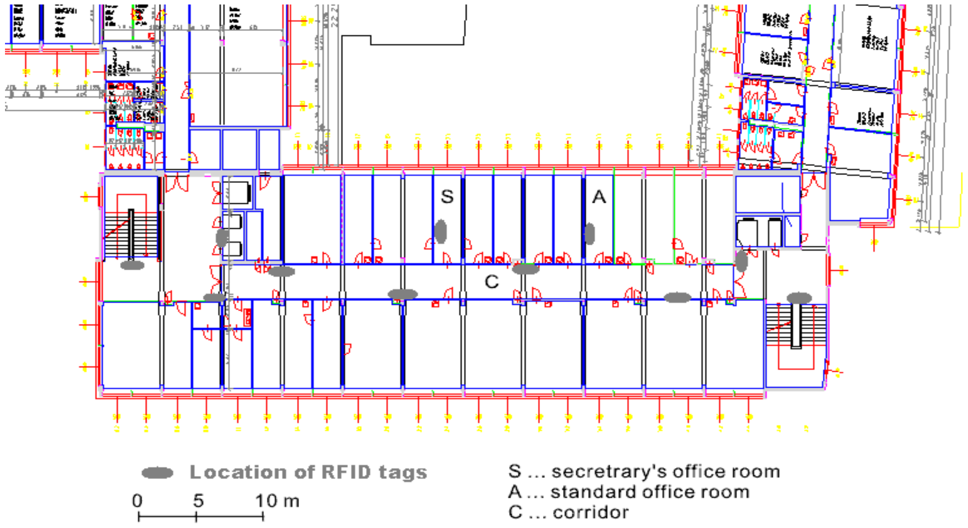

Fig. 7. Concept for location placement of RFID beacons in an indoor environment (i.e., 3rd floor of an office building of the Vienna University of Technology)

7 Conclusions and Outlook

Different location techniques and sensors for pedestrian navigation and guidance have been tested in the NAVIO project at the Vienna University of Technology, Austria. A new multi-sensor fusion model has been developed for the integration of all available sensor observations. Using the new multi-sensor fusion approach a high reliabilty and location accuracy for continuous position determination of a pedestrian in urban environments was achieved. The approach makes use of a knowledge-based component for a preprocessing of all available sensor observations [Retscher, 2007]. In this preprocessing step outliers and large errors are detected and these observations discarded before the central Kalamn filter. In addition, the knowledge of the preprocessing filter is used to adapt the stochastic Kalman filter model. Tests have shown that the positioning performance and reliability of continuous location determination can be significantly improved using this approach. Using the NAVIO system a user can be located in combined indoor and outdoor urban environments with high precision. In addition to GNSS, dead reckoning sensors such as a digital compass for heading determination, accelerometers for the measurement of distance and a barometric pressure sensor for altitude determination were employed. For indoor environments WiFi fingerprinting was used. In future the use of RFID for positioning using active landmarks is planned [Retscher and Zhang, 2006]. For indoor and outdoor pedestrian location determination we propose that RFID beacons are installed at known locations in the surrounding environment (e.g. at active landmarks, street crossings, entrances of buildings and offices, at regular distances inside of buildings, etc.). The system user would be equipped with a portable RFID reader module. If the tag’s information can be retrieved the user is located in a cell of circular shape with the location of the tag in the centre and a radius equal to the possible read range of the tag. The used location method is referred to as Cell of Origin (CoO) and this concept is also employed for the location determination of mobile or cellular phones. Several tags located in the smart environment can overlap and define certain cells that intersect. The position of the user can therefore be determined using the network of the tags which can be made available in a database.

Figure 7 shows an example for the proposed location of RFID on the 3rd floor of our office building at the Vienna University of Technology. In the chosen indoor environment the active RFID tags will be placed at active landmarks such as lift entrances and doors to offices, at the staircases at different levels, inside office rooms (e.g. the secretary’s office) and at regular distances along the corridor.

We propose to use wireless long-range RFID systems from Identec Solutions for the positioning of a pedestrian in the localization testbed at the Vienna University of Technology. Using the Intelligent Long Range® (ILR®) technique, the user can be located at a distance of up to 100 m [Identec Solutions, 2006]. Higher positioning accuracies can be achieved by reducing the sensitivity in the reader. It is therefore possible to limit the read range down to few meters. Although this positioning accuracy might be low for some applications, RFID positioning can be very useful if no GNSS positioning is possible due to satellite signal obstructions in urban areas.

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References

Gartner G., A. Frank, G. Retscher, 2004. Pedestrian Navigation System in Mixed Indoor/Outdoor Environment – The NAVIO Project, in: Schrenk M. (ed.): CORP 2004 and Geomultimedia04. Proceedings of the CORP 2004 and Geomultimedia04 Symposium, Vienna, Austria, February 24-27, 2004, pp. 165-171, http://corp.mmp.kosnet.com/CORP_CD_2004/archiv/papers/CORP2004_GARTNER_FRANK_RETSCHER.PDF, (Last date accessed: September 2006).

Honeywell, 2006. HMR 3000 Digital Compass Module, User's Guide, Honeywell International Inc., USA, http://www.ssec.honeywell.com/magnetic/datasheets/hmr3000_manual.pdf (Last date accessed: September 2006).

Identec Solutions, 2006. Intelligent Long Range® (ILR®) RFID System, Product Information, http://identecsolutions.com/ (Last date accessed: September 2006).

PointResearch, 2006 Gyro DRM™ Gyro-Stabilized Dead Reckoning Module, PointResearch Corporataion, U.S.A., http://www.pointresearch.com/datasheets/gyrodrm.pdf (Last date accessed: September 2006).

Retscher G., M. Thienelt, 2004. NAVIO – A Navigation and Guidance Service for Pedestrians, Journal of Global Positioning Systems, CPGPS, Vol. 3, No. 1-2, pp. 208-217, see http://www.gmat.unsw.edu.au/wang/jgps/v3n12/v3n12p26.pdf (Last date accessed: September 2006).

Retscher G., 2004. Multi-sensor Systems for Pedestrian Navigation, in: Papers presented at the ION GNSS 2004 Conference, Long Beach, California, U.S.A., September 21-24, 2004, CD-Rom Proceedings, 12 pgs.

Retscher G., M. Thienelt, 2005. Evaluation and Test of a Digital Compass Module Employed for Heading Determination in a Pedestrian Navigation System, in Grün A. and H. Kahmen (eds.), "Optical 3-D Measurement Techniques VII", Papers presented at the 7th Conference on Optical 3-D Measurement Techniques, Vienna, Austria, October 3-5, 2005, pp. 389-394.

Retscher G., E. Moser, D. Vredeveld, D. Heberling, 2006. Performance and Accuracy Test of the WLAN Positioning System ipos, in: Papers presented at the 3rd Workshop on Positioning, Navigation and Communication WPNC 2006, University of Hannover, Germany, March 16, 2006, Hannoversche Beiträge zur Nachrichtentechnik, Band 0.3, Shaker Verlag, pp. 7-15.

Retscher G., M. Thienelt, 2006. A Multi-sensor Personal Positioning System for Combined Indoor/Outdoor Environments, in: Papers presented at the 3rd IAG Symposium on Geodesy for Geotechnical and Structural Engineering and 12th FIG Deformation Measurement Symposium, Baden, Austria, May 22-24, 2006.

Retscher G., K. Zhang, 2006. Positioning Case Studies Using RFID and GNSS: Indoor and Outdoor, in: Papers presented at the IGNSS 2006 Conference, Surfers Paradise, Queensland, Australia, July 17-21, 2006, CD-Rom Proceedings.

Retscher G., 2007. A Knowledge-based Kalman Filter for an Intelligent Pedestrian Navigation System, Survey Review, Vol. 39, No. 306, October 2007.

Thienelt M., A. Eichhorn, A. Reiterer, 2005. Konzept eines wissensbasierten Kalman-Filters für die Fußgängerortung (WiKaF). Österreichische Zeitschrift für Vermessung und Geoinformation (VGI), Vol. 93, No. 2, pp. 96-104.

Vaisala, 2006. PTB220 Digital Barometer, Vaisala, Finnland, http://www.vaisala.com/businessareas/instruments/servicesupport/userguides/barometricpressure/PTB220%20User%20Guide%20in%20English.pdf (Last date accessed: September 2006).

Wang J. G., 1997. Filtermethoden zur fehlertoleranten kinematischen Positionsbestimmung, Schriftenreihe des Studiengangs Vermessungswesen der Universität der Bundeswehr München, Heft 52, Neubiberg.

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Mok E., G. Retscher, L. Lau, 2002. Development of an Event-Reporting Intelligent Vehicle Navigation System for Areas with Urban Canyons, Survey Review, Vol. 36, No. 284, April 2002, pp. 398-409.

Retscher G., E. Mok, 2004. Sensor Fusion and Integration using an Adapted Kalman Filter Approach for Modern Navigation Systems, Survey Review, Vol. 37, No. 292, April 2004, pp. 439-447.

Retscher G., M. Thienelt, 2004. NAVIO – A Navigation and Guidance Service for Pedestrians, Journal of Global Positioning Systems, CPGPS, Vol. 3, No. 1-2, pp. 208-217.

Retscher G., A. Kealy, 2006. Ubiquitous Positioning Technologies for Modern Intelligent Navigation Systems, The Journal of Navigation, Vol. 59, No. 1, January 2006, pp. 91-103.

Retscher G., E. Moser, D. Vredeveld, D. Heberling, J. Pamp, 2007. Performance and Accuracy Test of a WiFi Indoor Positioning System, Journal of Applied Geodesy, Vol. 1, No. 2, pp. 103-110.

Retscher G., 2007. Augmentation of Indoor Positioning Systems with a Barometric Pressure Sensor for Direct Altitude Determination in a Multi-storey Building. Journal of Cartography and Geographic Information Science (CaGIS), Vol. 34, No. 4, October 2007.

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