Indoor Navigation without usage of infrastructure sensors -based Local Positioning System

Harald Sternberg, Matthias Fessele and Christian Hönniger (HafenCity University of Hamburg)
The authors are with the HafenCity University of Hamburg, Hebebrandstraße 1, 22297 Hamburg, Germany
Email: (harald.sternberg, matthias.fessele, christian.hoenniger)@hcu-hamburg.de

ABSTRACT

This short document describes the evaluation of an indoor navigation system for pedestrians based on a small Low-Cost Inertial Navigation System (INS). The system components are explained and first investigations that were performed on the campus of the HafenCity University (HCU) are shown. The focus of the investigation was the transition from outdoor to indoor scenarios. The aim of the project is the optimal integration of the sensor data from the small INS /GPS with other sensors (e.g. cameras and GIS with a self-programmed Kalman Filter (KF)). The research is accomplished in the established Research Group 'Digital City' at the HCU. The interdisciplinary team will focus on the development of valued added information and innovative services for the requirements of citizens, employees, businesses and tourists.

Keywords: indoor-, pedestrian-, urban- navigation, low-cost GPS/INS, small IMU, algorithms, filters

1. INTRODUCTION

With changes in sensor technology the development of small, lightweight and low-cost sensors; and the recent increases of vehicle navigation popularity; the market for pedestrian navigation has arisen. As [1] stated, there are some differences between both kinds of navigation:

-- Dynamic behaviour of pedestrians is low in contrast to vehicle dynamics, these results in higher demands on relative sensors.

-- Pedestrians are not restricted to move on the road network and to behave conform to traffic rules (e.g. restricted manoeuvres and one-way streets). Therefore enhancement of positioning by map matching technologies is not as obvious as in vehicle navigation.

-- Pedestrian navigation requires advanced map data, using such features as pedestrian areas and subways.

-- Special effort has to be made in indoor navigation, especially regarding the transition from outdoor to indoor scenarios.

The focus of this paper is on the evaluation of low-cost INS with integrated GPS sensors and its utilisation for pedestrian navigation. Further questions such as the optimisation of routes and destination guidance or the design and setup of map databases for pedestrians are not taken into account.

The core of the Indoor navigation system is the determination of the position.

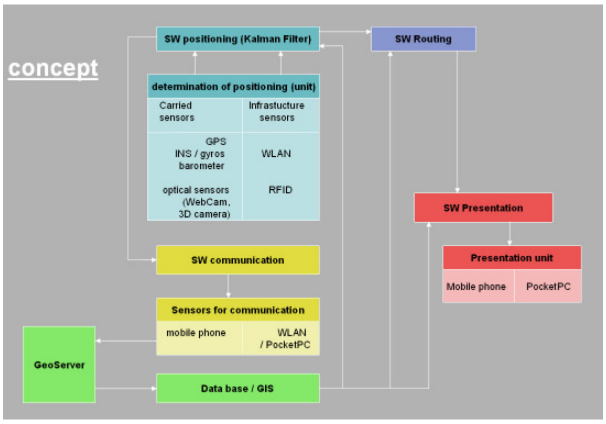

Figure 1: Overall Concept

Here different positioning techniques are possible. We focus on a solution free of infrastructure sensors. Only in the evaluation phase we will use these sensors for the verification of the trajectory. A positioning unit consists of the basic sensor: IMU, GPS and barometer. Additional sensors to support the orientation in the building could be optical sensors like webcam or 3D cameras.

The communication and data streaming is important for the exchange of building information from and to the geoserver. This data maintain the process of the routing but also of the determination of the position. At least we need an interface to present the result of the navigation process to the user in a user friendly, user adapted format. The man-machine interface will be developed with the colleagues from urban planning in the research group digital city.

2. TECHNOLOGIES OF POSITIONING

The advancement of pedestrian navigation and the challenging tasks evolving from the differences between pedestrian and vehicle navigation like those listed in section 1, subsequently result in manifold research activities. The focus herein is on the topics regarding the positioning itself.

With regard to indoor positioning different kinds of Local Positioning Systems (LPS) were developed to enable locally bounded positioning inside of buildings. Many of these systems can require a complex infrastructure. They differ in frequencies used in the way sending and receiving, and parts of the systems are divided between moving objects and infrastructure. Examples of frequencies and systems:

- Ultrasound, e.g. Active Bat, Cricket
- Infrared, e.g. Active Badge, WIPS
- Visible light, e.g. Cyber Code
- Radio signals, e.g. positioning via WLAN, Bluetooth

Further information on these systems and their applications can be found in [2]. First investigations to combine infrastructure sensors with mobile positioning system are made by [3] with the integration of INS and WLAN positioning.

Since LPS are restricted to small areas in which they are installed and their infrastructure might be high cost intensive, our focus is on positioning methods that exclude infrastructure-based technologies. The objective is the development of a pedestrian navigation system with all positioning sensors embedded in one unit, which is small, lightweight and easy to use. Additional sensors such as step counters/pedometers are useful for indoor positioning [4].

3. ON-BOARD SENSOR EQUIPMENT

3.1 Low-Cost IMU MTi-G

The MTi-G (Miniature GPS/INS) from Xsens Technologies is an integrated GPS and inertial measurement unit, belonging to a family of inertial motion trackers. The inertial sensors (3 axes) are based on MEMS (Micro-Electro-Mechanical System) technology; the GPS sensor is a miniature GPS receiver with external antenna.
The MTi-G is also aided by additional sensors including:

- 3D magnetometer
- static pressure sensor

Receiver Type	16 channels L1, C/A code
GPS Update Rate	4 Hz
Accuracy Position SPS	2.5 m CEP
DGPS/SBAS	2.0 m CEP
Timing Accuracy	50 ns RMS

Table 1: GPS receiver specification

The MTi-G enables navigation and determination of attitude as well as heading within a given reference system with an Attitude and Heading Reference System (AHRS) processor. The internal signal processor runs a real-time Kalman Filter which provides inertial enhanced 3D position and velocity estimates and GPS enhanced, orientation estimates, calibrated acceleration, rate of turn and earth-magnetic field data and the static pressure (barometer). Several interface options allow for different settings regarding specific usage scenarios. Further sensor specifications are given in [5].

	rate of turn	acceleration	magnetic field	static pressure
Unit	[deg/s]	[m/s²]	[mGauss]	[hPa]
Dimensions	3 axes	3 axes	3 axes	-
Full Scale	+/- 300	+/- 50	+/- 750	300 – 1200
Linearity	0.1 % of FS	0.2 % of FS	0.2 % of FS	0.5 % of FS
Bias stability (1σ)	5	0.02	0.5	100 Pa/year
Max Update Rate	512 Hz	512 Hz	512 Hz	9 Hz

Table 2: IMU sensor performance

3.2 First Results

Various output modes are available for subsequent processing, most of them in binary format for real time processing. Different levels of the data can be accessed:

Kalman Filter output:

- Orientation output
- Position (and velocity) output
- Calibrated inertial data

Raw data output:

- Uncalibrated raw inertial data
- Raw GPS data with estimated accuracies

To combine different data sources, three different predefined Kalman Filter models can be used. The scenarios differ in the determination of the heading as listed in Table 3. Additional Kalman Filter models can be developed and stored in the MTi-G.

	IMU	GPS	Magnetometer	Holonomic
General purpose	●	●		
Aerospace	●	●	●	
Automotive	●	●		●

Table 3: XKF-6G navigation algorithm

First tests using the inbuilt Kalman Filter of the MTi-G were carried out on the area of the HafenCity University with different scenarios:

- Mounted in a car
- Pedestrian / good satellite conditions (Figure 2)
- Pedestrian / entering a building (Figure 3)

In the first test mounted in a car the results are good until the GPS signal is lost e.g. in a tunnel. Here the different scenarios can be compared with respect to the deviation from true path and to each other. The best result can be reached with the holonomic function. This function in the automotive scenario assumed that the 'course over ground' will be equal to the heading and no sideways slips occurred. The result of the aerospace scenario with the magnetometer heading update is clearly worse because of the unfavorable error influence on the sensor in the car.
In the second scenario we have good satellite conditions for the pedestrian navigation outside the building, the standard deviation of the positioning with raw GPS data and the offset to true position is in the order of 2 m. The trajectory is smoothed and corrected in the Kalman Filter.

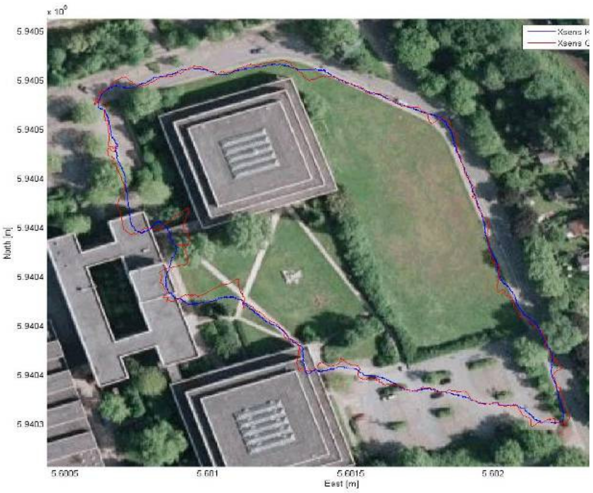

Figure 2: Representation of the same ground path 'raw GPS data' and calculated with Kalman Filter model aerospace.

For the third scenario, the transition from outdoor to indoor, two different Kalman Filter models (general purpose and aerospace) of the three predefined models (see Table 3) were examined. The holonomic function doesn't work if the velocity is less than 2 m/s, so this model cannot be used for pedestrian navigation. The plot of the ground path is shown in Figure 3.

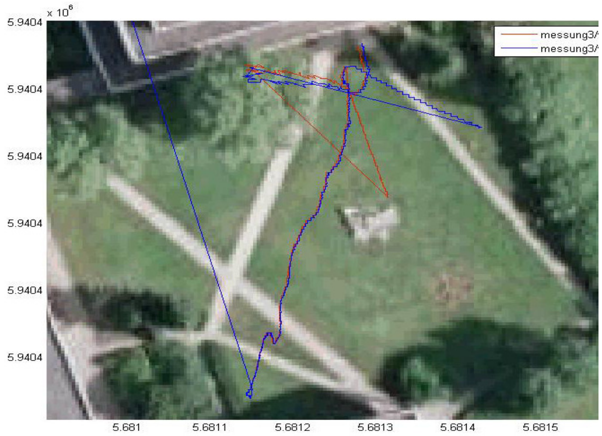

Figure 3: Same ground path calculated with Kalman Filter model aerospace (v3) and general purpose (v32).

Due to the fact that the system does not compute any position if the GPS signal is lost for more than 10 seconds, no Kalman Filter output can be obtained in the building. The magnetometer signal can be used to identify the entering of the building as shown in Figure 4.

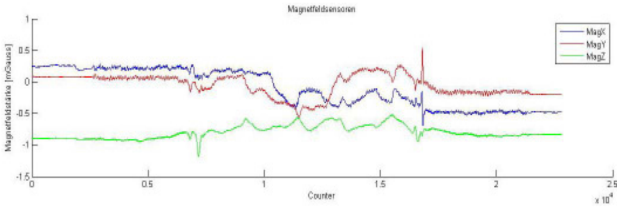

Figure 4: Significant peaks in the signal while entering (0.7 x 10^4) and leaving the building (1.7 x 10^4) because of the metal structure of the entrance

A second test for the transition scenario was performed with the newest version of the MT manager software from Xsens. Special attention was put on the actual transition into the building. The colours blue, red and green mark the areas before entering the building, in the building and after leaving the building respectively (Figure 5). GPS Positions are also available in the building with this version. It is, however unclear, whether these positions are led back by the Kalman Filter to the GPS computation in a closed loop or whether the sensitivity of the receivers were increased. The yaw angle is also resumed correctly also after the transition to the building inside.

A good positioning during the transition from outdoor to indoor can be achieved if the GPS signal and positioning outside the building is good enough to stabilise the INS. The magnetometer cannot improve the positioning but the signals can help to detect the entering of the building.

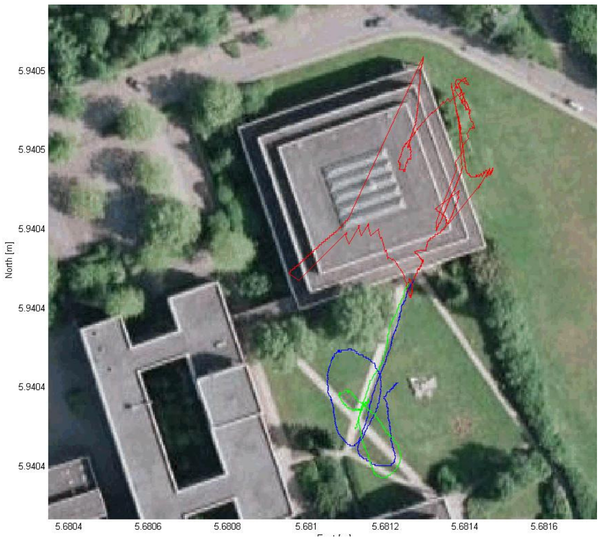

Figure 5: Ground path calculated with Kalman Filter model aerospace. Blue before entering, red in the building, green after leaving the building

4. KALMAN FILTER

The MTi-G contains a loosely coupled Kalman Filter for processing of the raw sensor data. The motion model formulated within the system equations is not application specific. For the purpose of pedestrian navigation different filter models will be developed. For flexibility regarding both system equation (dynamic model) and measurement equation (sensors used) a modular system concept is designed. Thus enabling simulation and testing of different scenarios and sensor combinations. Different MTi-G data sources can be integrated like accelerometers and the barometric altimeter for drift-free height determination [7]. External data sources like a step counter or digital camera can be integrated in the system.

The coordinate system used for Kalman Filtering is a NED-system (North-East-Down). It's a right hand system and its NE-plane corresponds with the UTM coordinate system.

As positions we use the positions from the MTi-G computed with Kalman Filter option "aerospace". The NED-system is used because in this way the height can be introduced to the Kalman Filter as a separate state variable.

The available measurements differ due to different time epochs. Because of this a case differentiation has to be used in the Kalman Filter. The following list shows the measurements for each case together with the configuration matrices and the covariance matrices.

Because we use the pre-filtered coordinates from the MTi-G we do not need GPS positions directly within our Kalman Filter. The used positions are also available for every filter step outside the building and even inside of it until the aerospace filter does not provide any further positions.

Case 1: Outside of buildings

$$l_k = \left(a_x[k] \quad a_y[k] \quad a_z[k] \quad v_{x,MTiG}[k] \quad v_{y,MTiG}[k] \quad v_{z,MTiG}[k] \right.$$
$$\left. x_{MTiG}[k] \quad y_{MTiG}[k] \quad h_{baro}[k] \right)$$
$$\vec{x}[k] = \left(x[k]\ y[k]\ z[k]\ v_x[k]\ v_y[k]\ v_z[k]\ a_x[k]\ a_y[k]\ a_z[k] \right)$$

s_a^2 = variance of the velocities (MTi-G inbuilt KF)

s_v^2 = variance of the speeds (MTi-G inbuilt KF)

s_x^2 = variance of the positions (MTi-G inbuilt KF)

s_h^2 = variance of the heights (Barometer)

Case 2: Inside of buildings

$$l_k = \left(a_x[k] \quad a_y[k] \quad a_z[k] \quad h_{baro}[k] \right)$$

$$C_l = \begin{pmatrix} s_a^2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & s_a^2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & s_a^2 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & s_h^2 \end{pmatrix}$$

state vector as above.

Step counters are very often used within pedestrian navigation. A step counter provides the step frequency. Based upon this frequency the walking speed of the pedestrian can be determined. It was proposed to not utilise a step counter and extract the walking speed out of the measurement from the acceleration sensors of the MTi-G.

The walking speed is a further quantity that can be used for sustaining within Kalman Filtering.

For pedestrian navigation Case 2 in the list above changes because of the implementation of the walking speed.

New measurement vector in Case 2:

$$l_k = \left(a_x[k] \quad a_y[k] \quad a_z[k] \quad v_{x,sfreq} \quad v_{y,sfreq} \quad v_{z,sfreq} \quad h_{baro}[k] \right)$$

5. FIRST RESULTS WITH OUR OWN PEDESTRIAN KALMAN FILTER (PKF)

The basic Kalman Filter model used in the MTi-G setup was "aerospace". For our own cascaded version of the Kalman Filter we used the Orientation output of the internal filter together with the calibrated inertial data from IMU and the raw data from GPS and the pressure sensor.

The raw data contained the following measurement:

- 3D Acceleration (IMU)
- 3D Velocity (GPS)
- 3D Position (GPS)
- Pressure

Our filters based on Kalman's Filter provide forward filtering and backward filtering of the data. In addition an optimal smoothing is provided to combine both filters to get an optimal result.

Figure 6 shows the ground path of a car. All result paths of our versions of the Kalman Filter and smoothers as well as the ground path of the internal Kalman Filters are represented.

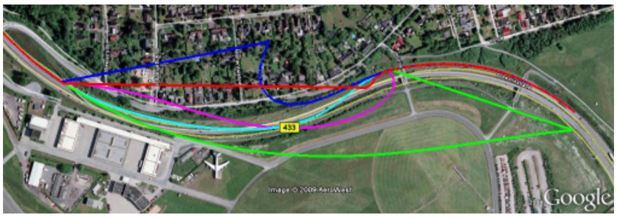

Figure 6: Ground path – driven by car at Airport-tunnel area in Hamburg

The meaning of the above displayed colours are as followed: red – inbuilt KF, blue – forward, green – backwards, cyan and magenta – KF optimal smoothed with different weights; cyan is used in the further follow-up.

Figure 7 shows the height path of the above trajectory. The height paths of the three filter results as well as the height path of the internal Kalman Filters "aerospace" are pictured again. In addition Figure 7 shows the height path of the GPS filter.

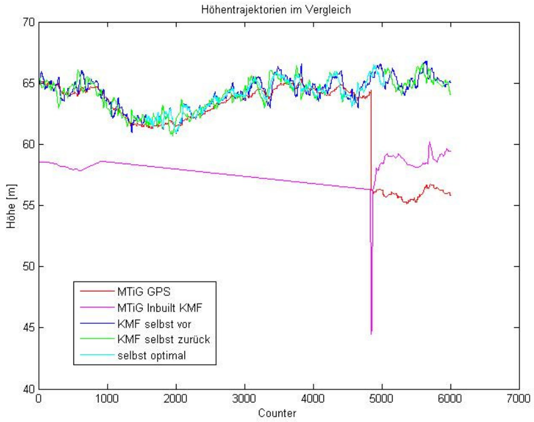

Figure 7: Comparison of the height-trajectories (WGS84)

It can be seen that there is an offset between the height path of the internal Kalman Filters and the GPS height path. This is the result of the integration of the internal pressure sensor in the "aerospace" Kalman Filter. Taking into account that the trajectory contains a period where no GPS data was available (Counter 1700 to 4800). After this period the GPS height path shows a downward spike, which corresponds with the re-initialization of the GPS receiver. This spike obviously effects the results of the aerospace filters. In effect after a time period where no GPS is available the height path of the internal Kalman Filter becomes incorrect. Our KF version uses the pressure measurements to compute the height with a higher weight for the filtering. The pressure data is shown in Figure 8.

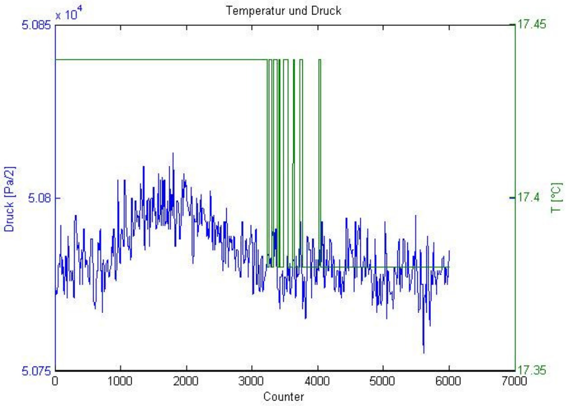

Figure 8: Temperature and pressure measurement series from MTi-G

The GPS message contains the pressure data. It can also be accessed indoors (still available) when no GPS fix is possible.

The use of the pressure sensor in pedestrian navigation:

To test the internal pressure sensor for height determination within a Kalman Filter we chose a path outside and not obscured by buildings (see Figure 9). The path is shown in Figure 10. It contains ground floor data, moving to a further two floors utilising two stairs.

Figure 9: Dockland building in the Hamburg harbour (photo by kang, available at Google Earth)

Figure 10: Dockland building in the Hamburg harbour with trajectory on the steps of the east part

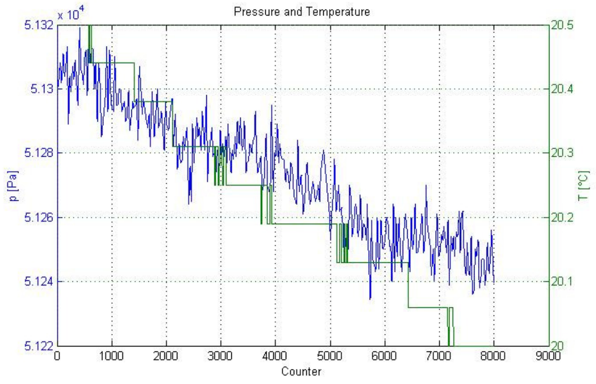

Figure 11: Pressure and temperature

Figures 12 and 13 show in comparison the speed provided by GPS sensor and the speed due to the step frequency and average step length.

The height path displayed in Figure 14 shows that the pressure sensor is needed to determine the floor on which the pedestrian is walking. Shown in Figure 11 is the series of measurements for pressure and temperature.

The GPS height path as provided from the GPS filter is not sufficient for a significant determination of the floor. The height computed with the help of a barometer has a standard deviation better than 0.8 m. So, the height can be achieved with sub metre precision which is good enough to determine the floor, especially based up on a geographic management system which contains the information about the floor heights.

The height provided by GPS is displayed in the Figure 14 and marked in magenta.

The plots in Figures 12-14 are results from the same series of measurement.

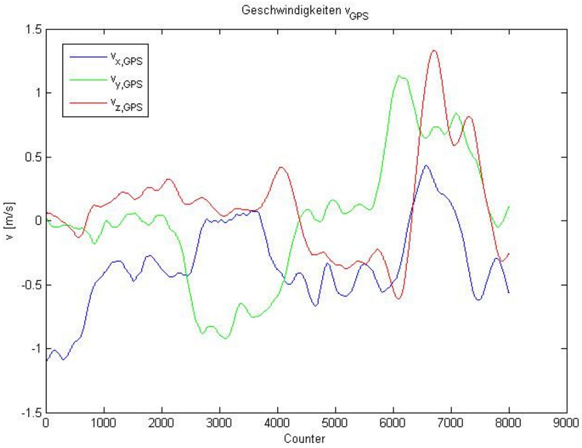

Figure 12: Speed provided by the GPS sensor

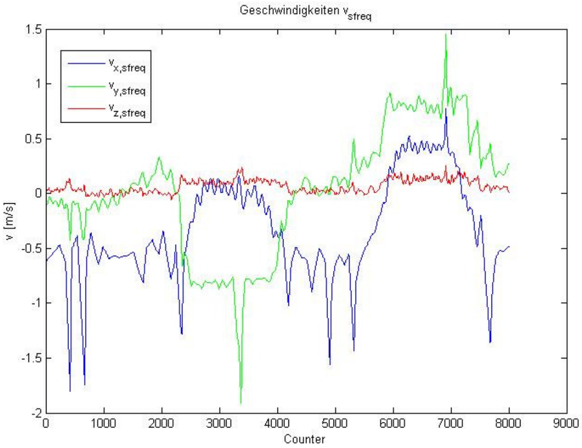

Figure 13: Speed due to step frequency and average step length

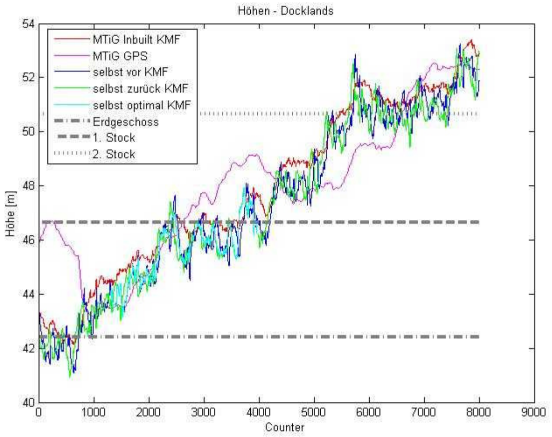

Figure 14: High-path in context to the floor plans

The navigation result can still be improved if the MEMS gyroscopes will be examined on a 3 axis turn table to check and calibrate this specific sensor. The calibration process will be similar to the process for automotive gyroscopes described in [6].

Further potential for improvement can be realized by estimate of the step length in the filter; adaptation for horizontal plane and stairs.

Advantages: The used system is a very compact low-cost inertial navigation system (all sensors in one unit) which is usable as full system as shown and it is quite user friendly.

6. FUTURE WORK

To improve the navigation within buildings, GIS data will be combined in the positioning process and also used for guidance. Here, not only the ground plan of the building but also the utilisation of the premises and most frequently used corridors are applied to support the navigation process. It is important to use a fast data transfer from the GIS server to the mobile measuring and visualization unit. Acquisition of cartographic and other descriptive elements are key to meaningful route guidance within buildings. Applications would be reserved in this larger version to particular demographics, who must navigate in unfamiliar buildings, e.g. for emergency services in significantly sized structures. This research aims to contribute to make smaller but still useful systems. It is necessary to control the sensors and the technology, to improve the algorithms, to use more geo-information, to build smaller units and to attach the sensors to existing mobile devices.

The project at the HCU Hamburg will be continued by using map-matching for the positioning, e.g. level plans of buildings. Hereby different kinds of heights and step width on horizontal plates or stairs will be taken into account.

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