A MULTI-SENSOR PERSONAL POSITIONING SYSTEM FOR COMBINED INDOOR/OUTDOOR ENVIRONMENTS

Günther Retscher and Michael Thienelt
Institute of Geodesy and Geophysics, Engineering Geodesy
Vienna University of Technology
Email: gretsch@pop.tuwien.ac.at

Abstract: Current personal navigation systems rely mainly on GNSS for location determination and an integration of other sensors has not been performed. To improve the reliability of continuous position determination in urban environments, however, the integration of dead reckoning sensors is essential. In the research project NAVIO at the Vienna University of Technolgy a multi-sensor system has been developed for pedestrian navigation and guidance. In the system a new multi-sensor fusion model based on an Kalman filter is employed for the optimal determination of the current user's position, velocity and direction of motion. In this paper test results of the location sensors and their system integration is presented. It could be seen that a high accuracy and reliability can be achieved for location of the user in combined indoor/outdoor environments.

1. Introduction and Motivation

The acceptance of mobile personal navigation systems has grown in recent years. Typically systems for vehicle navigation are employed, but also the number of systems is growing for the navigation of cyclist and pedestrians. Most of these systems rely on location determination using GNSS in combination with map matching. In general, these systems show a high performance in case of availability and positioning accuracy. Very challenging, however, is the continuous position determination in urban areas where satellite signals are frequently blocked. In the NAVIO project [2] the navigation of a pedestrian in combined indoor/outdoor environments is investigated and a system has been developed. Thereby one of the main challenges which have been investigated were the usage of dead reckoning sensors for the continuous position determination of a pedestrian. For this purpose different sensors have been tested and integrated into a system. The reliability of the location determination has to be improved in our system by the use of new multi-sensor fusion model based on a Kalman filter. As more sensors have been integrated than the minimal number required for continuous position determination, 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 the test of the sensors is presented in the paper.

2. Employed Sensors in NAVIO

Suitable sensors for pedestrian location determination were selected from a great variety of sensors available on the market. For that purpose tests of different sensors were performed.

Starting from the preselection the following sensors have been integrated in our system design:

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

In the system the selected GPS sensor 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 traveled distance, the direction of motion and changes in altitude can be determined. For the data acquisition a software module has been developed using Matlab. 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.

3. Integration of the Sensors

A prerquisite for the analysis of the sensor observations is their integrated data acquisition. Then the integration of all sensors to obtain an optimal estimate of the current user's position, its velocity and direction of motion can be performed using a Kalman filter approach. For the development of the multi-sensor fusion model based on an Kalman filter two different kinematic filter models were tested which describe a linear radial movement behaviour of the pedestrian. Then the accelerations are 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 is performed [see 12] whereas in the second model also sudden changes in the direction of motion of the pedestrian are taken into account [see 1].

For the first filter model the following system equations are used:

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

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

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

$$v_t(k+1) = v_t(k) \qquad (4)$$

$$a_r(k+1) = a_r(k) \qquad (5)$$

where $X(k)$ and $Y(k)$ are the 2-D coordinates, $\alpha(k)$ is the azimut, $v_t(k)$ 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 selcted time interval the impact of the disturbances is reduced to a minimum. Therfore for the expectation value $E\{a_t\} = 0$ und $E\{\dot{a}_r\} = 0$ can be assumed. In one epoch of the filter the two disturbance values can also be considered as constant.

Apart from the central Kalman filter also a concept for a knowledge-based preprocessing of the sensor observations has been developed [see 8, 10]. In the knowledge-based preprocessing filter 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).

4. Performance Test of the Location Sensors

The performance and the accuracy of these sensors was tested in different test areas. For the test areas different environments representing the real world situation for the system were chosen. One test area was in the park of Schönbrunn palace with free satellite visibility, the second in urban environment in the surroundings of 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 model of the multi-sensor fusion model based on an Kalman filter for the integration of the sensor observations. Figure 1 shows the sensors and their integration.

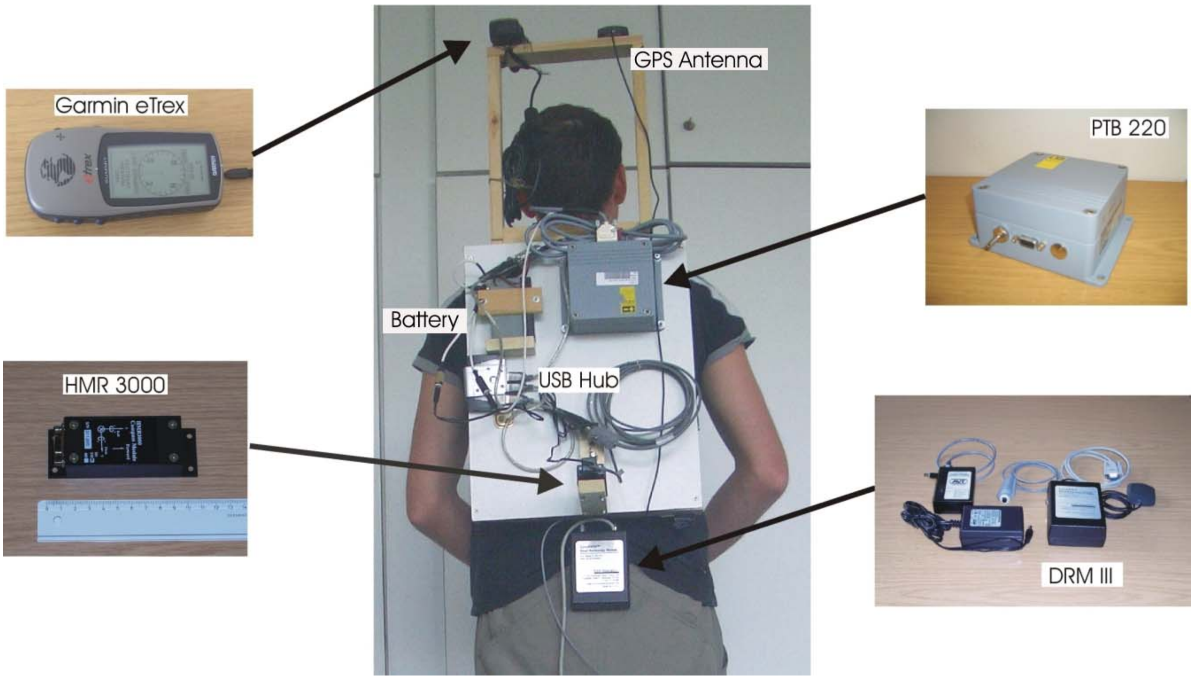

Figure 1. Sensors of the NAVIO system

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 [4]. The availability and reliability of this sensors in urban areas has been tested. The observations have been 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 lab observations for determination of the sensor drift and test observations in the real world situation have been performed. From the long term observations the manufacturers specs can be checked and a significant drift can be detected. In the tests of the Honeywell HMR 3000 heading sensor [see 3] no significant drift could be seen and an average standard deviation of ± 0.22 degrees with maximum deviations of 1.2 degrees was obtained. For the heading sensor of the PointResearch DRM III a standard deviation of ± 0.85 degrees with maximum deviations of 3.6 degrees was obtained. In addition, the influence of magnetic disturbances on the heading observations was tested. The results were presented in [7] and can be sumarized as follows. Deviations of 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 any sources that can cause disturbances such as mobile phones, coins, metallic lighters and keys.

If the sensors are employed for the heading determination of a pedestrian in the real world situation, however, larger standard deviations than in the lab tests could be seen. The main reason for this is that the movement of a pedestrian depends very much on the walking surface (e.g. paved road, uneven surfaces, etc.) and the walking behavior (i.e., walking, running, etc.). On asphalt surfaces standard deviations of ± 2 to 3.5 degrees were obtained for the DRM III sensor and ± 3.5 to 4.5 degrees for the HRM 3000. As the limiting factor is the movement behavior of the pedestrian and the walking surface, we can conclude that the use of such low cost sensors for the heading determination is sufficient.

4.3. Barometric Pressure Sensor

The direct altitude determination is especially necessary in indoor environments. Using a barometric pressure sensor we want to be able to locate the user on the correct floor of a multi-storey building. Two different sensors have been analyzed, i.e., the internal barometer of the PointResearch DRM III module and the Vaissala pressure sensor PTB 220 [11]. First of all the accuracy and the drift rate of both sensors were investigated in long term lab tests. In this tests we could see that the standard deviation 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 our office building of the Vienna University of Technology for location determination of a user on the correct floor. Figure 2 shows the observations with the PTB 220 and DRM III inside the building. As can be seen from Figure 2, the PTB 220 can determine the floor of the user very precisely (Figure 2 on the left) whereas the deviations of the barometer in the DRM III are much larger (Figure 2 on the right). Using the DRM III it could happen that the user is located on the wrong floor of the building as the standard deviations are larger than the height difference of the floors (i.e., 3.7 m). To conclude we can therefore recommend that a more precise and expensive barometric pressure sensor should be integrated into a pedestrian navigation system if the user has to be located also in indoor environments.

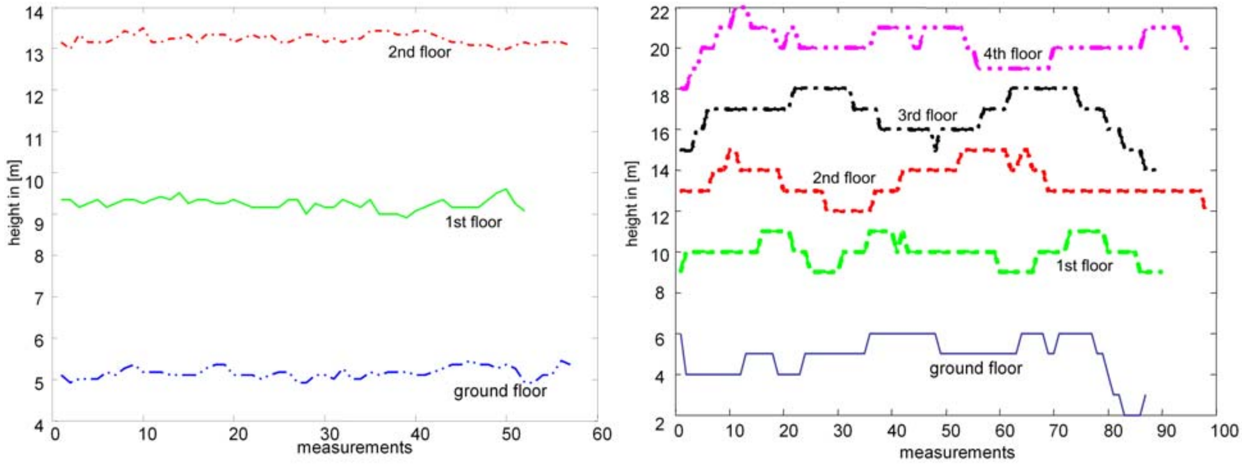

Figure 2. Indoor observations with the PTB 220 (left) and barometer of the DRM III (right) for determination of the correct floor of the user

4.4. Measurement of Traveled Distance

The measurement of the traveled distance is performed using the acceleration sensors of the PointResearch DRM III. The DRM III module is clipped on the users belt on the back and the observations of the acceleration sensors are used to detect the steps and count their number. In several tests the quality of the stride detection was tested in dependance of the walking behavior of the pedestrian. For that purpose the number of steps was counted manually from the user 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 could be seen. This would result in an error in distance of about 1.5 m. The error, however, is larger if the pedestrian changes quickly the walking speed between walking and running as only an average value for the stride length is taken into acount.

Apart from the determined standard deviations of each employed sensor described in section 4.1 to 4.4., a main result of the sensor tests was also that it is very challenging to determine the correct traveled distance and the direction of motion of the user. For the determination of the direction of motion of the user not only the quality of the heading observations using the digital compass is the limiting factor but also the movement behaviour of the walking pedestrian is very critical.

5. Sensor Integration Performance Test

A main goal of the development of the new sensor fusion model is the improvement of the reliability of location determination in urban environments. To test our approach the system was tested in the surroundings of our University. Figure 3 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, then it continues along Argentinerstrasse and Gusshausstrasse to Karlsgasse. At the intersection of Gusshausstrasse and Karlsgasse our office building is located. Figure 3 on the left shows the positioning result of the PointResearch DRM III module and Figure 3 on the right the result of all suitable sensor observations of the NAVIO system. The red line in Figure 3 (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 is not able perform a continuous position determination from the start point in the Resselpark (in the north) to the same end point as in the Karlsgasse the drift of the dead reckoning sensors is to large and no update from GPS is available. On the other hand, Figure 3 on the right shows the result of our calculated trajectory using the new multi-sensor fusion approach. As can bee seen from Figure 3 (right), a continuous postion determination is possible using all suitable sensor observations. Also the positioning accuracy of the determined trajectory is much higher. The maximum deviation from the reference trajectory in the range of 7.5 m occurred only at the intersection of the Gusshausstrasse and Karlsgasse. A further improvement at sharp turns is expected by using the improved Kalman filter approach mentioned in section 3. The refined approach will take also sudden changes in the direction of motion of the pedestrian into account [compare 1].

Figure 3. Urban test area in the 4th district of Vienna with DRM III trajectory (left) and NAVIO multi-sensor system trajectory (right)

6. Conclusions and Outlook

Using the new multi-sensor fusion approach a high reliabilty and location accuracy for continuous position determination of a pedestrian in urban environments can be achieved. The approach will be refined using a knowledge-based component for a preprocessing of all available sensor observations [see 8, 10]. In this preprocessing step outliers and large errors are detected and these observations are then not used in the central Kalamn filter. In addition, the knowledge of the preprocessing filter is used to adapt the stochastic Kalman filter model.

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. Using the Vaisala PTB 220 pressure sensor we were able to determine the correct floor of a user in a multi-storey building. Tests have been performed in our office building of the Vienna University of Technology. For the absolute position determination inside the building the use of Wireless LAN (Wireless Local area Networks) was tested [see 9]. This approach has the advantage that already available infrastructure in our office building can be employed. For this purpose a cooperation with the German company IMST GmbH was established and they provided the indoor location system 'ipos'. The system 'ipos' uses standard WLAN hardware and the location determination of a mobile user can be performed on the mobile terminal or a server in the network. The accuracy and performance of the system was tested in a diploma thesis. 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.

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Acknowledgements: The research work presented in this paper is supported by the FWF Project NAVIO of the Austrian Science Foundation (Fonds zur Förderung wissenschaftlicher Forschung) (Project No. P16277-N04).