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Tracking Persons using a Radio-Based Multi-Sensor System

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Abstract—**A multi-sensor system for 3D localization was developed and named BodyGuard. It combines body movement sensing and a guard system for the tracking and recording of the status of persons. BodyGuard was designed to monitor and transmit the movement of a person radio-based and to transform that data into a spatial coordinate. This paper describes how the BodyGuard system works, what components the system consists of, how the individual sensor data is converted into 3D motion data, with which algorithms the individual sensors are processed, how individual errors are compensated and how the sensor data are fused into a 3D Model.**

Keywords—wireless sensor network (WSN); embedded systems; sensor calibration and validation; person tracking, inertial navigation system, inertial measuremt unit

I. Introduction

The development of systems for locating people is a growing trend and many research institutions around the world are engaged in it, because accidents involving the relief units occur consistently while they carry out their activities. For this reason, a project to locate injured or endangared persons in order to rescue and salvage them, was launched. From this motivation, the project partners developed a small, easy to handle and robust 3D localization system for determining the position of relief units.

The Inertial Measurement Unit (IMU) presented in Fig. 1 consists of several independently operating electronic components, which implement in their combination a system with 6 degrees of freedom. It was designed to detect and collect spatial movements of various objects, especially the movement of people.

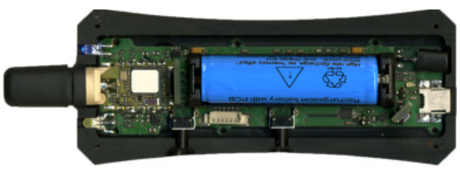

Figure 1. The BodyGuard-System

This short paper will specifically address the localization of people and describe how the developed hardware and software implement this. Thereby, the individual components as well as the specific modifications and optimizations are described. Additionally, the progress from individual sensors to a multi-sensor system, the adaption to the application and the necessary calibration are shown. Furthermore, a description of the pre-processing of the measured data, as well as the filtering and the detection of individual data for an IMU system are included. Finally, the aggregation of information to a data package that is stored on the system and transferred via USB or radioed to a remote station is presented.

II. Experimental Investigations

A. Components

The components used for the BodyGuard system were selected with respect to their use in harsh environments and are designed for usage from -25 °C to 70 °C, which was validated in experiments in a climate chamber. All components are commercially available.

The core of the system is a microcontroller, which offers many AD converters and various other external interfaces and therefore all possibilities to implement an IMU system. To determine movements the 3-axis accelerometer is used. It provides an analog voltage depending on the acted acceleration and the set sensitivity for each axis. A gyroscope is used to determine the angle change and which provides an angular velocity of ±300 °/s. For determination of the absolute angle, the 2D Compass is used to ensure an initial starting torque with respect to the direction for the system. For the separate detection of changes in altitude, an additional air pressure sensor is installed. This makes it possible to detect a height change decoupled from the acceleration sensor. For external positioning and set-off of the current position, an additional GPS system was integrated. In order to record the vital signs of probands, which was a further consideration of the project, an additional temperature and humidity sensor and a heart rate measuring system with a chest harness were integrated in the system. These two sensors enable the monitoring of the vital functions. Communication with the system is realized by two independent methods: using a serial communication via an USB port, which is also used to charge the Li-Ion battery and an ISM transceiver in the 868 MHz frequency band. Additionally, all data can be saved on the integrated micro-SD card and thus evaluation is possible either online or offline. Therefore, data loss due to transmission errors can be caught and compensated in an online analysis.

B. Sensor Setup

The sensors are connected to the microcontroller in different ways: the acceleration and angle sensors provide analog signals, while the remaining sensors have a digital interface, I²C, SPI or UART. For the analog sensors, special hardware filters are implemented. The hardware filters implemented at both sensors realize low pass filters, which remove the high frequencies from the signal and thus withhold them from the digital signal detection. The filters are designed to filter frequencies above 1 kHz, as these do not occur in the movement of persons and would only result in misinterpretations during the signal evaluation. Another specific characteristic is provided by the gyroscope: the change of the angle operates around a reference voltage generated by the sensor. Unfortunately, the output voltage is not equal to the reference voltage at the position of rest, which makes it possible, but not useful, to plug the reference voltage and the output voltage to a differential amplifier. The BodyGuard system generates the reference voltage using a digital potentiometer with 4 independently adjustable analog outputs, as can be seen in Fig. 2. Thus, the reference voltage for the amplifier can be set individually for each gyroscope by software. The used amplifier operates in its basic circuit as a non-inverted amplifier with reference voltage and virtual mass. Additionally, this circuit increases the accuracy of the 12-bit AD converter, as the applied input voltage and the used gain have been extended on the entire sample range of the AD converter. No special adjustments were necessary for the digital sensors.

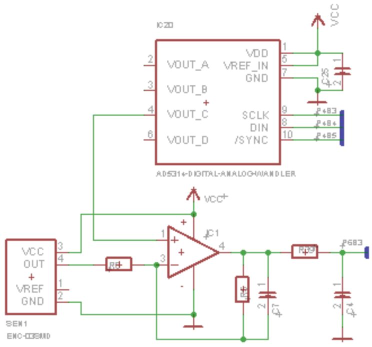

Figure 2. Optimized gyroscope adaptable with individual reference voltage and additional reinforcement

C. Experimental Setup

Experimental tests were carried out. These should determine if the sensors meet the manufacturer's specified characteristics, and thus enable a 3D localization. The BodyGuard system has always been attached at the waist of the subjects. The attachment in or on the shoe [4] [5] [12] was investigated, but was rated as difficult to handle as well as not practical and therefore discarded for the desired application.

A wired (during laboratory experiments) and a wireless (during field tests) transmission were used to transmit the sensor data (see Fig. 3).

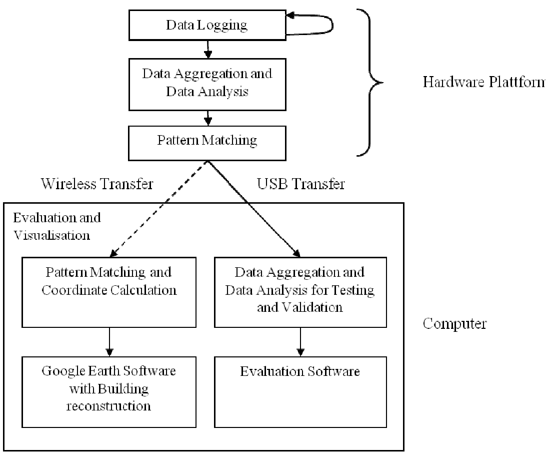

Figure 3. Data Processing Model

In specific experiments to validate the data, the system was directly moved, turned or lifted under defined conditions. Thus, the experiments were performed in a defined environment and can be reproduced at any time. Experiments on a treadmill were used to determine the parameters for pattern recognition of the different walking or running styles and the different speeds. Field tests were conducted in different environments. Several probands followed defined paths in order to detect differences based on subtleties, such as the differences in motion profiles between women and men as well as in cushioning properties between sport shoes and safety shoes, so that they can be compensated in the analysis.

D. Sensor Validation

To study the properties and accuracy of the different sensors, several experiments were carried out:

- treadmill tests with stepped speeds
- tests with a 1-axis translation stage
- tests with a turning lathe

These experiments were validated using a high-speed 3D-stereo-system [1], to verify the results of the sensor data from the developed IMU. These investigations were necessary to compare the set of transaction data to a reference and to perform a quality rating of the measured sensor data. The comparison of the values determined by the calibrated measurement system and the BodyGuard system resulted in deviations of several percent, depending on the axis and / or angle.

Fig. 4 shows the basic design of the experiment with the treadmill. The probands walked or ran at different speeds for a predetermined time.

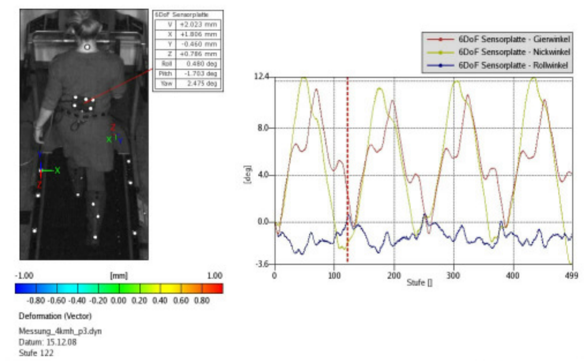

Figure 4. Treadmill tests, rotation of the hip in all degrees of freedom

The change of speed in the experiment was 1 km/h for each step. In addition, the step sizes of the probands were recorded using a video camera next to the treadmill. The results of the calculation compared to the measured values show a maximum difference of ±7 cm per double stride, which corresponds to an absolute error of ±4 cm/m. This error is minimized in the following section of sensor calibration.

The investigations on the treadmill were accompanied by investigations on a 1-axis translation stage, to analyze defined short acceleration pulses and defined uniform movements which affect one, two or all axes of the accelerometer depending on the positioning of the accelerometer.

The shuttle car was moved 0.5 m to the left, 1 m to the right and 0.5 m to the left, back to the middle position of the translation stage. The movement of the shuttle car is a uniform motion with constant speed. The maximum speed of the translation stage was 0.33 m/s. The path was determined from the acceleration values. The travelled path at a defined distance of 2 m (0.5 m + 1 m + 0.5 m) was determined with a difference of less than 4 cm, as shown in Fig. 9.

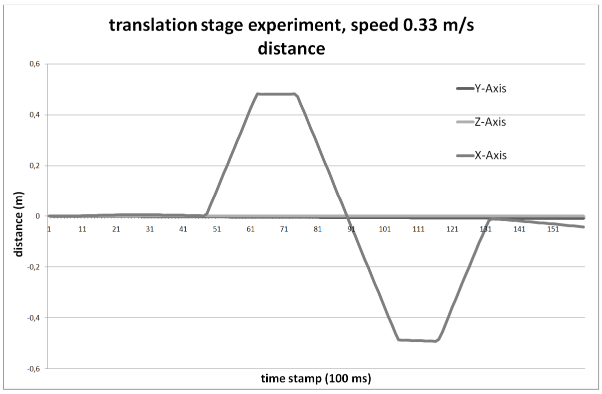

Figure 5. Translation stage experiment, travelled path calculation from the determined speed data

The calculated error of the travelled path determined from the acceleration data of the acceleration sensors is within the set limits of the project, but as can be seen in Fig. 5, a drift occurs on the X- and Y-axis at the end of the experiment. This drift is described in the following section sensor calibration together with a solution.

The gyroscopes were tested separately in further investigations. The system was tested on a turning lathe with different rotational speeds to determine the quality of the gyroscopes and their accuracy. The results are shown in Fig. 6.

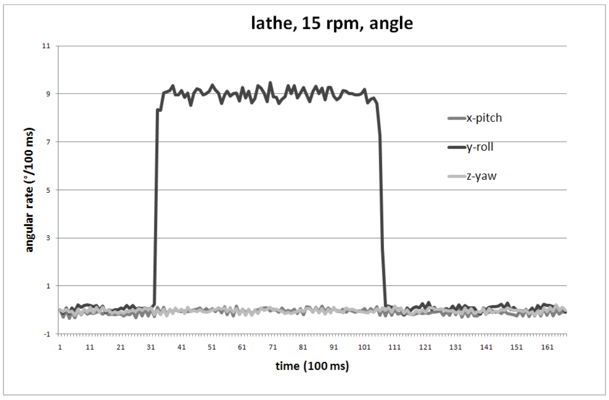

Figure 6. Lathe investigation at a speed of 15 rpm

In order to determine an angle α_i from the values AD_i of Fig. 6, equation (1) is used. The total angle is determined of the sum of the angles α_i. The signal amplification v_{Gyro} of the gyroscope, the gain of the operational amplifier v_{OP} and the measurement interval $(t_{i-1}-t_i)$ are factors affecting the determination of the angle α_i.

$$\frac{AD_i \cdot AD_{12Bit} \cdot U_{VCC} \cdot v_{Gyro}}{\left(t_{i-1} - t_i\right) \cdot v_{OP}} = \alpha_i \qquad (1)$$

In further investigations, the angle sensors were compared to the integrated compass module and the accuracy respectively the deviation was determined. The result of the investigations was a deviation of ±2 °.

In Fig. 7 the comparison as well as the software developed for validation can be seen.

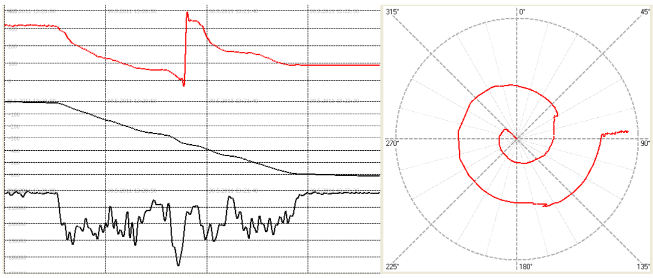

Figure 7. Gyroscope and compass data presented in the analysis and evaluation algorithms

The figure 7 shows an example of the problems with individual sensors. The top graph on the left side and the pie chart show the absolute angle of the compass module, determined with an accuracy of 0.1 °. The middle graph on the left side shows the same change in angle of the gyroscope, determined from the values of the bottom graph on the left side. The middle graph on the left side shows that the continuous summation of the single changes in angle to the existing current angle, results in an error and a drift in the angle calculation. This error is reflected in the further increase of the angle, whereas the measured value (bottom graph on the left side of Fig. 7), remains the same after the rotation is concluded. This shift is caused by a lack of precision in the determination of the start value or the orientation of the sensor at starting time. The influence and the reduction of the continuous shift of a path or an angle are explained in the section sensor calibration.

Additionally to the sensors for the acceleration and the change in angle, an air pressure sensor is integrated in the system, which allows the determination of changes in altitude independently from the acceleration values. This characteristic is described and illustrated in Fig. 8.

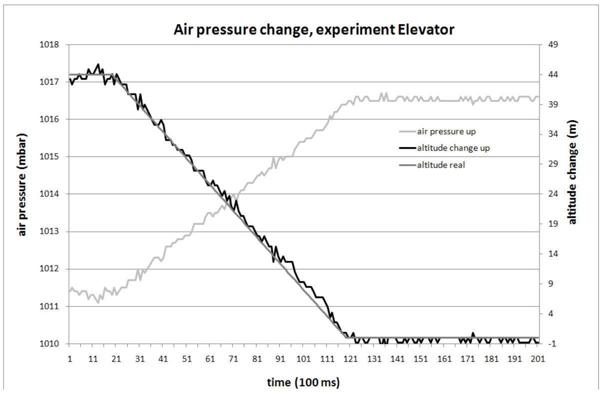

Figure 8. Air pressure change with altitude change in the elevator experiment

The quality of the used air pressure sensor detects a change in altitude in 0.8 m steps, which corresponds to 0.1 mbar pressure changes because of the accuracy of the sensor-internal 16 bit AD converter. When used in a building, this accuracy of the air pressure allows the detection of changes of the floor level, determined only from the values of the air pressure sensor.

In addition to the previously mentioned sensors, GPS modules have been integrated in the system to determine the relative distance travelled. This module provides the absolute position for the system at starting time or additional supporting points during the operation. The accuracy of the determination of the location is with ±5 m within the limits of the GPS system, which allows the determination of a good starting position in the outdoor area [7]. In indoor applications [9], the GPS system is only used if multiple GPS data signals are correct and harmonize with the system established by the IMU data. This minimizes or extinguishes the effects of confounding factors, such as reflections of GPS signals [8] on the determined position. This skillful combination of several sensors to functional units reduces the effects of errors from individual sensors.

E. Sensor Calibration

As mentioned in the previous sections, the individual sensors are not adapted perfectly yet. This is shown in the measured results from various investigations of the acceleration and the angle sensors, which do not reach the aim of localization with a deviation of less than ±2 m at a travelled distance of 100 m. The cause of this problem lies in the manufacturing tolerance of the individual sensors [2] [3]. E.g. the initial assumption, that 0 g corresponds to 1.65 V shows a module-dependent fluctuation of approximately ±0.125 V resulting in an error of > 7 %. The voltage of the gyroscopes at the position of rest varied at 1.35 V ±0.08 V, leading to a computational error of about 6 %. The sensor calibration prevents the drift of the IMU and allows to optimize the accuracy to the desired level of less than ±2 m and to achieve a deviation of less than 2 %.

F. Operations

The BodyGuard system works in two different transmission modes, the wired and the wireless data transmission. The wireless mode operates using a packet-oriented wireless transmission of 60 bytes per packet and a data transfer rate of 400 kbits. Fig. 9 shows the actual USB stick, which realizes the matching station for the WSN.

Figure 9. USB Stick

The BodyGuard system captures the motion data with a sampling frequency of 1 kHz for the analog sensors. The various digital sensors can be queried with 10 Hz and summarized to a radio packet. In a network test, at most 3 BodyGuard systems have been operated simultaneously. The application for the 3D positioning of the person is implemented in a card surface using Google Earth.

It shows the path of motions, the movement type and the change in height [10] in respect to the starting position of the observed person. The perspective of the viewer is adjustable and therefore enables the exact routing [6] of the relief units to the searched or injured person.

G. Results

The investigations with BodyGuard revealed the successful development of a usable IMU system with 6 degrees of freedom by using the introduced hardware components and calibrating the sensors. Errors occurring because of component dependent shifts in values caused by external factors such as temperature or vibrations are compensated. The data is collected, pre-processed and summarized into a 3D vector data with the BodyGuard system. The movement data is sent to a processing unit via WSN, where it is combined to a movement tensor. This is possible for up to 40 BodyGuard systems and enables the localization and observation of several persons.

The movement data can be visualized as raw sensor data for algorithm identification and testing (Fig. 7), as well as 3D vector data in a card surface using Google Earth. Currently the quality determined in the experiments shows an accumulated error of less than ±2 m at a travelled distance of 100 m. Therefore, the developed system is able to detect the observed person with floor-precision.

III. Conclusion

The developed system meets many requirements that are placed on an IMU system. The main difficulty of the current system is the data processing. Currently, the processing takes place on the connected PC, but in further development, it will be integrated on the BodyGuard system additionally to the pre-processing of the data.

The accuracy of the following system will be improved further to enable a room-precise 3D localization. Additionally, the measured RSSI data from the transceiver and the determined transmission time of the radio signal will be used to generate a building plan, which will be integrated in the card surface.

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