Custom MEMS-Based Inertial Measurement Unit For Pedestrian Navigation Use

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***Abstract*—As part of STEPPING project, which aims at developing a robust smartphone-based pedestrian indoor navigation system, a custom inertial navigation system based solely on MEMS sensors is developed. The INS consists of a linear accelerometer, a gyroscope, a magnetometer and a barometric pressure sensor and connects to a smartphone. The latter two sensors are used to support the inertial measurements. The system is evaluated with regard to the viability of the produced data and the mobility constraints it imposes on the user. It is found to be equal to the demands put to it and the qualification process of the INS is continued.**

Keywords: Inertial navigation, MEMS, DSP, sensor fusion, indoor navigation, pedestrian navigation

I. Introduction

Smartphones are becoming ever more powerful in terms of features and computational power. To harness that power, STEPPING project [1], [2], developed at Department of Geomatics, HafenCity University Hamburg, aims at creating a smartphone-based pedestrian navigation system, which is independent of a particular indoor navigation technique. The system depends on a MEMS-sensor based inertial navigation system (INS) and integrates whichever information is available from pre-installed indoor navigational infrastructure. In turn, the INS is dependent on the smartphone to provide support information required to aid the inherent short term validity of its position estimate.

As present smartphones do not yet include a full set of inertial sensors and supporting sensors, a custom INS has been developed and its evaluation with regard to the usability under pedestrian navigation conditions will be the focus of this paper.

II. The STEPPING Project

STEPPING project acknowledges the variety of existing and ever improving solutions for indoor positioning and navigation. However, dedicated clients of a particular system are often highly specialized and only very few support several system types at the same time. STEPPING aims at implementing a robust pedestrian indoor navigation system on a smartphone. *Robustness* here implies the system's ability to cope with a changing set of external support information. The system core consists of a robust fusion algorithm which is impartial towards the origin of the position data it receives: In one building it may utilize the installed WiFi nodes in combination with RFID tags distributed at strategic points, whereas in another building, it may have to rely on radio beacons in combination with a bluetooth network. The algorithm assumes that there is at least one source of (valid) position information available at all times. This requirement is met by the INS, as it continuously supplies a position solution. Owing to their nature, position estimates from an unsupported INS become invalid after short periods of time, as their accuracies tend to deteriorate rapidly. Here, the external navigation information comes into play, supporting the INS solution.

For an efficient robust sensor fusion, the algorithm depends on some form of quality index – a so called *quality of location* (QoL). The index is used to weight the received information and integrate it into the currently valid position estimate according to its accuracy. Thus, the algorithm can integrate virtually any position information, as long as it is supplied with a QoL.

As shown in Fig. 1, the INS interfaces with the Smartphone as external component. However, when inertial MEMS[1]-sensors are implemented on smartphones by the manufacturers, the external hardware will become unnecessary, increasing mobility even further. The smartphone is supplied with a floor plan and a map with infrastructure reference points by a GEO-server upon entering a building.

[1] micro-electro mechanical system

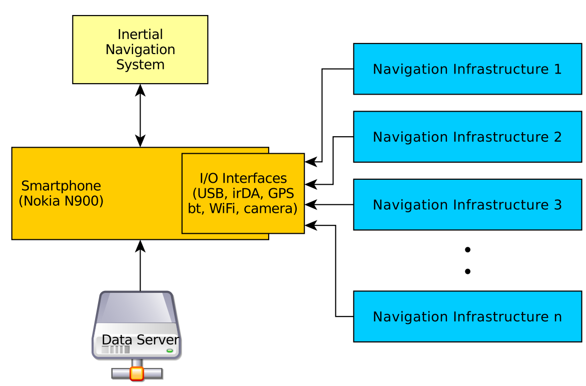

Fig. 1. STEPPING System Concept: External navigation information is integrated by the smartphone to support the drifting INS. A GEO server supplies floor plan and infrastructure data upon entering the building

III. Pedestrian Navigation Conditions

Pedestrian navigation conditions, as opposed to conditions for car navigation or any other kind of navigation, can be described by the following properties: Pedestrian motion is rather random and of relatively low velocity as compared to car- navigation. A car is restricted in its lateral motion and has a limited short-term ability to change its attitude. A human on the other hand may turn on the spot at relatively high angular velocities. Both pedestrians and cars are restricted to the respective surface they are moving on, thus limiting vertical motion.

The outside pedestrian navigation is usually supported through GNSS signals, which (using low-cost, single-frequency receivers) means continuously available and long-term stable position estimates of relatively high accuracy. Here, the motion between valid position updates can be neglected, due to the GNSS measurements being independent of the previous position measurement.

Indoors, or under conditions where these GNSS signals are not continuously available, estimating a person's position becomes more of a challenge. The basis, providing continuous, yet only short-term stable estimates is provided by inertial navigation systems (INS), which compute the position from angular velocities and linear accelerations. Here, the motion between measurement updates is indeed relevant, as the algorithms used to compute the current position estimate are based on the previous position estimates.

Furthermore, certain practical issues need to be considered. An individual navigating a particular environment has tight constraints on the additional gear and components to carry along for navigation. Batteries, extra navigational devices, wires or other components soon become a bother when used on a regular basis.

IV. System Components

A. Sensors

All sensors used in this system are built as micro-electromechanical systems (MEMS). MEMS sensors are small, light-weight and consume very little electrical energy. This makes them the ideal type to use when power consumption is critical and the additional weight for the system user needs to be kept to a minimum. In short, they are ideal for use under pedestrian (indoor) navigation conditions.
The following sensors and components are used in the INS:

1) Gyroscope – IMU-3000: The IMU-3000, a recent development by Invensense [3] is a digital three-axis gyroscope with programmable scale ranges between ± 250 and $\pm 2000°/s$. It communicates over an I2C interface and consumes a low 12mW of power.
The IMU-3000 was chosen because of its variable scale ranges and the low power consumption. Since this system is a study and evaluation project, as many sensor parameters as possible are required to be configurable without having to exchange the sensor chip on the PCB. The sensor's low physical dimensions

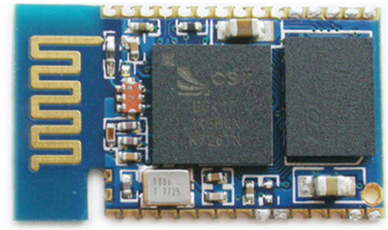

Fig. 2. BTM182: Class two bluetooth module (V2.0 + EDR), low current consumption and small outline: $25 \times 14.5 \times 2.2mm$ (©Rayson)

($4 \times 4 \times 0.9mm$) make it easy to fit onto the PCB[2] close to the accelerometer. The angular rate output from the gyroscope is used to compute the system's orientation relative to a locally level coordinate frame.

2) Accelerometer – LIS3LV02DL: The LIS3LV02DL is a digital three-axis accelerometer developed by STmicroelectronics [4]. Its scale range is programmable as well – the user can choose between a $\pm 2g$ (3.9mg resolution at 640Hz sampling rate) or a $\pm 6g$ range. Communication is established either via SPI or I2C bus interfaces.
This sensor has been tried and tested in many applications and its properties are well-known. The output from the sensor is used in computing position increments.

3) Compass – HMC5843: The HMC5843 is a digital three-axis magnetometer developed by Honeywell [5]. It measures Earth's magnetic field strength and direction between 10μgauss to 6gauss and communicates over an I2C interface. With its dimensions of $4 \times 4 \times 0.9mm$ and low voltage operations (2.5 to 3.3V) it fits well into the system's design parameters. The sensor will be used during initialization of the INS platform and to limit gyroscope drift during operation.

4) Barometer – SCP1000: The SCP1000 is a digital absolute pressure sensor made by VTI [6]. The sensor has a measuring range of $30k$Pa to $120k$Pa and is a fully calibrated and compensated component. Its high resolution of 1.5Pa (equivalent to $\sim 10cm$ at sea level) deem it the optimal choice to stabilize the INS's vertical channel. The SCP1000 is low power enabled and with a diameter of 6.1mm and a height of 1.7mm does not provide much of a challenge to the PCB. The barometric pressure measurements output by this sensor are used to stabilize the altitude or vertical channel of the INS, as this is known to show the highest error rates.

B. Processing and Communication

1) BT – BTM-182: The BTM-182 is a bluetooth module made by Rayson [7]. The module is fitted with a PCB antenna and can be used directly with no extra design effort required. This saves the non-trivial task of developing and debugging the PCB antenna. Its UART[3] interface connects directly to the DSP's UART port for communication with the smartphone. Compared with the other components' dimension

[2] printed circuit board

[3] Universal Asynchronous Receiver/Transmitter – A common serial communication interface

the bluetooth module appears to be rather bulky with its $25 \times 14.5 \times 2.2mm$, however the low costs do not warrant a more intricate integration into the system's PCB.

2) DSP – PIC24FJ64GB004: The PIC24FJ64GB004 is a state-of-the-art digital signal processor (DSP) developed by Microchip [8]. The 16-bit DSP performs up to 16 MIPS[4] at 32MHz operating at 3.3V. It was chosen for its two SPI and two I2C interfaces, as there are several sensors it needs to communicate with. Also, the DSP supports USB-OTG[5], which allows the device to act either as a USB peripheral device or as a USB embedded host with limited host capabilities and thus to draw power from the hosting smartphone's USB port. The two UART ports ensure communication through the bluetooth module as well as simultaneous debugging via a serial console.

V. Sensor Integration

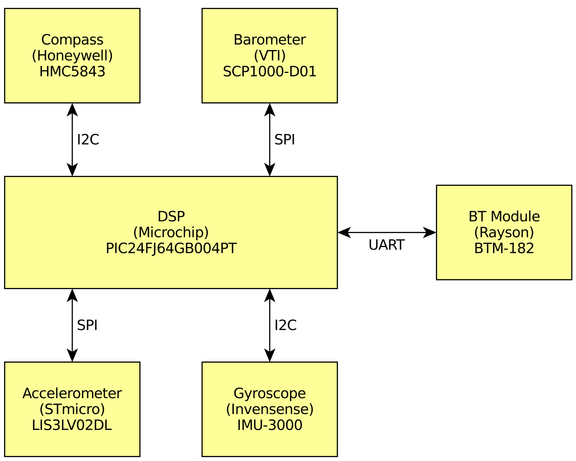

Fig. 3. System Block Diagram: 16bit-DSP integrates digital accelerometer, gyroscope, compass and pressure sensor to communicate via USB and bluetooth

The sensors and DSP, as well as the bluetooth module are arranged on a double-layered PCB together with supporting components. The compass module and the gyroscope use the DSP's I2C ports for communication, whereas pressure sensor and accelerometer are connected to the SPI interface, as can be seen in Fig. 3.

External communication with the DSP is handled through multiple channels. Primary communication is established through the DSP's USB interface. One UART port is connected to the bluetooth module, the other one can be used directly as serial communication port (through a MAX232[6] level-shifter), which is vital during early firmware development stages.

Power is supplied by an external battery or via the USB port. This feature is particularly useful, as it allows for the system to be connected to the smartphone and draw on its battery, thus eliminating the need for an additional battery for the INS.

[4] million instructions per second

[5] USB-on-the-go

[6] manufactured by MAXIM

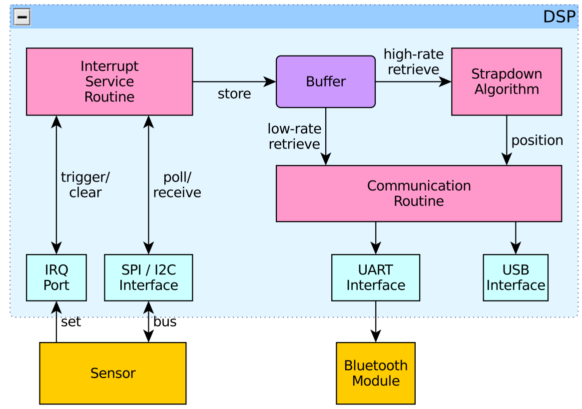

Fig. 4. Sensor Integration: Whenever a new reading is available, the sensor requests an interrupt, which is then handled by a service routine. The data are written to a buffer and the interrupt request is cleared. The data is now available for direct transfer to the smartphone or for further processing on the DSP.

As depicted in Fig. 4, all sensors have interrupt lines, which change state if there is a new reading available. Data assembly is performed asynchronously at the sensor level. Thus, the firmware on the DSP runs interrupt service routines for each of those lines and writes the new reading into a buffer. An internal timer then triggers a collection routine, which reads the current values from the buffer and outputs them to the smartphone. Thereby, a global sampling rate for the entire system can be enforced independently of the individual sensors' data rates.

Also, in that manner, internal algorithms on the DSP, which solve the mechanization equations (*strapdown algorithm* [9]) and which require much higher data rates, can obtain those data independently of the data output to the smartphone.

The evaluation version of the resulting hardware is shown in Fig 5.

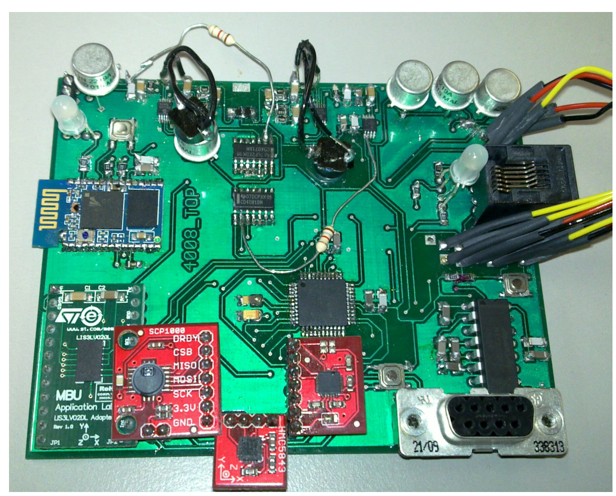

Fig. 5. PCB with mounted sensors, DSP and peripheral devices: Accelerometer, Pressure sensor, compass and gyroscope (bottom, left to right), bluetooth module (centre-left, blue), serial port (lower right corner), USB and power (wiring on right hand side), DSP programming (center-right, RJ-45 connector)

VI. Evaluation

Evaluation of the presented system must answer two questions: Firstly, if the system itself is able to perform as designed with regard to power consumption and measurements. And secondly, if the system meets the requirements of an INS used under pedestrian navigation conditions, and how those conditions may be formalized.

The chosen testing strategy involved the formulation of test parameters which had to be fulfilled by the INS. A similar procedure applied to land-based vehicles was used in [10]. Tests show that the data produced by the system are viable under pedestrian navigation conditions and the choice of components was justified. As the current implementation is still at a study stage, the effect on user mobility is still considerable: The INS still has more communication ports than strictly required for production use, but which are required for hardware debugging. Also, the system requires an external power supply and cannot be powered through USB yet. These issues add to the physical dimensions of the system and thus to the amount of equipment the user has to carry.

VII. Conclusion and Outlook

The presented INS is able to provide inertial measurement data (linear acceleration and turn rates) in combination with support data such as static air pressure and magnetic heading. The data can be output through the various communication interfaces or processed on the DSP itself.

The study has shown the system's ability to constitute a viable component of STEPPING project and will undergo further optimization. The goal here will be the reduction of physical dimensions and reducing power consumption.

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