

Pedestrian Smartphone-Based Indoor Navigation Using Ultra Portable Sensory Equipment

Christian Lukianto*, Christian Hönniger**, Harald Sternberg***

HafenCity University, Geomatics, Hamburg, Germany.

Email: *christian.lukianto@hcu-hamburg.de, **christian.hoenniger@hcu-hamburg.de, ***harald.sternberg@hcu-hamburg.de

Abstract—Smartphones are largely benefiting from the ever increasing rate of integration of mobile IT components. Their increasing processing power and the fact that they are fitted with GNSS-receivers make them ideal for hand-held pedestrian navigation solutions. This document proposes a pedestrian indoor navigation system based on a custom inertial navigation system and the N900 smartphone made by Nokia. The system does not depend on a particular indoor navigation system, but attempts to support its inertial navigation system by selecting the optimal set of auxiliary information from available infrastructure such as WLAN and bluetooth. Analysis focuses on the development of the inertial navigation hardware, the definition of an optimal set of support information and the development of an efficient sensor fusion algorithm.

I. INTRODUCTION AND MOTIVATION

More and more current smartphones are being fitted with a satellite-based navigation system. This usually consists of a simple GPS receiver whose output is then used in a map application to display the current position. Often, the GPS receiver is supported during its acquisition phase using *Assisted GPS* (AGPS) techniques resulting in a valid fix being available after mere seconds.

However, as soon as the user of said mobile navigation device enters a region of poor satellite coverage, the system falls back to cellular network-based positioning. This is especially the case when navigating through buildings and urban canyons. Nevertheless, the position obtained thus is not precise enough to perform successful indoor navigation. In such cases, the position estimate will be supported using inertial navigation systems, which base their navigation solutions on the integration of linear accelerations and angular velocities.

This document addresses both the issues of high portability and reliability in absence of viable satellite signals, as well as keeping costs to a minimum, by proposing a system, which is based on a state-of-the-art smartphone and a highly integrated, custom inertial navigation system, utilizing only *micro electro-mechanical system (MEMS)*-architecture sensors.

II. SYSTEM CONCEPT

As shown in Fig. 1, the hardware used to implement the solution outlined above mainly consists of two blocks: The inertial navigation system (INS) discussed in Sec. III-B and the smartphone discussed in Sec. IV. The geo server (providing maps and geo context information) will not be part of this discussion.

The INS provides a continuous estimate of the current position, speed and orientation. These data are sent to the smartphone to be visualized to the user. The smartphone in turn collects sensory inputs available to its various communication interfaces and the (A)GPS receiver system. All the additional sensor information are then processed for plausibility and quality and used to correct the inertial navigation solution provided by the INS. The updated position is then fed back into the INS. Apart from classic Kalman filtering a variety of sensor fusion algorithms can be executed and will be analyzed on the smartphone; they do not, however, affect the performance of the INS.

III. SENSORY EQUIPMENT

A. Xsens MTi-G

Initial research was undertaken based on a miniature *attitude and heading reference system (AHRS)*, namely the *MTi-G* by Xsens (see Fig. 2). Being only $55 \times 55 \times 33\text{mm}$ in size and 68g in weight, the system constitutes a relatively low-cost AHRS with moderate portability. It consists of sensors to measure acceleration, turn rates, magnetic field strength and static pressure. The device's performance details are listed in Tab. I and the individual built-in sensors' performances are listed in Tab. II. GPS receiver capability is implemented via a GPS mouse, which is connected externally to the device.

Xsens provides a software package with data acquisition and processing tools, as well as COM-Dlls and C-header files

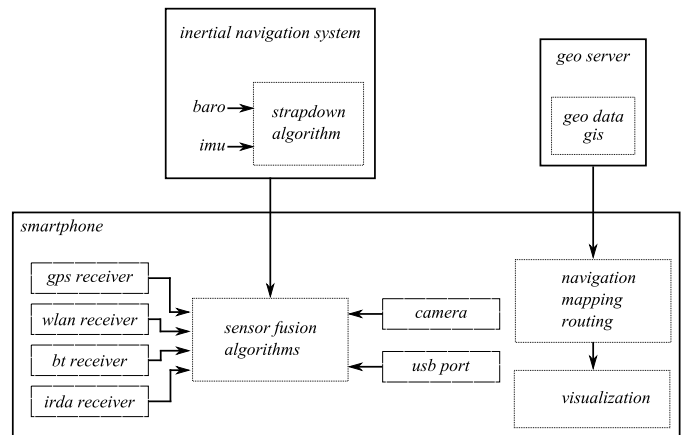


Fig. 1. Smartphone-based ultra-mobile navigation solution

TABLE I
MTi-G – DEVICE PERFORMANCE (XSSENS 2010)

Attitude and Heading		Interfacing	
Static accuracy (roll/pitch)	$< 0.5deg$	Digital interface	RS232,
Static accuracy (heading)	$< 1deg$		USB
Dynamic accuracy	$1deg$ RMS	Operating voltage	5 – 30V
Angular resolution	$0.05deg$	Power consumption	610mW
Dynamic range:		(max)	910mW
– Pitch	$\pm 90deg$	Interface options i/o	SyncOut,
– Roll/Yaw (heading)	$\pm 180deg$		AnalogIn
Maximum update rate:		GPS Antenna	SMA,
– Onboard processing	$120Hz$		active
– External processing	$512Hz$		
Position		Operational Limits	
Accuracy position:		Altitude	$18km$
– SPS	$2.5m$ CEP	Velocity	$515 \frac{m}{s}$
Maximum update rate:		Ambient temperature	$-20 \dots$
– Onboard processing	$120Hz$	operating range	$+60^{\circ}C$
– External processing	$512Hz$	Specified performance	$0 \dots$
		operating range	$+55^{\circ}C$

for easy (cross-platform) application development and Matlab interfacing. The device's internal sensor fusion algorithm is based on an extended Kalman filter which can be adapted for different navigation scenarios such as aero, car and pedestrian navigation and also, if static air pressure is to be included in the calculations, to stabilize altitude. Also, raw (taken directly from the *analog-to-digital converters (ADCs)*) and coarsely calibrated sensor data can be obtained from the device. These data constitute merely the ADC readings multiplied by a scale factor and corrected for offsets:

$$x_{calib}^i = f_{scale} \cdot x_{ADC}^i + c_{bias}$$

These data lack fine calibration and corrections for cross-axis sensitivities, which are not available to the system user.



Fig. 2. Xsens MTi-G – MEMS-based Attitude and Heading Reference System (Xsens 2010)

TABLE II
MTi-G – INDIVIDUAL SENSOR PERFORMANCE (XSSENS 2010)

	turn rate	accel.	mag. field	pressure
Dimensions	3 axes	3 axes	3 axes	–
Full Scale (FS)	$\pm 300 \frac{deg}{s}$	$\pm 50 \frac{m}{s^2}$	$\pm 750^{\dagger}$	$30 - 120^{\ddagger}$
Linearity (% of FS)	0.1	0.2	0.2	0.5
Bias stability. (1σ)	$1 \frac{deg}{s}$	$0.02 \frac{m}{s^2}$	0.1^{\dagger}	$100 \frac{Pa}{yr}$
Scale factor stab. (1σ)	–	0.03%	0.5%	–
Noise ($\frac{FS-unit}{\sqrt{Hz}}$)	0.05	0.002	0.5	4
Alignment error	$0.1deg$	$0.1deg$	$0.1deg$	–
Bandwidth	40Hz	30Hz	10Hz	–
Max update rate	512Hz	512Hz	512Hz	9Hz

[†] mGauss [‡] kPa

Analyses performed using the MTi-G device both indoors and outdoors returned the following results:

In the first study, the device's performance during the transition from outdoor to indoor conditions was examined. Focus was put on velocity estimation using a step-counting-algorithm which processes accelerometer readings. The full analysis can be found in [1]. The second study focused on Kalman filter development with the objective of finding the optimal Kalman filter configuration for pedestrian navigation. Results also include an evaluation of altitude estimates made by the MTi-G with regard to the detection of vertical position in multi-story buildings. For the full analysis, refer to [2]. Both analyses returned good results.

However, bearing in mind the objectives stated for this project, even its relatively small dimensions make the system appear bulky. Also, the fact, that the GPS antenna is connected to the INS by a 3m-length cable which in turn is connected by a 5m-length cable (and a RS232-to-USB converter) to a computer (and that there is even a need for such a computer) contradicts the main objective that the system be highly

portable.

Also, the MTi-G with a price of 3500€ may seem relatively low-cost compared with larger and more complex INS, which can easily come at a cost of 10,000 - 150,000€. However, even when including the smartphone in the calculation, the presented system's total cost will not exceed 1000€.

Lastly, owing to the nature of the proprietary firmware implemented on the MTi-G, the user has only two options of using unfiltered data. They can either use the output of the ADCs (uncalibrated) or the coarsely calibrated data after the first processing stage. As these data do not include fine alignment information, users can either perform their own calibration using tilt- and turn-tables or use the (Kalman-) filtered and otherwise processed output. However, this renders the device unsuitable for sensor fusion algorithm development, as this effort requires extensive use of optimally calibrated, yet otherwise unprocessed data.

Furthermore, analyses on the pressure sensor data show that even when stationary, the standard deviation of the computed pressure altitude (σ_{alt}) is between 1.0 and 1.5m, which will be an issue when using the pressure sensor to stabilize the vertical channel. Fig. 3 shows a few seconds of pressure altitude obtained from a MTi-G measurement. The device was at rest during that measurement. Two obvious issues arise, when examining this plot: Standard deviation σ is at 1m, which is unacceptable if the intended resolution is to be high enough to facilitate the distinction between two levels. Furthermore, the signal noise is far too high for vertical channel control, as this process requires accurate measurements of the changes in pressure altitude from one time step to the next.

B. Custom MEMS-based Inertial Navigation System

Because of the characteristics described before, for the purpose of more in-depth analyses, the decision was soon made to develop a custom INS, one which exactly fits the

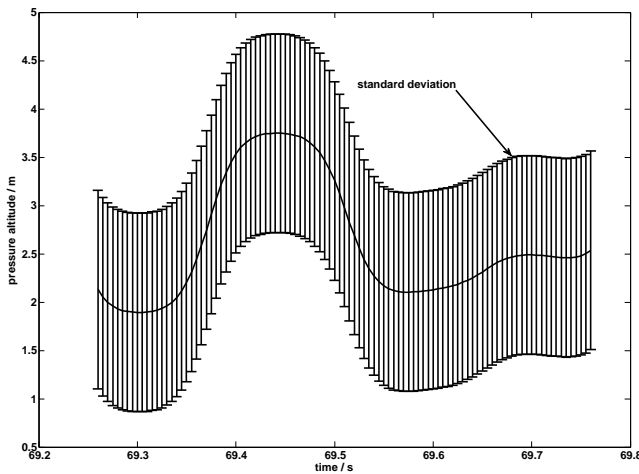


Fig. 3. Pressure altitude computed from MTi-G static pressure sensor. Sigma-value 1.05m, device stationary

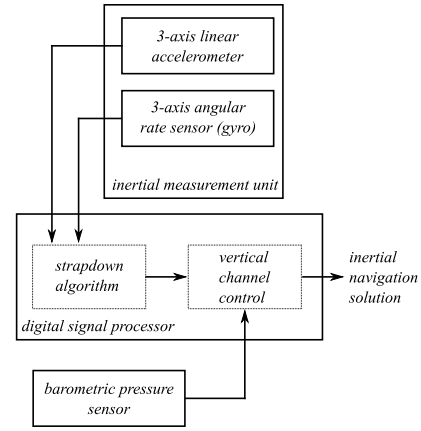


Fig. 4. Custom INS – Block diagram of custom MEMS-based INS hardware

demands put to it. The advantage clearly is, that the custom INS can be developed independently of the current hosting smartphone, for it to be potentially used on any smartphone. Furthermore, the device can be optimized for low power consumption and portability and the parameters and characteristics are completely available.

The custom INS consists of highly integrated MEMS sensors: Accelerometer and angular rate sensor form an inertial measurement unit (IMU) which is aided by a barometric pressure sensor. The type and performance of the sensors used are listed in Tab. III. For alignment and further support purposes, the hardware also comprises a three-axis magnetic field sensor.

Angular rate sensor, accelerometer, magnetic field sensor and the static pressure sensor all have digital interfaces which are connected to a *digital signal processor* (DSP). The DSP performs the polling of the sensors and data processing in real time, and handles communication with the smartphone.

As depicted in Fig. 4, the linear acceleration sensor and the angular rate sensor are continuously polled for their readings. These are then integrated in a strapdown algorithm. As with all INS, the current altitude estimate is highly dependent on the precise determination of the current acceleration due to gravity (g). Because errors in this determination tend to

TABLE III
CUSTOM INS – INDIVIDUAL SENSOR PERFORMANCE

	turn rate	accel.	mag. field	pressure
Sensor	ITG-3200	LIS3LV02DL	HMC5843	SCP1000
Dimensions	3 DOF	3 DOF	3 DOF	–
Full Scale (FS)	± 2000	± 6.0	± 3	30 – 120
FS Unit	$\frac{deg}{s}$	g	Gauss	kPa
Resolution	–	1.0mg	7mGauss	1.5Pa
Sensitivity $\frac{LSB}{FS_{unit}}$	14.375	1024	–	–
Noise $\frac{FS_{unit}}{\sqrt{Hz}}$	0.03	–	–	4
Non Linearity (% FS)	0.2	2	0.1	0.5
Bandwidth	256Hz	640Hz	10kHz	–
Max update rate	4kHz	2560Hz	50Hz	9Hz
Current	6.5mA	650 μA	0.8mA	< 10 μA

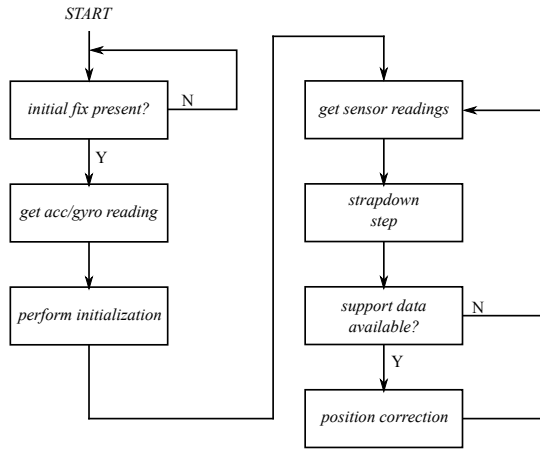


Fig. 5. INS-Smartphone Cycle: This diagram shows the initialization and operation stage of the INS

increase exponentially, the strapdown algorithm is supported by controlling the vertical channel (altitude) through the signal obtained from the static pressure sensor.

During the initialization stage (as shown in Fig. 5), the system waits for the smartphone to provide an initial position fix, consisting of latitude and longitude. Then, assuming stationary conditions (zero velocity), the remainder of the initialization procedure is performed independently of the smartphone. Upon successful initialization, the measurement cycle begins, where firstly, a set of sensor readings is acquired and then used to advance the strapdown algorithm to the next step. If available, the thus obtained navigation solution is corrected by support fixes from the smartphone. These fixes can be available GPS data or other information obtained from infrastructure navigation aids.

Total power consumption of the custom INS is estimated at approximately $400mW$ (max). This puts it well below the $610 - 910mW$ required by the MTiG device, as shown in Tab. I. This also means that the entire device can be powered solely by the USB-connector on the phone without stressing the battery too much, making additional external power sources unnecessary.

IV. PLATFORM – NOKIA N900

The system’s basis is provided by a state-of-the art smartphone. The decision fell in favor of the Nokia N900 (see Fig. 6), which is both fitted with a high-performance processor (600MHz ARM Cortex-A8) while at the same time providing easy access to its components through its open Linux-based architecture.

The N900 is equipped with a standard set of wireless communication interfaces. Apart from the 3.5G/3G/2G communication capabilities, it also offers IEEE 802.11b/g WiFi (WLAN) and a bluetooth 2.1 transceiver. Its integrated GPS antenna supports AGPS and a three-axis accelerometer sensor provides coarse orientation information. The phone also houses two cameras.

The main argument, however, for choosing this particular device is the fact that it uses the Linux-based *Maemo 5* mobile operating system developed by *Nokia*. *Maemo 5* is Debian-based and uses an adapted version of the *Gnome Desktop Manager* as graphical user interface, which is widely used as a desktop manager on Linux desktop computers. This has the advantage, that after cross-compilation for the ARM-Cortex architecture, it may run almost any native Linux application. Also, contrary to *Google Android* or *Apple iOS*-based devices, *Maemo 5* allows easy low-level access to virtually all of the system’s components via a command line interface (CLI). This is essential for keeping software development within a reasonable time frame.

V. EXTERNAL INPUTS

INS in general provide mere short-term solutions, owing to their double integration of (potentially) noisy measurements. To increase long-term stability, external (valid) position information is required to ensure accurate navigation solutions. Outside buildings or urban canyons, in other words: in areas with available satellite coverage, this support is realized using *global navigation satellite systems (GNSS)*. If coverage is not guaranteed or intermittent, non-satellite support information is used to obtain INS support data.

There are several studies and papers available discussing various specialized solutions for indoor positioning with different degrees of complexity and demands regarding infrastructure set-up. A study on *ultra wide band (UWB)* navigation can, e.g. be found in [3], [4] and a comprehensive comparison about the current indoor navigation technologies (wireless networks, GNSS, sound- and light-based systems) can be found in [5], [6]. Even multi-sensor and multi-system studies have been undertaken. Examples are presented in [7] and [8].

Considering the various indoor positioning solutions already available, the aim of this part of the project is not to re-evaluate the individual solutions, but rather to harness their individual advantages to create an optimal set of support data to be



Fig. 6. Smartphone – Linux-based Nokia N900 (Nokia, 2010)

used in potentially any existing (public) building. Optimality implies the presence of a way to evaluate the quality of each available signal to be able to apply a weighting scheme. This part of the project focuses on this means of quality assessment. It will ultimately provide a way to select the (analytically) optimal set of support signals for the INS under any condition.

The system will be dependent on *pre-existing* infrastructure, rather than complex, highly integrated (and costly) navigation hardware. For that reason, techniques such as *iGPS* or *UWB* will not be utilized in this analysis, as they are not available in the average (public) building. Instead, emphasis will be put on wireless network infrastructure such as *WLAN* and *bluetooth* and possibly *radio frequency identification (rfID)*, because especially *WLAN* infrastructure is a very common characteristic of modern (public) buildings.

VI. ALGORITHMS

Another part of the research effort is to evaluate suitable algorithms for sensor fusion, especially with regard to the varying composition of available signals. As mentioned briefly in Sec. III-B, the central algorithm which continuously calculates position and orientation based on linear acceleration and turn rates is called a *strapdown algorithm*. The algorithm implemented here is adapted from [9], [10]. The navigation solution provided by this algorithm provides the basis for all further computations.

Independently of the strapdown algorithm, which is executed on the INS hardware, the smartphone's computational power allows for the evaluation and implementation of several classes and types of fusion algorithms. Kalman filter algorithms will be investigated firstly as a means of INS/GPS-integration. The concept of *particle filtering* will be investigated for viability, providing a means of 2D localization if a detailed map of the building is available. This class of filters is discussed in [11]. Considering the complexity of the sensor fusion problem, *artificial neural networks (ANN)* will be investigated regarding their potential to provide sensor fusion functionality.

VII. CONCLUSION AND OUTLOOK

The proposed system provides a highly portable and yet powerful navigation system, and a platform for the development of efficient sensor fusion algorithms. The discussed independent inertial navigation hardware can be used on other smartphones as well. The MTi-G device has been disqualified due to its characteristics. While the INS hardware is being developed presently, the sensor fusion algorithms will be part of the next project stage. This stage will include algorithm selection, development and evaluation.

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