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STEPPING – Smartphone-Based Portable Pedestrian Indoor Navigation

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ABSTRACT: Many current smartphones are fitted with GPS receivers, which, in combination with a map application form a pedestrian navigation system for outdoor purposes. However, once an area with insufficient satellite signal coverage is entered, these navigation systems cease to function. For indoor positioning, there are already several solutions available which are usually based on measured distances to reference points. These solutions can achieve resolutions as low as the sub-millimetre range depending on the complexity of the set-up. STEPPING project, developed at HCU Hamburg - Germany aims at designing an indoor navigation system consisting of a small inertial navigation system and a new, robust sensor fusion algorithm running on a current smartphone.
As this system is theoretically able to integrate any available positioning method, it is independent of a particular method and can thus be realized on a smartphone without affecting user mobility. Potential applications include -- but are not limited to: Large trade fairs, airports, parking decks and shopping malls, as well as ambient assisted living scenarios.

1. INTRODUCTION

Presently, most smartphones are equipped with GPS receivers, which, in combination with a map application turn the phone into a sophisticated pedestrian outdoor navigation system. However, once the user of such a navigation system enters a region of insufficient satellite signal coverage, e.g. an urban canyon or even a building, this navigation system ceases to function immediately.
At the same time, research on indoor positioning systems has effected the output of various solutions for the indoor positioning problem: how to determine the position with the desired accuracy in the absence of viable satellite signals. Various techniques achieve different accuracies and ranges, depending on the set-up and the complexity of the system. Solutions are based on light (laser/infrared or optical markers), ultrasound and (high-frequency) electromagnetic waves, such as rfID, WiFi, Bluetooth or UWB systems. A comprehensive list and comparison of achievable ranges and accuracies can be found in (Mautz, 2009).

This paper proposes a research project, which recognizes the ever increasing processing power and degree of integrated features of mobile IT devices (i.e. smartphones). It aims at combining these smartphones with available indoor navigation infrastructure to form a robust pedestrian indoor navigation system. The project's goals are presented followed by a detailed discussion of the individual components and concepts and a description statement of the current state of development.

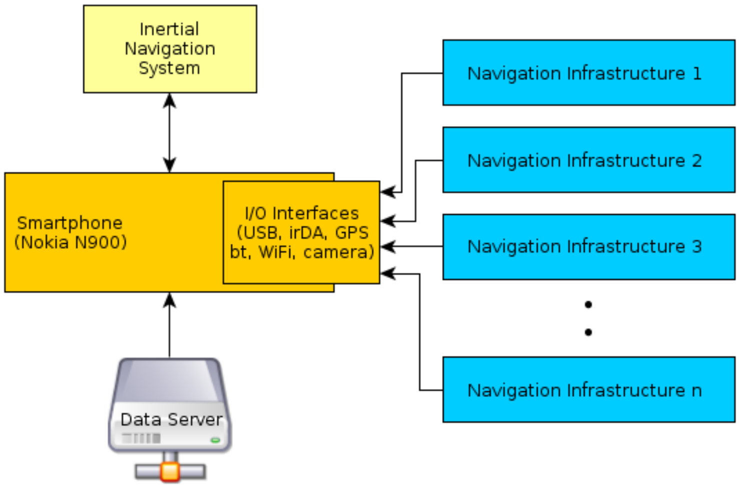

Fig. 1 STEPPING System Concept - External navigation information is integrated by the smartphone to support the drifting INS. A geo server supplies floor plan and infrastructure data upon entering the building

2. PROJECT DESCRIPTION

Any kind of navigation system requires a continuous, long-term stable position update. Outdoors, this is achieved by using the permanently available satellite signals of global navigation satellite systems (GNSS) such as GPS, GLONASS or GALILEO.

Indoor navigation conditions usually imply the absence of, or at least only partial coverage by the aforementioned satellite signals. As, under these conditions, a continuous position update is difficult to guarantee using standard satellite receivers, an inertial navigation system (INS) is used to provide the continuous position update.
However, owing to accumulated measurement errors, the position estimates provided by the INS are only valid in the short term. INS require external support information to correct these errors and to ensure the continued viability of the position estimate (Grewal, et al., 2007).

STEPPING project acknowledges the fact, that there may not always be the same *particular* kind of indoor navigation infrastructure available. However, it assumes that, as the user moves through the different (indoor) environments, there is always *some* kind of navigation infrastructure installed. The information provided by the external infrastructure is then used to support the INS while at the same time making the system independent of a particular navigation infrastructure type.
The smartphone, already equipped with a plethora of wireless communication interfaces, is the optimal choice of platform, as it interfaces effortlessly with the available navigation infrastructure (see Figure 1).

3. SYSTEM CONCEPT

The proposed system consists of three main parts, of which two are in motion.

As depicted in
the smartphone serves as communication interface to the various navigation infrastructure realizations available in the environment currently being navigated. More importantly however, it also provides the processing power required to execute the sensor fusion algorithms necessary to compute the optimal position estimate from the available sensor information.

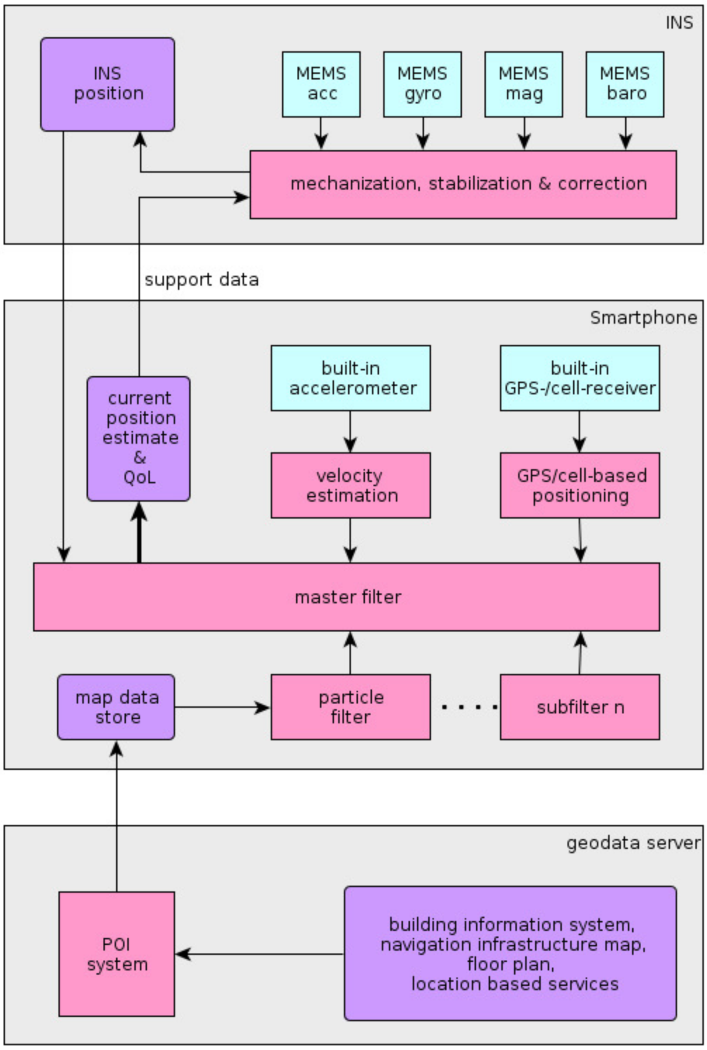

Fig. 2 STEPPING System Block Diagram

At time of project launch, smartphones did not yet include the required sensors to perform inertial navigation. For that reason, a custom INS was designed and implemented to provide the system's navigation foundation. The INS is continuously supported by the external information available to the smartphone and thus forming a co-dependence with it.

Lastly, upon entering the environment to be navigated through, the system is supplied with the necessary maps and/or floor plans, as well as the required information about the installed navigation infrastructure. This feature lets the system be used in virtually any environment, as long as environment data is available. The system's individual components are discussed in the following sections.

3.1 Master Filter

The master filter constitutes a new fusion algorithm, which computes the optimal position estimate from the data provided. It does so regardless of the actually available number of uncorrelated external navigation inputs. For obvious reasons, the filter requires at least one valid set of readings. This requirement is fulfilled by the use of the INS, as it continually provides a position estimate.
Apart from the actual position estimate, the filter requires some means to compare and rank the different datasets provided. For that purpose, a weighted index is introduced. The index is called the *quality of location* (QoL). The QoL combines statistical information as well as inherent parameters of originating source of each dataset (e.g. distance measurement with associated uncertainties) to an index value. This provides the filter with a means to evaluate the information it receives. Also, the filter saves a history of position estimates and their QoL to be able to evaluate the current position estimate by comparison with past estimates.

In this manner, the filter algorithm is independent of the type of information it is supplied with, as long as the QoL is supplied along with the data set. The resulting theoretical limitless number of simultaneous input datasets is only bounded by the smartphone's system resources.

3.2 Subfilter

The master filter combines available external information to compute the current optimal position estimate. To prepare this external information for use with the master filter, the individual readings need to be pre-processed and analysed continuously before being sent to the master filter. For that reason, the term *subfilter* is used as a generic term for any method, device or component providing readings to the master filter. The STEPPING subfilters are introduced in the next subsections:

3.2.1. INS Hardware

The INS is the most important subfilter. In the absence of continuously available satellite signals, it is the prime source of position data. As shown in the INS-portion of Figure 2 it combines the data of two inertial sensors, gyroscope and linear accelerometer to compute position increments. Data from the magnetometer and the barometric pressure sensor are used to stabilize gyroscope drift and the altitude channel respectively. Also, the magnetometer is used during initialization.

Owing to the inherent short-term validity of INS position estimates, the INS is supported by the current global optimal position estimate from the master filter as long as the global QoL is better than local INS QoL.

3.2.2.Step Counter

This subfilter can be used in two ways. In the first mode, the filter operates as a velocity estimator. Dynamic models, describing the human walk and the relationship between step frequency and velocity have been discussed in the literature (Jahn, et al., 2010). The Nokia N900 smartphone has a built-in accelerometer sensor, which in this mode, provides an INS-independent reading used for step-counting. The resulting velocity estimate can be used to support the INS velocity estimate, or to detect stationary segments.

The combination of the velocity estimate with the orientation estimate from the INS constitutes a second mode of operation. The so called *pedestrian dead reckoning* (PDR) algorithm (Widyawan, et al., 2008) computes position increments from the velocity and direction of motion. From a known point of origin, velocity is integrated to yield a distance estimate. Since the direction of motion is known, a new position estimate can be computed adding the increment to the known point of origin.

3.2.3.GPS/Cell-based Positioning

The smartphone includes a GPS receiver. Given sufficient satellite signal coverage, this module provides a long-term valid and accurate position. The module is directly connected to the 3G/2G communications module which in itself can provide cellular network based position information. The combination of both considerably reduces the time to first fix and usually yields a valid GPS position after mere seconds.

Yet, even if there is no valid fix available, cell-based positioning can still be used to aid the master filter. The accuracy is dependent on the density of the surrounding cellular network masts.

Also, the GPS-related values for *dilution of precision* (DOP), which are supplied by the antenna with every reading, can be used directly in the computation of QoL.

3.2.4.Particle-Filter

Particle filters are also known as *sequential monte-carlo methods* (SMC). They belong to a group of stochastic methods to estimate the states of dynamic processes which have the following properties: Only their mean dynamic behaviour is known and not all states are observable (Wendel, 2007).

A particle filter treats the state vector as a random variable whose probability density function is approximated numerically. At each propagation step, states below a certain probability threshold are eliminated by including (not necessarily continuous) measurements until the filter converges on the most likely solution, i.e. the state with the highest probability.

In this particular implementation, all possible positions inside a (known) building are modelled on a floor plan. If then, at each propagation step, some (partial) state observations are added to the filter (e.g. some distance measurements in combination with a direction estimate), more and more improbable positions can be eliminated until the filter converges. This is also possible for a moving target.

3.2.5.Discrete WiFi-Fingerprinting

WiFi networks are already used for positioning in many research activities. A major difference between two groups of techniques is, if the absolute position of the WiFi nodes is known or not.

In the first case, methods from the field of cell-based positioning are employed, such as triangulation or the *cell of origin* (COO) method.

In the second case, the absolute position of the nodes only plays a minor role: Here, the *received signal strengths* (RSS) are measured and recorded for every point on a grid covering the floor plan. For positioning, the current measured RSS is compared with the reference values.

The process is called WiFi-fingerprinting and is very elaborate and expensive. Also, it is very sensitive towards small changes in the environment (e.g. a displaced piece of furniture) or the equipment used, as RSS values are not unique over a range of node/receiver combinations.

Fig. 3 Sample QR-Code encoding textual information

For that reason, a more robust method will be employed, as described by (Sayrafian-Pour, et al., 2008). The method still uses RSS but only compares relative strengths. Only the orders of magnitude of the RSS are compared. Using relative instead of absolute signal strengths makes the method independent of the used node/receiver combination and thus more robust. It is to be investigated further, if the use of certain models for signal attenuation by the surrounding walls is able to render the fingerprinting process unnecessary.

3.2.6.Further Subfilters

As mentioned earlier, the number of employed subfilters is only limited by the smartphone's system resources. However, as not all subfilters run at the same time and have different requirements regarding power, memory or CPU cycles, there are several other subfilters possible:

3.2.6.1.Door-identification using magnetometer

The magnetometer is sensitive towards ferrous metals in its immediate surroundings. This temporarily affects the sensor's ability to detect magnetic north, but may be used to detect the passage through a steel door frame. This method may not yield unique results, but if combined with a particle filter, may help to eliminate a few solutions and expedite convergence.

3.2.6.2.QR-Codes

The so-called *quick response codes* or QR-codes are now seen everywhere on billboards and posters. There they are mostly used to encode a URL. The user just has to scan the code using his internet-enabled smartphone and is directed to the website for further information. This technique may also be used to transmit the position of the code to the smartphone. This can be achieved either by a unique identifier which is transmitted to a server, matched to a database and the position sent back to the smartphone, or by hard-coding the position data into the code itself. The accuracy is depending on the distance of the smartphone to the QR-code and the accuracy inherent to the method used to measure the QR-code's position upon set-up. An example code can be seen in Fig. 3.

3.2.6.3.Line recognition, pattern recognition, scene analysis

The smartphone's camera provides a continuous, high-resolution image and can be used for image analysis. This can start from simple line detection and the consecutive recognition of hallways and intersections. Pattern recognition algorithms from the computer vision field of research may be able to identify objects such as doors, windows and stairways. Finally, camera input can be used in a complex scene analysis of a part of the building to provide orientation and position information. The limiting factor here is again the smartphone's system resources.

3.3 Smartphone Platform

Upon selecting a smartphone platform for the project, the decision fell in favour of the N900 (Fig. 4) smartphone by Nokia. The N900 is a Linux-based phone with touch screen and sliding keyboard. It runs the open *Maemo 5* operating system which is a Debian-based distribution. Contrary to Google Android-based phones, which are also Linux-based, Maemo 5 can run almost any Linux application as long as it has been cross compiled for the ARM Cortex architecture.

As there is no complex virtualization and abstraction layer between the hardware and the application (as is with Android), applications developed for Maemo 5 can gain direct and low-level access to any attached (or internal) piece of hardware. This feature is essential for the development and the main argument in favour of the N900 smartphone: Apple's iOS or Google's Android allow much less access or no access at all to low level hardware functions or to custom hardware. It is possible to create a custom driver for Android phones using *Java Native Interfaces* (JNI), yet this effort would exceed the time requirements of this project and may be only undertaken should this navigation system ever reach production stage.

Nokia Qt-Framework is used as software development platform. The framework is platform independent and runs on numerous system architectures both smartphone- and PC-based. It is shipped (among others) with the Mobility API, which allows relatively easy access to internal smartphone hardware functions. This means that code can be reused on other smartphones if they are able to run the Qt-Framework.

Fig. 4 Smartphone Platform - Nokia N900 is a Linux-based smartphone equipped with an ARM Cortex A8 processor, touch screen, pen and sliding keyboard. Image by Nokia.

3.4 Geodata Server

The geo-data server or short geo-server provides the required navigation data upon entering the building. These consist to a large degree of floor plans and detailed information about available indoor navigation infrastructure, especially their precise position inside the building.

A communication interface is being developed, which transmits the required data to the smartphone using a wireless protocol. Optimization criteria here are clearly data compression and transmission times, as users cannot be required to wait several minutes in front of the building before they enter. The geo-server is updated regularly with changes in the floor plan, navigation infrastructure, or information about the occupants of parts of the building. The communication interface can easily be implemented within smart displays at entrances to public buildings, shopping malls or large plants.

3.5 Visualization

After the position has been determined within the building, it must be presented to the user. To accomplish this in an efficient manner, visualization concepts are being evaluated for their use on the target platform. The presented concepts are always limited by the smartphone's system resources. A complete analysis and implementation of a visualization concept warrants an independent research project on its own. STEPPING project acknowledges this and thus the following discussions only constitute possible implementation concepts, rather than an in-depth research description. STEPPING focuses on the generation of the position estimate.
However, of *digital city research group* at HafenCity University some members possess specialized knowledge about the subject area of visualization. Thus, this part of STEPPING project provides an opportunity to interface with the research group who in turn can benefit from the exchange.

3.5.1. 2D vs. 3D

There are two ways to represent an in-building position on a map. The first way is to present a top-down view of a moving or static map with a marker representing current location and an arrow pointing in the direction of motion. This requires the user to possess a certain degree of familiarity with the map to be able to visualize the surroundings inside the 2D-representation. Also, the system needs to be able to present an optimal level of detail, depending on the zoom level, the part of the map currently in focus and the current velocity.

The other way is a three-dimensional virtual representation of the user's point of view. This helps the user compare the display with the reality and is especially useful if they navigate an unknown area.

3.5.2. Vision vs. Sound

Apart from a visual representation of a map and the current position within that map, navigation instructions may be presented to the user as turn-by-turn voice instructions. Much like early car-navigation systems with small screens, this enables the user to concentrate on the surroundings rather than keeping the phone in front of the eyes at all times. Optimization criteria for voice instructions are determined through experiments.

3.5.3. Augmented Reality

If the smartphone's camera provides a continuous image feed, it can be used in an *augmented reality* (AR) system. AR makes use of the current image's orientation and position to display information directly as additional elements in the image shown to the user.

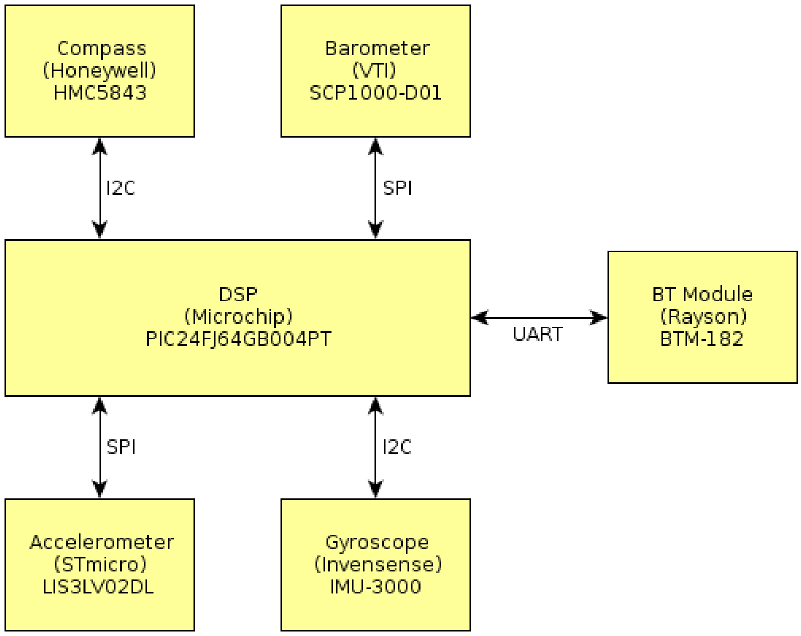

Fig. 5 Custom INS - Linear accelerometer and gyroscope form the basis of the INS. They are supported by a barometric pressure sensor and a magnetometer. All sensors are integrated using a single digital signal processor and digital interfaces.

Each image is being geo-referenced and the additional information scaled and orientated inside it according to the respective coordinates taken from a database. In that manner, the reality as taken by the picture is *augmented* by the additional information.

4. APPLICATIONS

Generally, any application requiring the real-time knowledge of a person indoors may make use of the proposed system. A few cases are introduced here:

4.1 Public buildings and large plants

On large plants business travellers often lose their way between production halls and office buildings. Using this system, however, they will not only find their way to the right building, but also to the right office inside that building, once they have crossed its threshold. This problem exists as well at large airports or public buildings such as libraries or universities. Assisted by the existing WiFi infrastructure the system will guide quickly to the destination counter, bookshelf or gate.

4.2 Trade-fair or Congress navigation

Visitors of large fairs or congresses usually have a limited amount of time to spend making contacts or negotiating business deals. For that reason they plan their visit beforehand and pick the booth identifiers from the exhibitor catalogue. However, the halls are huge and routes through them unclear. The problem is here one of efficient routing to the selected booths as well as between the different halls.

This system, in combination with pre-installed navigation infrastructure in the buildings will address that problem.

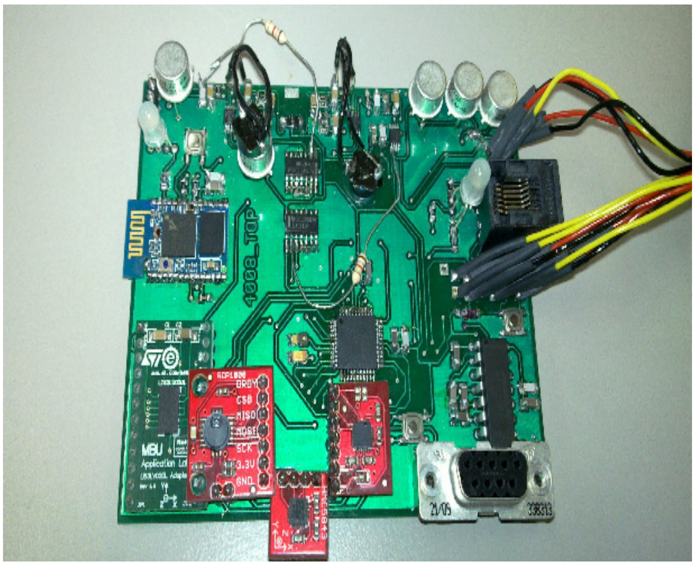

Fig. 6 PCB with mounted sensors, DSP and peripheral devices: Accelerometer, Pressure sensor, compass and gyroscope (bottom, left to right), Bluetooth module (centre-left, blue), serial port (lower right corner), USB and power (wiring on right hand side), DSP

4.3 Ambient Assisted Living

Demographic studies show an ever increasing age of the members of our western civilization. Especially elderly citizens do not want to give up their independence by moving into retirement homes, surrender their driver's licenses or having to rely on other people. They want to live in normal dwellings as long as their mental and physical capabilities allow them to.
Ambient Assisted Living (AAL) is a concept, which describes the combination of smart appliances and networks within the building to aid its inhabitants with day-to-day tasks.

This system is ideal for AAL-enabled homes as it does not hinder the user's mobility but may even in cases of emergency be used as an alarm device to call for help.

5. CURRENT PROJECT STATE

Currently, development efforts focus on the development of the custom INS and the evaluation of the smartphone's internal devices.

5.1 Custom INS

The INS consists solely of digital MEMS sensors which are integrated using a single digital signal processor (DSP), as is outlined in Fig. 5.
The linear accelerometer and the gyroscope sensor form the basis of the INS as their information is continuously processed in a *strapdown algorithm* (Savage, 2007). The magnetometer is used during the initialization stage and to help reduce gyro drift. The barometric pressure sensor is used in a feedback loop to control the vertical channel, i.e. the altitude computation of the strapdown algorithm.

As the INS is a feasibility study to evaluate MEMS sensor capabilities under pedestrian navigation conditions, multiple communication interfaces on the INS are being evaluated: There is a serial interface, a USB interface and a Bluetooth transceiver on the INS, of which the best will be kept during the next design stage. The current INS PCB with mounted sensors and DSP is shown in Fig. 6.

5.2 Smartphone Internal Devices

So far, the internal accelerometer and the GPS receiver have been examined. The accelerometer chip is connected via an I2C interface to the smartphone's central processor. Its readings can be accessed directly through the Linux *sysfs*-interface, or by using the Qt-Mobility API. Readings are available at rates up to 250Hz.

The GPS receiver is not available as a separate module. Instead, it is connected to the 3G-communication module, resulting in a combined GPS/3G positioning module which is accessible through the Qt-Mobility API. The advantage here is, that GPS positioning and cell-based positioning, as well as their combination: the combined position measurement is available without much programming effort. The API allows for a selection of either or both positioning methods.

6. CONCLUSION AND OUTLOOK

The proposed system presents a robust approach to the indoor navigation problem by making use of the ever increasing power of today's smartphones and the increasing quality of MEMS-based inertial sensors. Robustness with regard to missing external inputs is achieved by the modular nature of the implemented sensor fusion algorithm and the custom inertial navigation system connected to the smartphone.

As this is a work in progress, further effort is to be invested on the fusion algorithm itself and the development and evaluation of the whole system in combination with the various external input types and consequently their respective subfilters. Furthermore, the INS will be improved so it can be used in a test environment outside of laboratory conditions.

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