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Overview of Current Indoor Navigation Techniques and Implementation Studies

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SUMMARY

Navigation under conditions with only insufficient or no satellite coverage is commonly known as indoor navigation. As satellite-based navigation techniques are well-researched and its navigation solutions available to the public, the need arises for equally efficient and portable solutions indoors. Examples include large public office buildings, shopping malls, or even support technology for visually impaired people or the elderly.
This paper presents an overview of current indoor navigation techniques, highlighting the underlying principles, prerequisites and limitations. Among the most important solutions presented are the satellite-based navigation method and inertial navigation systems. The overview is followed by the discussion of some possible combinations of the presented techniques. Combinations are deemed successful, if the resulting positioning accuracy is higher than the individual accuracies and if some of the issues inherent to the individual technique are reduced, if not overcome. Finally, two particular implementations of indoor navigation systems are being described. Both were and are developed and evaluated at the authors' home department in an attempt to develop a portable and robust indoor navigation system.

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1. INTRODUCTION

Mobility and mobile information technology have become an integrated part of modern civilization and culture. The increasing capabilities of current mobile phones have turned them into portable information, communication and navigation devices, thereby putting the vast information available on the internet into a local context. Location-based services, delivering the locally relevant information to the phone just in time, are a growing part of the web-service industry.

As long as the mobile device is used in outside areas, where there is sufficient satellite coverage for GPS positioning, the location can be determined very well. However, once a building is entered, i.e. an area with insufficient satellite coverage, the position becomes either invalid, or, if positioning is achieved through the cellular network, not accurate enough for navigational purposes. The industry already provides several dedicated solutions addressing the issue of indoor navigation. However, research is still ongoing, focusing on the ideal combination of solutions, as there is none yet, which can be considered ideal.

This paper first gives an overview of available indoor navigation techniques and algorithms. It then presents possible combinations of solutions and finally presents two studies which discuss particular implementations of indoor navigation solutions.

2. INDOOR NAVIGATION TECHNOLOGY

The following overview presents the key concepts of the current major indoor navigation techniques in general and highlights some of the advantages of particular implementations. Conditions present during indoor navigation almost imply the absence of viable satellite signals, with some exceptions. This is why, for completeness sake, the satellite-based navigation techniques are still mentioned in the next section.

Fig. 1 summarizes the achievable accuracies of the techniques presented. Accuracies vary, depending on the particular implementation and the environmental conditions, especially distribution density of receivers and the complexity of the building to be navigated. An empty cargo hall as compared to a cluttered, multi-storey shopping mall does significantly affect the individual systems' performances. Some information in this section is based on (Wendel 2007, Mautz 2009 and Retscher 2006)

2.1 Satellite-based techniques

Satellite-based navigation techniques are among the most prevalent solutions to date. Most solutions are based on the American *Global Positioning System (GPS)*. An alternative system has been implemented by Russia, the *GLONASS* system and a joint European project under current development is the G*ALILEO* system.

In May 2002 the US-government removed the artificial signal degradation (called: *selective availability, SA*) from the GPS-signals, which allowed for up to ten times more accurate civilian positioning and made them feasible for individual navigation applications. This SA-removal spurred the development of civilian navigation devices first for cars but more and more for handheld navigation devices. Today, satellite-based personal navigation devices are cheap and easy to handle, providing anything from car-based navigation systems up to pedestrian city guides (Farrell 1999).

2.1.1 Working principle

In Global Navigation Satellite systems (GNSS), the satellites continually transmit their position and a highly accurate time-signal. The receivers measure the time of travel of the signal. The thus determined distance from the satellite combined with the knowledge of the satellite's position in space results with the calculation as a three dimensional arc section in an area of possible locations on the earth's surface in the shape of a circle. The receivers are not equipped with high-precision clocks to measure the time of travel. Thus a fourth signal is required to precisely determine the time.

2.1.2 Prerequisites and limitations

A GNSS's setup effort is enormous. Not only requires it many satellites in space (GPS: 24 active satellites), but the maintenance and control efforts are very high as well. Thus, only large countries or multi-national organizations are prepared to install such a system.
Satellite-based navigation systems require an unblocked line of sight between the satellite and the receiver to function properly. If this prerequisite is not met, satellite navigation is degraded. In those cases other methods like assisted GPS (aGPS) in combination with the cellular network or high sensitive receivers are needed. Using high sensitive GPS systems in indoor environments also requires the properties of the materials on the direct line of sight to the satellite and multipath models to correct the time of arrival of the satellite signals. However, even partial signal coverage may be used to supplement other positioning techniques.
Under ideal conditions, an accuracy of a few meters or less can be achieved depending on the number of available satellites and employed aids. (Wendel 2007)

2.2 Inertial navigation

Inertial navigation systems (INS) have been in use since the early 1900's, mostly to guide missiles through the air. Since the introduction of satellite-based navigation systems, they have been slightly neglected. However, as the limitations of such satellite-based systems are being tackled, they have enjoyed increased attention recently. Nowadays, they are especially popular with the aerospace industry (Wendel 2007).

2.2.1 Working principle

An INS' core unit is the *inertial measurement unit* or IMU, which consists of linear accelerometers and angular rate sensors. The measured gravimetric information is used in an algorithm to compute first the velocity vector and then the position vector by integration of the specific forces acting on the IMU. As IMUs only measure specific forces, they cannot be

perturbed by other external inputs. Also, IMUs tend to have a relatively high update rate (Savage 2007).
Highly accurate IMUs use relatively large laser-gyroscopes and pendulum accelerometers to make the gravimetric measurements. However, recently the semiconductor-based MEMS (*micro-electro-mechanical system*) sensors make this type of navigation technique ready for hand-held and mobile device integration. For more information on MEMS sensors and their properties, refer to (Sternberg 2008, Tanigawa 2008).

2.2.2 Prerequisites and limitations

For initialization, the INS requires a position fix and an initial orientation. These are usually provided by a GPS antenna and a magnetometer to determine magnetic north. A barometric pressure sensor is used in addition to stabilize the altitude measurement.
The IMU always measures total acceleration, since it is technically impossible to measure the required specific forces independently from acceleration due to gravity. Hence, acceleration due to gravity is estimated using present position and an earth model, and then added to the measurement. Modeling errors and measurement noise, and the accuracy of the initial fix tend to adversely affect INS accuracies: If unsupported by external, independent position updates, the navigation solution tends to drift and become unviable after a short time, depending on sensor quality (Grewal 2007).

2.3 Sound-based navigation

Sound-based navigation systems use ultrasound to measure distances between receiver and transmitter, or directly measure distances between the measuring device and an obstacle such as a wall (Hazas 2006, Minami 2004).

2.3.1 Working principle

Measurement can take place in an independent manner, where receiver and transmitter are both installed on the navigation device, or by receiver infrastructure being installed in the walls and ceiling of the building to be navigated. These receivers then determine the position by *trilateration*, using the time of flight of the signal transmitted by the navigation device. An example indoor location system using this technique is the *active bat* system.

2.3.2 Prerequisites and limitations

The active bat system requires pre-installed ultrasonic receivers in the building to be navigated. Also, a direct line of sight between the receiver and transmitter is necessary for the system to work, as the sound waves are unable to penetrate walls. Achieved accuracies lie within the lower centimeter range.

2.4 Electromagnetic wave-based techniques

Electromagnetic waves include visible and invisible light-based methods and those which are based on high frequency radio waves, in the GHz-ranges. Among the latter techniques are popular candidates such as wireless LAN and Bluetooth positioning or UWB methods (Blankenbach 2006).

2.4.1 Working principle

Light-based methods usually employ distance measurements through time of flight calculations. These are either infrared-based (e.g. *active badge system*) or laser-based as used in laser-scanners. In the active badge system, the user wears a badge which continuously emits a unique sequence of infrared light pulses. This sequence is received by one or more sensors in a room or building to be navigated, thus making the resolution dependent on the amount of installed receivers.

Radio wave-based methods usually work either by proximity detection in the case of rfID tags or by measuring the *received signal strength (RSSI)* of installed infrastructure nodes such as wireless LAN, *ultra wide band (UWB)* or Bluetooth access points (Blankenbach 2007).

2.4.2 Prerequisites and limitations

The active badge system requires individually encoded transmitters and the setup of a sufficient number of receivers to provide at least room-level resolution.

The setup of WiFi navigation systems is more elaborate: for the navigation environment, a map is required, which holds the RSSI at strategic points in that area, usually in form of a grid. The process, during which the RSSI is recorded at each grid point, is called *fingerprinting* and is a very time consuming one. It is usually only valid for a particular antenna/access point pair and is very sensitive even to the slightest change in the surroundings (e.g. the removal of a particular item of furniture). Radio waves have the advantage of being able to penetrate walls, at least to some degree. Also, especially wireless LAN infrastructure can nowadays be safely assumed to be available in most public buildings.

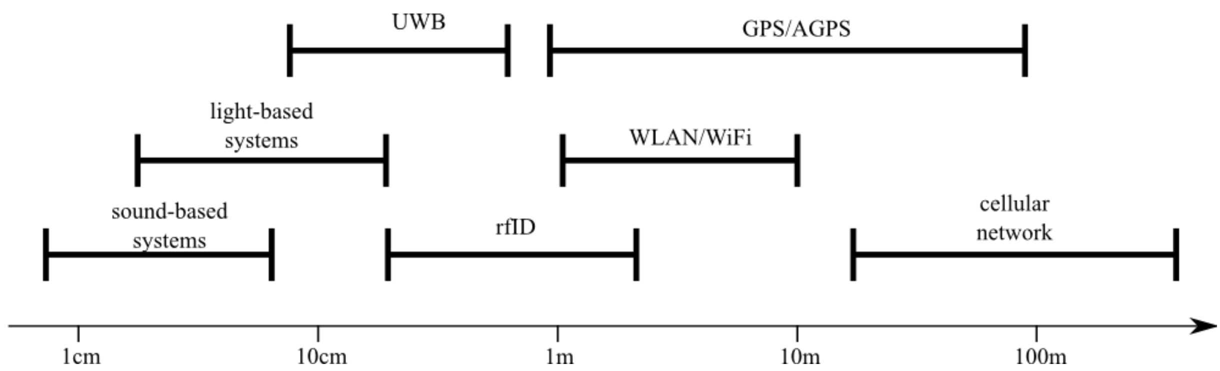


Figure 1: Overwiev of resolutions achieved by the presented navigation techniques

2.5 Optical methods

Optical methods are techniques which require some means of image analysis by the navigation system. They use visual information supplied either still or continuous images provided by a camera.

2.5.1 Working principle

These methods can range from optical marker detection such as encoded markers or *quick response codes (QR codes)*, otherwise known as “2D-barcodes” to line detection in hallways and even complex scenery analysis, depending on the computational power of the device. With QR codes, the position determined is then the position of the marker.

2.5.2 Prerequisites and limitations

The encoded markers need to be distributed around the navigation environment. Each marker's position is then to be predetermined and stored to the desired accuracy. There is, however, a drawback, as the determined position is always the position of the marker. So the navigation device used must be placed in close proximity of the marker to produce a viable position fix. The range depends on the resolution of the utilized camera; the accuracy depends on the accuracy of the measured marker position.

3. INDOOR NAVIGATION ALGORITHMS

The overview discussed so far focuses on hardware solutions for indoor navigation. In the following, a few prevalent algorithms for measured data processing and position estimation will are discussed.

3.1 Strapdown algorithm

The strapdown algorithm first computes the INS orientation from the measurements provided by the angular rate sensors. The thus obtained orientation is then used to transform the measured accelerations into the navigation coordinate frame and to be able to correctly add the estimated gravity acceleration. The results are the specific forces acting on the body in the correct coordinate frame required for the double integration process which eventually yields the position update. An accurate determination of the body's orientation is thus crucial for the quality of the calculated position (Savage 2007).

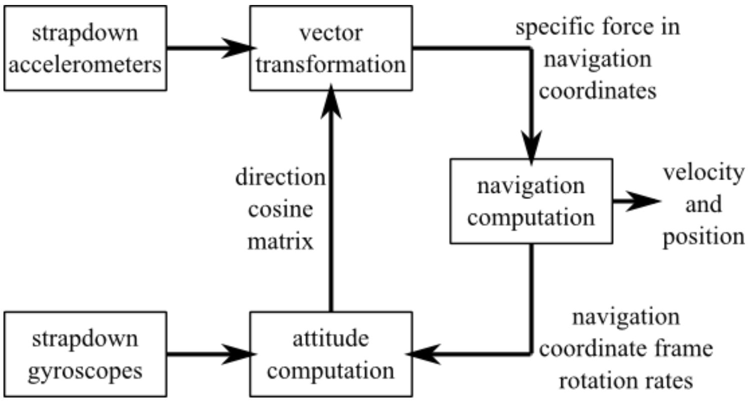


Figure 2: Strapdown algorithm block diagram

3.2 Pedestrian dead reckoning

Pedestrian dead reckoning (PDR) is a two-part algorithm, namely velocity estimation and orientation measurements, which also bases its position calculations on inertial measurements. PDR algorithms are optimized for pedestrian usage.

The velocity estimation is usually based on an accelerometer reading

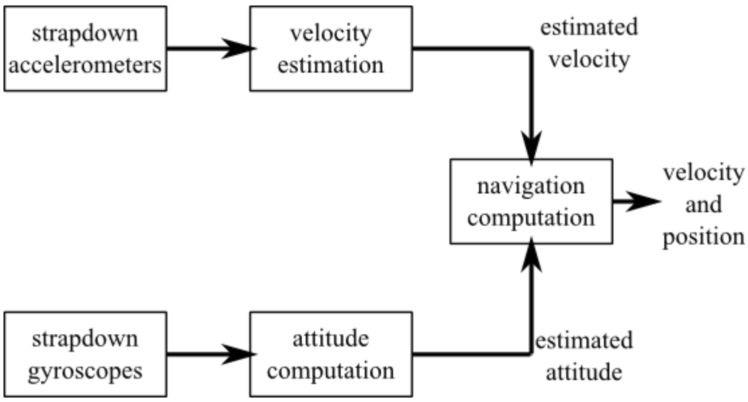


Figure 3: Pedestrian dead-reckoning algorithm block diagram

which shows the characteristic profile of human walking, i.e. spikes in vertical acceleration, each time the foot touches the ground. A model, which maps the relationship between velocity and the user's characteristics such as leg-length, weight and gender, is then used to estimate the user's current velocity.
The second component, the orientation measurements are, as with the strapdown algorithm, computed from the angular rate sensors' measurement.
Finally, the position is calculated by integrating the (estimated) velocity in the (estimated) direction of movement (Widyawan 2008).

3.3 Kalman filter

A Kalman filter is an algorithm which estimates the state of a linear system. To do this, the filter processes measurements which need to be linearly dependent of the system state. To obtain a state estimate, the kalman filter requires a model of the observed states, and a term to include process noise, taking into account model uncertainties and a term for system noise to account for measurement noise in the input data.
If the observed system is a non-linear system, an *extended kalman filter (EKF)* or other methods to overcome the restrictions of a linear model can be used.
Theoretically, there is no limit on the size of the filter's state vector, which is why it is the most prevalent method to use for sensor fusion. If the statistical properties and the measurement model of the particular sensor are known, they can simply be added to the filter's measurement equation and thus be included in the state estimation process (Grewal 2008, Wendel 2007).

3.4 Particle filter

Kalman filters, model the system state as a Gaussian distributed random variable. Its probability density function is this completely described by mean and covariance matrix. However, Gaussian distributions only remain so if transformations performed on them are linear.
Particle filters use the sum of particles to approximate the density function; each particle represents a possible realization of the state vector. The particle distribution is random, initially and the number of particles can be seen as a 'tuning knob' for the filter performance: higher numbers of particles allow for a better approximation of the density function, too few may result in non-convergence (Grewal 2007, Widyawan 2008).

4. COMBINATION OF TECHNIQUES

No technique by itself can claim to address all issues arising when navigating through indoor conditions, i.e. poor or no satellite coverage. Thus, research and implementations attempt to combine techniques to obtain a solution whose combined advantages minimize the individual shortcomings.

4.1 GPS/INS integration

The combination of GPS and INS is a widely used method, as both techniques complement each other perfectly.

The INS cannot be perturbed by external influences and guarantees a continuous and complete navigation solution. Also, the update rate is rather high, which is essential with many applications, especially in the aerospace sector. However, the solution only possesses short-term validity as the errors tend to accumulate over time. This can be overcome by the combination with a GPS receiver.

A GPS receiver provides a precise long-term navigation solution, however no orientation information can be obtained by using only a single antenna. Update rates with standard receivers are relatively low (only about one to four measurements per second). Also, the continuity cannot be guaranteed, as position determination is impossible if less than four satellites are in view.

Data fusion is almost exclusively achieved by error state kalman filters, which estimate and correct the error of the INS by using the obtained GPS fix as correction data. Depending on the information used to support the INS, literature distinguishes *loosely-coupled*, *tightly-coupled* and *ultra-tight/deep integration* by different levels of integration (Wendel 2007).

4.2 INS support

Systems using INS as their main navigation solution always require support data to correct the long-term errors. GPS support, as has already been described, is the method of choice for INS support. However, under indoor navigation conditions, GPS information may not be as readily available as compared to outdoor navigation conditions.
In those cases, other means of support information are required to ensure the long-term stability of INS-based navigation techniques. The most sensitive channel in an INS is the altitude, which is usually supported by barometric pressure sensors. Algorithm development needs to focus on a robust way to be able to use any support information the system may be presented with, including a means to evaluate the accuracy of said support information.

4.3 Particle filter and distance measurements

Assuming a building floor plan is available, the combined information of a distance measuring technique and a particle filter can be used to find the initial (unknown) position within the building. Assuming further, that velocity and gyroscope information are available as sensor data, the particle filter requires only a few steps to uniquely determine the position within the floor plan.
Initially, as there is no information available about the position, an even distribution of particles across the floor is assumed. However, continued measurements allow the algorithm to exclude improbable positions which would arise by the user walking through walls or outside the boundaries of the floor plan.
This is only possible owing to the multi-modal density functions of particle filters. After the position has been determined, the positioning can be switch back to the uni-modal density function-based kalman filter, which requires less computational resources (Grewal 2008, Widyawan 2008).

5. IMPLEMENTATION EXAMPLES

As part of an ongoing research effort to evaluate various combinations of indoor navigation techniques for their feasibility under pedestrian indoor navigation conditions, the authors' home research institution has begun to implement and evaluate promising solutions. The first one presented is based on a low-cost GPS/INS navigation solution, whereas the second study focuses

5.1 GNS/INS with step counter-based velocity estimation (offline)

The system analyzed in paper (Sternberg, 2009), is based on the GPS/INS low-cost navigation system *MTi-G* by Xsens. The navigation system is relatively small, and connects to a computer via USB cable.

Evaluation of the system included the assessment of how well it performed under indoor conditions. Results were then improved by using the IMU data in a custom step counter algorithm and a custom kalman filter. Data processing took place in an offline fashion, with forward and backward kalman filtering.

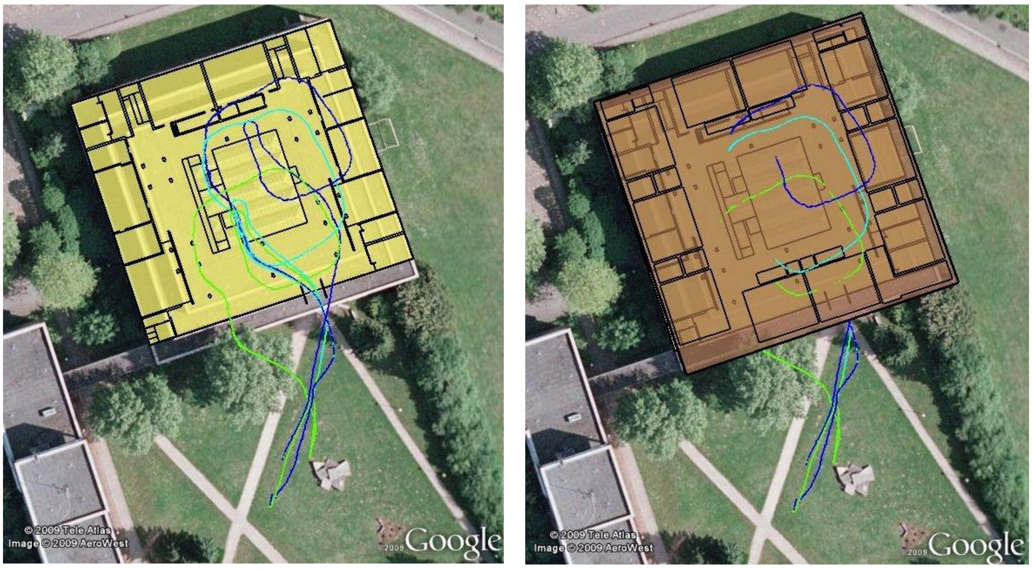
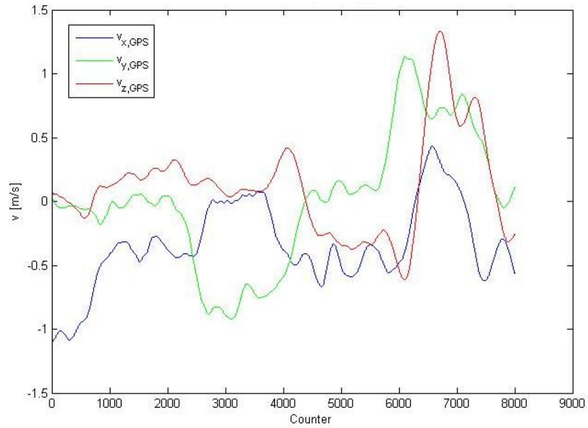


Figure 4: MTi-G indoor navigation results, including the stairs transitions. Left: ground floor, right: first



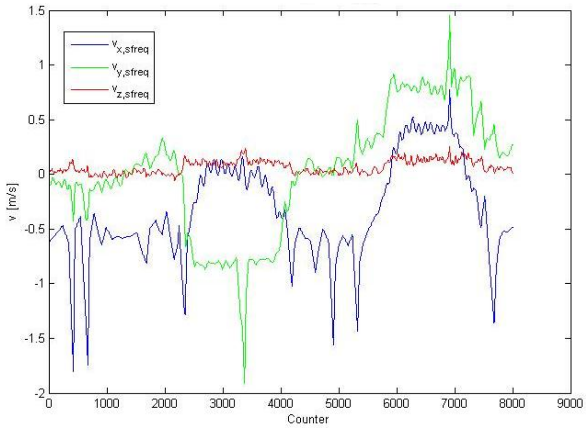


Figure 5: Speed measured by MTi-G GPS sensor
floor (blue – forward filtering, green – backward filtering, cyan – optimal filtering)

Figure 6: Speed estimated from step frequency and average step length

Fig. 4 shows the performance of the MTi-G system under indoor conditions with different types of filtering applied. The system performed relatively well as to its design specifications. Under indoor conditions, the step counter was able to supplement the missing GPS information. However, the highly integrated nature of the system design prevents the usage of calibrated, yet otherwise unprocessed sensor data for further algorithm design. Also, long connection wires and the fact that online processing was not achieved for indoor conditions render the solution ineffective for day-to-day pedestrian use. Figures 5 and 6 show a comparison between the speed provided by the GPS sensor and the speed calculated from step frequency and average step length.

5.2 Smartphone-based indoor navigation (online)

After realizing that, for further algorithm development, the system used for the above implementation does no provide sufficient data quality, the decision was made to design and implement a custom inertial navigation system. To increase portability, the system's platform

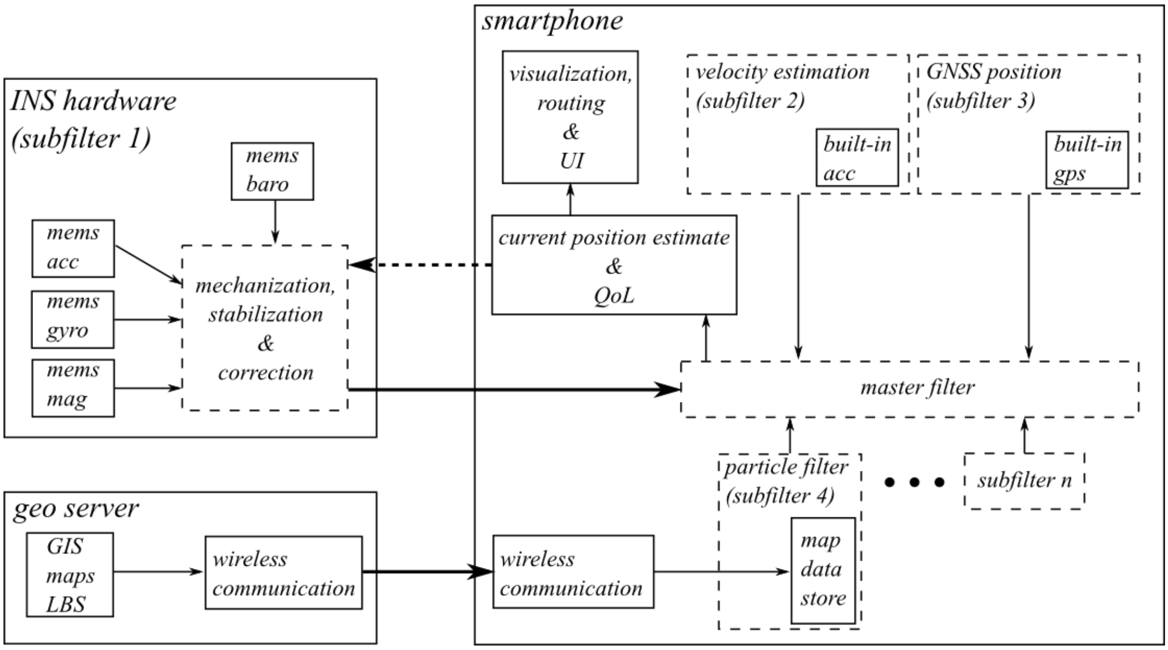


Figure 7: STEPPING project block diagram: smartphone-based indoor navigation

is formed by a state-of-the-art smartphone. Current smartphones already are optimized for outdoor navigation through built-in GPS receivers and are fitted with a plethora of communication interface, all the while having strong processors and being extremely power efficient. In other words, they are ideal to form the basis of a highly portable pedestrian indoor navigation system. Along that objective, the custom INS, currently under development, is formed entirely by MEMS-based sensors and a modern *digital signal processor* handling sensor integration, thereby hardly taxing the devices' power supply. The system will base its navigation solution on the position estimate provided by the custom INS, while being completely open to any available supporting position updates. This renders the system independent of any particular dedicated method, although not independent of supporting information in general. Fig. 6 shows the project's system concept map, whereas the full concept is presented in (Lukianto, 2010).

6. CONCLUSION AND OUTLOOK

Following the formalized statement of the increasing need for an efficient, portable indoor navigation system, this paper presented the common indoor navigation techniques and some algorithms used to combine the obtained sensor information.

Then, possible combinations of said techniques have been presented, following the brief introduction of research projects undertaken by the authors in an effort to find an efficient navigation solution for pedestrians.

Research still continues in that area, especially to find a robust support algorithm for inertial navigation systems. As smartphones are benefiting from the ever increased capabilities of mobile processors, more computationally intensive algorithms will be evaluated for their potential.

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BIOGRAPHICAL NOTES

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