INTEGRATING MEMS SENSORS WITH GPS TECHNOLOGY FOR OBTAINING A CONTINUOUS NAVIGATION SOLUTION IN URBAN AREAS

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ABSTRACT

This paper presents a new Hybrid Navigation System (HNS) that combines the performances offered by inertial sensors with the ones offered by the Global Navigation Satellite System (GNSS). This way the HNS is able to estimate the 2D navigation solution even if GNSS signals are currently unavailable or intermittent. This means that a continuous navigation solution can be provided even for urban areas, indoor or underground environments.

Keywords: *MEMS sensors, inertial navigation, dead reckoning.*

1. INTRODUCTION

In the past decades, several studies were conducted in order to improve the accuracy and reliability of the land vehicle navigation systems. The aim of such a system is to locate a vehicle on a road network as accurate as possible. For this, several technologies exist, but only two are commonly used. The first one is the Global Positioning System (GPS) which relies on the Radio-Frequency (RF) signals provided by the satellites. The second technology is the Inertial Navigation System (INS), based on the Dead Reckoning (DR) algorithm able to provide a continuous navigation solution regardless of the environment (open spaces, urban areas or even indoor [1,2]).

In recent years, GPS receivers had evolved rapidly, becoming more accurate and more accessible from the economic point of view. This made them suitable for the design of land vehicle navigation systems. The primary advantage of using GPS is the ability of providing accurate navigation solution for long periods of time, especially when used in differential mode (also known as DGPS). However, being a satellite-based navigation system, the antenna of any GPS receiver must be all the time in the line-of-sight with several satellites. This means that for urban environments, tunnels and even some underground parking places, the signal from the satellites can be partially or entirely lost (even for the most sensitive GPS receivers). As a result, the continuity of the navigation solution for any GPS-based navigation systems is affected [3].

On the other hand, an INS can provide position and velocity information through the measurements collected from an Inertial Measurement Unit (IMU). Usually, IMU contains three accelerometers and three gyroscopes, one for each of the X, Y and Z axes [4]. The INS's main advantage over GPS consists in its independence from the external signals, and consequently its ability to operate in all environments [5].

However, the accuracy of such systems is adequate only for short term use (couple of minutes). For longer periods of time the accumulation of the computing errors grow (especially for heading computation) deteriorating the system accuracy. As an example, a heading error of 7° would cause a cross-track error of about 12 meters after 100 meters of navigation, which obviously is inadequate for long-term autonomous navigation. However, by using high quality inertial sensors, like Ring Laser Gyroscopes (RLG), the accuracy requirements for land vehicle navigation can be maintained for longer periods of time. Even so, the use of these sensors has its limitations, which inhibit them for being integrated in mass production land vehicle navigation systems. Such a limitation is the price, which for a high-end IMU can be over 90000 USD [6].

In these conditions, one possible solution is the use of Micro-Electro-Mechanical System (MEMS) sensors. In the last years, the performances of these sensors increased, while the cost, size and power consumption were kept low. Furthermore, in a previous work [2] we have proved that by properly compensating the angular rate data collected from our MEMS gyroscope sensor, we were able to obtain a heading accuracy within 2° for a 30 minutes navigation solution. During the entire measurement the user walked inside a building, changed floors, and used the elevator. Also, no additional location systems were used to update the inertial navigation solution. Based on these results, for short periods of time (less than 5 minutes), the accuracy of our previous MEMS-based navigation device can meet the requirements of land vehicle navigation systems [6].

In this paper we present a Hybrid Navigation System (HNS) which combines the advantages of GPS navigation with the advantages offered by the INS technology. From this merge we expect to get a 2D navigation solution able to accept 300 seconds of no GPS signal with an accuracy better than 10 meters. Similar developments, [5–8], point out that the differential inertial sensors use can improve the accuracy and the continuity of the GPS navigation solution.

The rest of the paper is organized as follows. Navigation algorithm is explained in Section 2. Measurement setup is presented in Section 3 while Section 4 analyzes the results of our research. Finally, Section 5 concludes the paper.

2. NAVIGATION ALGORITHM

As we previously mentioned, INS are based on the DR algorithm. This algorithm determines the changes in position by integrating the system speed (in our case the speed of the car), which usually is measured by using accelerometer sensors. The HNS basic idea is to use the speed information as it is provided by the car onboard computer. This way the traveled distance can be determined by integrating only once the car speed. Furthermore, for computing the 2D navigation solution, the distance must be combined with the heading of the car. To this end we used a MEMS gyroscope sensor. Finally, based on these two measurements, the DR solution is computed with respect to a fixed reference point. The reference used in HNS are the last GPS coordinates determined just before the receiver lost the connection with the satellites. The HNS navigation algorithm is presented in Figure 1. In order for the algorithm to work, the first part of the navigation solution must be determined by using the GPS receiver. Otherwise, the initial conditions required by the DR algorithm can not be established. The notations presented in Figure 1 are explained below:

- *DR_PozRef* and *DR_HeadingRef* denote the initial 2D coordinates / car heading, both representing initial conditions required by the DR algorithm determined just before the GPS receiver went off-line;
- *COG* represents the course over ground in degrees determined from the GPS data;
- *NavSol* contains the navigation solution of the GPS/DR HNS.

Even though the complexity and structure of our algorithm is suitable for real time applications, all the results presented in this paper were processed off-line using MATLAB 2008 software.

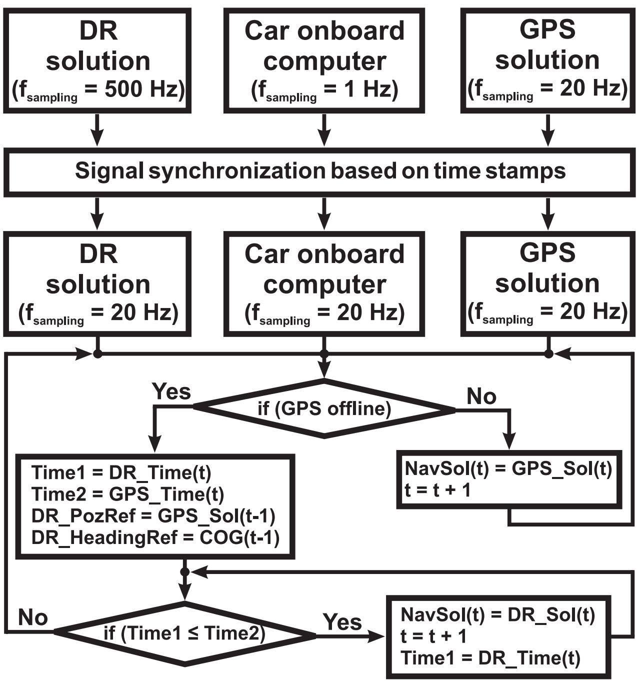


Figure 1*: HNS navigation algorithm flowchart.*

3. MEASUREMENT SETUP

The measurements were performed with the GPS antenna positioned on the top of the car, and the SCC1300-D02 sensor (accelerometer and a single axis gyroscope) on its floor. Technical specifications for the gyroscope sensor are presented in Table 1, while the hardware components used in the physical implementation of our HNS are presented below:

- ***DR system***
  - *SCC1300-D02 sensor:* a combined 3-axis accelerometer and a single axis gyroscope sensor; it was manufactured by VTI Technologies and released at the beginning of year 2010 [9];
  - *SPI interface:* the National Instruments USB-8451 device that provides I^2C and SPI communication interfaces with 8 chip select lines [10];
  - *Voltage regulator:* this component stabilizes the input voltage for the SCC1300-D02 sensor;
  - *Power supply:* a GP battery of 7.2 V and 3000 mAh;
  - *Dell Laptop:* to read and save the data collected from the SCC1300-D02 sensor.
- ***GPS system***
  - *Antenna:* a high performance NovAtel GPS–700 Series antenna [11];
  - *Receiver:* a DL–4*plus* receiver from NovAtel [12];
  - *Power supply:* a 12 V connection from the car battery to power the GPS receiver.

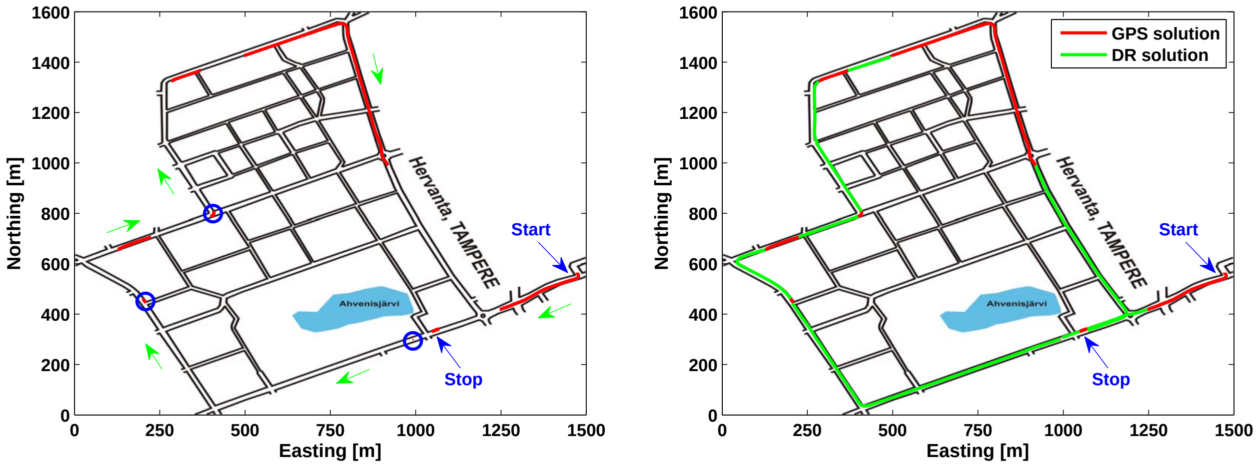
For the DR components presented above we used basically the same connectivity like in our previous work [1, 2]. Also, the algorithm required for computing the DR solution is similar. The differences between these two DR systems consist in the way that the traveled distance is computed. For the system presented in [1, 2] the distance was estimated as a combination between a fixed step length and a determined number of steps (based on the acceleration data), while for the current DR system we integrated the car speed (measured by the car onboard computer). Furthermore, since only a 2D navigation solution was required, the barometer sensors were removed from the current DR setup.

4. EXPERIMENTAL RESULTS

For collecting the results presented in this paper all the HNS hardware components were mounted on a car. Then

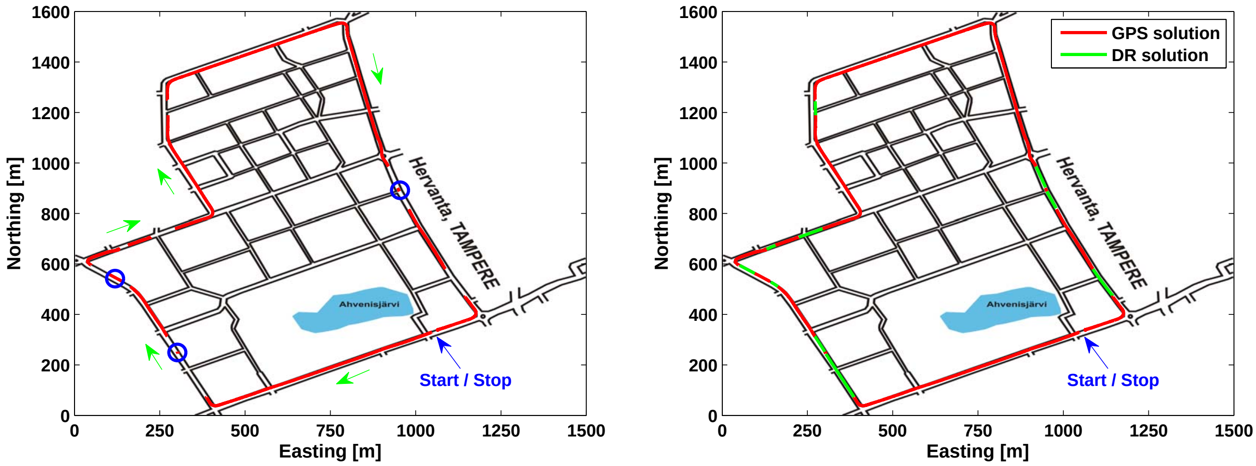
Table 1: SCC1300-D02 sensor specifications [9].

Parameter	Gyroscope	
	Value	*Unit*
Operating range	± 100	°/sec
Noise (RMS)	0.06	°/sec
Sensitivity	50	LSB/(°/sec)
Quantization	0.05	°/sec
Short term instability	< 2	°/h
SPI clock rate	0.1 – 8	MHz



(a) GPS navigation solution. (b) GPS/DR navigation solution.

Figure 2: *Navigation solution of approximately 4.6 km.*



(a) GPS navigation solution. (b) GPS/DR navigation solution.

Figure 3: *Navigation solution of approximately 4.2 km.*

we drove through Hervanta (Tampere) neighborhood for approximately 30 minutes. During this time we traveled a distance of around 12 km and followed two separate routes. The first route is presented in Figures 2 and 3. The blue circles point out the areas where short GPS navigation solutions were determined, while the green arrows suggest the car's traveling direction. Two marked positions (*Start* and *Stop*), in both figures, denote the locations where the car stopped for several minutes between different navigation stages. Furthermore, besides the results presented in Figures 2 and 3, an additional measurement was made. During this measurement the car followed a shorter route (of approximately 3.2 km). The purpose of this measurement was to establish a better connection between the GPS receiver and the satellite network. For this reason the measurement was not included in this paper.

As shown in Figures 2(a) and 3(a), the GPS navigation solution is accurate even for short time solutions (see the blue circles). This is due to the fact that we used a high performance GPS antenna with a receiver that provides a navigation solution only when it is certain that the position fix is very accurate. However, even with this high performance GPS we were not able to obtain a continuous navigation solution, especially for the result presented in Figure 2(a). This means that for commercial GPS systems the accuracy and reliability can drop even more. As a result, for some urban environments the GPS solution can not be even provided, letting the drivers without any GPS navigation support. Under these conditions a HNS is required. The results obtained by using the proposed HNS are presented in Figures 2(b) and 3(b). As it can be seen, for the area where the GPS was off-line, the HNS was able to maintain with adequate accuracy the navigation solution until the next GPS coordinates were available. All the errors introduced by our DR system during the navigation phase (when the GPS was off-line) are presented in Table 2. The reference used to compute these errors was the GPS navigation solution.

The last row from the table represents the mean values

Table 2: Errors of our DR system for X and Y axes.

Time	**Route 1 (≈4.6 km)**		Time	**Route 2 (≈4.2 km)**	
[sec]	*X [m]*	*Y [m]*	[sec]	*X [m]*	*Y [m]*
421	3.9651	3.8901	1437	0.3172	0.7780
511	1.9825	3.8901	1443	1.7446	3.8901
565	5.1546	3.1120	1463	2.9341	1.5560
627	1.1102	0.0778	1472	2.3394	0.7780
681	1.5860	2.4118	1535	9.1641	3.8901
699	3.1720	4.9793	1547	0.3172	0.1556
877	5.5511	3.8901	1598	0.0793	4.6681
-	-	-	1714	1.5860	2.8786
-	-	-	1722	0.6344	3.8901
-	-	-	1773	0.7930	2.3340
Mean	***3.2174***	***3.1788***	***Mean***	***1.9910***	***2.4819***

of X and Y axes for each of the two routes. As expected, the values decrease only when the traveled distance, computed with our DR system, decreases. Furthermore, all the values presented in Table 2 were determined at the exact moment when a valid set of GPS coordinates was received. We marked this in the table by inserting the time stamp extracted directly from the GPS data. This means that for each road segment when the GPS was off-line the errors (on X and Y axes) of our DR system were below the values presented in the table.

This is due to the fact that the errors of any DR system are cumulating during the navigation phase, so that the last measurement should contain all the previous errors. Even so, all the errors showed in Table 2 are lower than 10 meters, which for commercial GPS receivers (used for land vehicle navigation) represent an adequate level of accuracy. Such accuracy is suitable even when trying to find specific addresses. Finally, to conclude this section we can say that with our HNS we were able to maintain a continuous navigation solution with good accuracy for the entire duration of the measurement, even if no GPS signals were available during the navigation.

5. CONCLUSION

In this paper we have proposed a hybrid navigation system that combines the advantages offered by GPS and DR technology. Based on this association we were able to obtain a continuous navigation solution despite the fact that for some areas the line-of-sight between GPS receiver and the satellites was lost. With the proposed GPS/DR HNS we achieved an accuracy within 10 meters during the entire navigation solution. This level of accuracy is suitable for land vehicle navigation systems even if the user needs to find a specific address.

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