POSITION ACCURACY WITH REDUNDANT MEMS IMU FOR ROAD APPLICATIONS

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INTRODUCTION

Context of Positioning in Road Transportation

Traffic problems have mainly resulted from an increase in mobility over the last decades involving an increase in traffic congestion and degradation of environmental conditions. The employment of new systems – namely, Intelligent Transport Systems (ITS) is being considered for their mitigation ([1], [2]). ITS offer a high number of applications providing different types of support to the user: usually the driver or the traveller. These may range from "simple" solutions dedicated to comfort (e.g. parking aid, e-toll) or information services (e.g. navigation, Variable Message Signs) to more complex ones such as Advanced Driver Assistance Systems (ADAS). One may distinguish pre-crash ADAS (e.g. collision warning, lane warning), post-crash ADAS (e-call) and fully automatic driving systems like Automated Highway Systems (AHS). The complexity is characterized through the maturity level and market distribution.

A key role in most ITS applications is the estimation of the position of the vehicle. The GNSS forms a global and free tool providing suitable data under most conditions. The following criteria should be met: accuracy, integrity, continuity, availability, interoperability and timeliness. Data accuracy requirements differ and depend on the various ITS applications. Accuracy is not that crucial for navigation devices but it is for AHS. For such systems, requirements have been identified: 0.01-0.5 m for the location, 0.01-0.5 m/s for the velocity and 10-100 Hz for the update rate [3].

For most applications, though, especially considering pre-crash ADAS functions, there are three types of required accuracies that may be used as targets, depending on the system functionality: *which road*, *which lane* and *where in lane*. For navigation or tolling systems, knowing *which road* is sufficient; for lane departure warning systems, intelligent speed adaptation systems or road user charging the *which lane* level should be met, whereas for collision avoidance the *where in lane* level is required. Positioning accuracy targets are set at 5, 1.5 and 1 m respectively for absolute positioning and 5, 1.1 and 0.7 m for relative positioning ([4], [5]). For AHS, often referred to as active control, higher accuracy is required [6].

The diversity of ITS services makes the definition of positioning performance a real challenge. The high penetration of navigation systems in the road sector has increased the number of Location Based Services and the users assume that the localization is fully integrated in several services. However, this common use of location information gives a wrong message, that this type of on-board unit provides suitable positions in all types of situations. This is not the case, because the quality of positioning is not guaranteed and it may be insufficient for some categories of ITS services like for the safety and liability critical ones. For that reason, it is necessary to make the distinction between the positioning terminal and the ITS application. The terminal combines positioning sensors, digital maps and localization processes, which provide positioning quantities with quality indicators. The application is using the outputs of the positioning terminal for their combination with other data sources, in order to provide specific services to the users. This architecture and the relevant role of the assessment of positioning performance is described in the White Paper of the COST Action SaPPART [7].

GPS Alone is Not Sufficient

The GNSS system installed on a car has to tackle different challenges concerning the satellite signal reception. The availability of satellites (e.g. GPS, Glonass, Galileo) is increasing steadily and poses no problem if direct visibility is assured. This is almost always possible in rural regions where buildings and hills do not excessively obstruct the sky.

The problems arise when navigating in cities, where tall buildings obstruct a big part of the sky. This leads to several problems. Firstly, missing signals from hidden satellites lead to a deteriorated position solution. Secondly, reflections and multipath from nearby vehicles and walls introduce interference. Here too, the position cannot be computed or worse: a wrong position is calculated. Hence, the limited satellite availability induces gaps and blunders in the navigation solution.

Depending on the application, these limitations are not always a problem (e.g. the position of a bus/train in real time [8]), but some of the examples mentioned in the first section require a continuous position update rate without any gap or outage.

Improving the Position: the Synthetic Inertial Measurement Unit (SIMU)

The gaps in the navigation solution (obtained by GNSS only) can be bridged with additional sensors. Different systems can be used to get information about the pose of the vehicle: accelerometers, gyroscopes, magnetometers, odometers or cameras. Our investigations will focus on the use of Inertial Measurement Units (IMUs). They are usually composed of a triad of accelerometers and gyroscopes packaged in a single housing. Navigation grade IMUs provide excellent data, but they are heavy, bulky and costly (several 10 k$). Therefore, their use is not of interest in a mass-market. Micro-Electro-Mechanical-Systems (MEMS) are proposed here as a solution for a multitude of reasons. The first reason is the weight: they are small and light. The second reason is the favourable cost factor. The trade-off is lower performances compared with a navigation grade IMU.

Using multiple MEMS sensors in some arrangement allows to increase the overall performance, as demonstrated previously [9]. Furthermore, by introducing redundancy into the system, a sensor failure may be identified and the parallel sensors can still provide enough information for the navigation process [10].

In this paper we aim at comparing the performances of a single MEMS-IMU with the ones from multiple MEMS-IMUs. The results obtained are also compared with those from a navigation grade IMU, which provides the reference trajectory. The different IMUs are coupled with a GNSS system. The measurements are obtained under various conditions ranging from rural to suburban sites, where the reception conditions are less favourable. Studying their impact on the navigation solution will show to which extent this redundant system can bridge the gaps in the satellite signals.

In the first chapter, the terminology is reviewed. In the second chapter, the test setup is presented and the performance of the sensors is introduced. In the third chapter, the concept of the redundant IMU is presented. Then, the measurements obtained are processed and their navigation solutions are presented. The final chapter focuses on comparisons between the reference trajectory and those obtained from the other sensors.

CHARACTERIZATION OF VEHICLE TRAJECTORY ACCURACY

Two statistical features are used to describe the positioning accuracy of a moving vehicle; specifically, the *precision* and the *trueness* of its location and velocity estimates. The precision characterizes the performance of a vehicle navigation system that relies solely on its own error estimates and refers to the repeatability (under same conditions) or reproducibility (under various conditions) of measurements, whereas the trueness of a vehicle trajectory expresses the proximity of the navigation solution to the actual (true) trajectory [11]. In this context, the term *accuracy* relates to a combination of both *trueness* and *precision*. In statistical terms, the dispersion of the error probability distribution of a positioning terminal reflects its precision capability, whereas the deviation of the mean position from the true trajectory is associated with the trueness of the system.

For navigation and ITS related applications it is essential to transform originally derived accuracy figures from a global coordinate system (e.g. eastings, northings) to their along-track and off-track equivalents to produce meaningful accuracy metrics. Clearly, this error representation adheres to the motion characteristics and facilitates the assessment of the longitudinal and lateral vehicle kinematics. In order to assess the trueness of a navigation solution, a reference trajectory is required, against which a comparison is made. In this case, the along- and off-track accuracies of an observed travel path reflect its deviation from the ground-truth.

The integration of a geodetic grade GNSS receiver with a high-end Inertial Navigation System (INS) offers today the most widely accepted way to establish a high quality vehicle trajectory ([12], [13]). In fact, the complementary properties of the two systems make them ideal partners, as the long-term accuracy of the GNSS bounds the drifts of the INS, whereas the INS can bridge the gaps in the GNSS positioning resulting from signal blockage (e.g. due to buildings or tree canopies). Depending on the GNSS receiver, the INS sensor characteristics, the processing technique, and the environmental conditions a precision at the centimetre level can be expected [14].

EXPERIMENTAL SETUP AND FIELD TEST

Navigation System Used

Three different navigation systems are used. The first one is a high-end GNSS/INS system. It is composed of the navigational grade INS “IXBLUE AIRINS” [15] and the geodetic grade GNSS receiver “Javad Delta” with OEM board G3T [16]. Data logging for the system is performed in custom acquisition unit, which also provides the power supply for the INS, the GNSS receiver and the whole acquisition apparatus. Their fusion provides the reference trajectory.

The second navigation system consists of the MEMS-IMU “Navchip” [17]. The datalogging and powering is done via a custom board “Gecko4Nav” developed internally [18]. A total of four MEMS-IMUs are installed on this board side by side. In the beginning, the individual performances are tested in combination with the GNSS. Then, we will use the SIMU concept in order to fuse four of those MEMS-IMUs into a single *fictitious* sensor [19], which out-performs a single IMU. The following Tab. 1 summarizes some properties of the systems used.

Tab. 1. Performances of the two IMUs

Property	Gyro bias [°/hr]	Frequency [Hz]	Power [W]	Weight [kg]	Size [mm]
AIRINS	<0.01	200	15	4.5	180 x 180 x 160
Navchip	10	250	0.2	0.006	24 x 13.5 x 9.1

Setup Configuration

The whole setup (AIRINS, MEMS-IMUs, GNSS antenna) is mounted on a special platform which can be directly mounted on the roof of a car (see Fig. 1). This platform offers a stable and secure mount for all the test equipment.

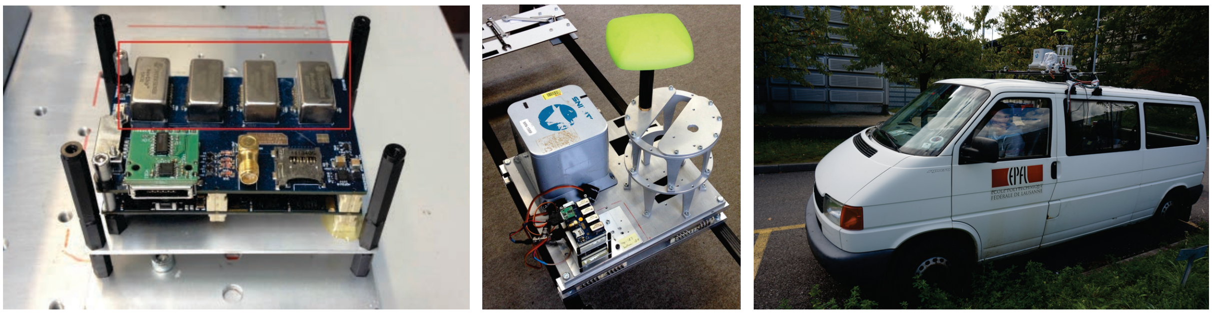

Fig. 1. Left: ‘Gecko4Nav’ housing the 4 MEMS IMUs; Middle: everything mounted on the support platform; Right: equipment mounted on a mini-van

Data Collection

The data were collected in the surroundings of Vuarrens, 20 km North of Lausanne, Switzerland. The path is a 10 km loop, which follows rural and suburban roads. Fig. 2 gives an overview of the path. For the first part of the trajectory, good visibility to the satellites prevails (represented by green and blue dots). The last section passes through an urban part of Vuarrens, which is characterized by an unfavourable satellite visibility due to buildings (represented by red and violet dots).

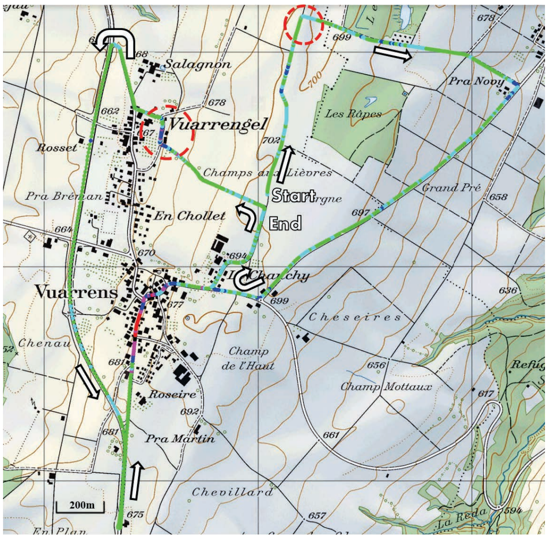

Fig. 2. Travelled trajectory with quality indicators: green - best, blue - decreased, violet - low, red - very low. Red circles indicate the locations for the performance assessment

Measurement of Vehicle Trajectory

The integration of GNSS and INS data is a highly demanding computational process that requires extensive experience. Noisy accelerations and rotation rates from the INS are integrated to obtain the position, velocity and orientation of the vehicle. The Position-Velocity-Time solution from the satellite receiver suffers from errors too. These are manifold: biases in the satellite clocks and orbits, delays in the signal transmission through the troposphere/ionosphere as well as multipath/reflections around the receiver. The majority of these errors can be reduced by using a dual frequency receiver and corrections from a base station via the implementation of special processing techniques that make use of the complete spectrum of the GNSS signals (differentiation of carrier phase and pseudo-range code). Provided that the entire process is undertaken carefully, a high positioning accuracy at the centimetre level can be achieved. Fig. 3 depicts the processing scheme, which shows the different steps.

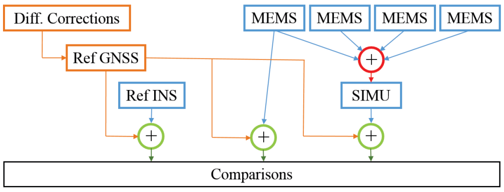

Fig. 3. Processing scheme from the data collection to the comparisons of the different data sources

Establishment of Reference Trajectory

In a first step, the differential carrier phase GNSS solution is calculated with the data gathered from the car and the data from a Virtual Reference Station. This station is based on the Swiss Positioning Service, which uses a total of 30 GNSS reference stations [20] and provides corrections either in real-time or for post-processing. The fusion of the data with the corrections is achieved using the commercial software *GrafNav*.

The left part of Fig. 4 shows one of the many different results of the process. Here, the standard deviation of the estimated GNSS position is shown. One can see it increasing to several metres due to unfavourable signal reception (e.g. houses, trees), whereas it stays at the decimetre level when the reception is good.

This solution can be further refined with an IMU. In fact, the GNSS and the INS measurements are combined by means of a Kalman Filter, which compensates the errors in the observations in an optimal way (i.e. according to the *least squares* principle). However, the output is adequate only if the models and parameters are chosen correctly. This demands a certain expertise from the user. Its estimated precision is shown in the right part of Fig. 4.

The loosely coupled integration is chosen here, where the positions and velocities produced by the GNSS and the IMU are fused in the filter. Estimated corrections are re-injected into the INS processor to account for the systematic effects in inertial measurements.

The high-grade IMU can effectively bridge the gaps in the GNSS data and further improve the precision of the estimated position, as seen in the right part of Fig. 4. If the satellite visibility is good, an excellent cm-accuracy is achieved with carrier-phase differential processing. In the absence of GNSS signals, the navigation grade IMU AIRINS keeps the estimate low, as it has a very small drift. This allows to stay on the path confidently. In the absence of bad reception of GNSS, the estimated precision stays well below the decimetre level for gaps less than a minute.

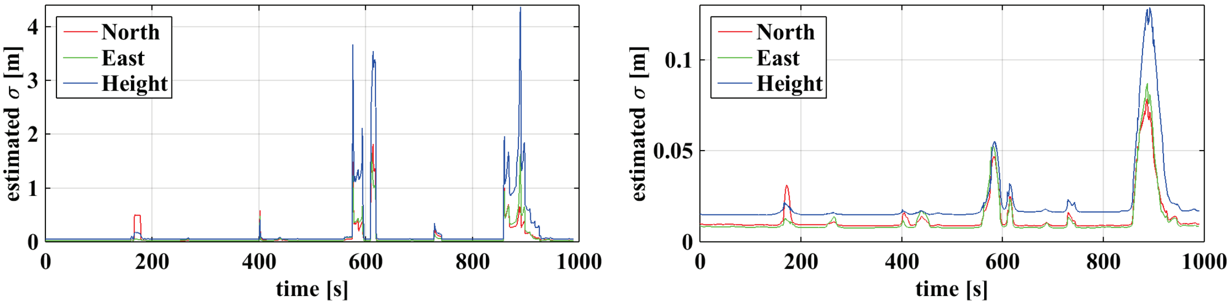

Fig. 4. Standard deviation of the estimated position. Left: GNSS only. Right: high-end carrier-phase differential GNSS/INS. The two peaks around time 600 s and 900 s correspond to spots with less favourable satellite reception (Fig. 2 for comparison)

Integration with *One* MEMS-IMU

As mentioned before, the IMU measurements (i.e. accelerations, rotation rates) are integrated in order to get the attitude, the velocity and finally the position. For this, the initial conditions need to be known precisely enough. If not, the direction of the movement will be somehow erroneous and the corrections will worsen the process.

The signals from small MEMS sensors have the drawback of being noisy. The physical properties of the sensors influence the nature of the noise. Integrating the accelerometer readings in order to get the velocity results in integrating not only the signal, but also the noise. This noise is the main error source when integrating a second time to determine the position. This is why the position based on inertial coasting drifts away with time.

In a data fusion algorithm (e.g. Kalman Filter) the drift of the IMU is bounded by the GNSS data. The latter has an excellent long-term stability and does not drift at all. A disadvantage is that the frequency at which the GNSS receiver provides information is relatively low and the satellite signal availability is intermittent (for cars). Hence, using a fast-sampling IMU to bridge the gaps in the measurements completes the system.

Integration with *Synthetic* MEMS-IMU

The redundancy in the navigation process can be achieved in two different ways [21]. The first possibility is to have redundancy at the system level. This means having multiple navigation systems (e.g. INS, GNSS) operating independently. Each of them provides a navigation solution, and these are merged in the end.

The second method consists in having the redundancy at the sensor level. This means fusing the data from multiple sensors (i.e. 4 MEMS IMUs) together before they are, as a whole, fed into the fusion algorithm. Different mechanizations exist and are explained in detail in [9]. In this study we will focus on the SIMU. The fusion of the available sensor data is achieved by taking the mean over the measurements x_{ij} for each of the three axis i ($i \in [1,3]$) over the four IMUs j ($j \in [1,4]$):

$$\bar{x}_i = \sum_{j=1}^{4} \frac{1}{4} x_{ij} \qquad (1)$$

Each sensor is assigned the same weight yielding in the “un-weighted SIMU”. In order to compute the average between the sensors, the data of the IMUs must be projected onto the same frame. This will constitute the frame of the synthetic sensor. This can be done only if the boresight (relative attitude) and the lever arm (relative vector) between the sensors are known. Although the sensors appear to be mounted correctly on the board, their alignment deviates up to several degrees. An initial calibration step is needed to determine those parameters. Fig. 5 shows the steps required. The SIMU is then reintroduced into the same processing scheme as the AIRINS or the single MEMS-IMU. The fusion of four MEMS-IMUs results in an IMU with less noise and a signal that matches the reference signal better.

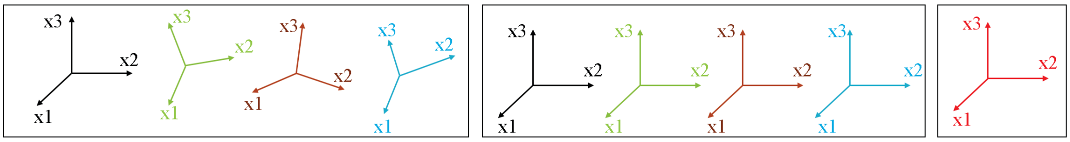

Fig. 5. Left: individual IMUs, each one has its own orientation with respect to the reference IMU (black); Middle: the information is projected into the first reference frame; Right: averaging over the axis gives the synthetic IMU.

VEHICLE TRAJECTORY COMPARISON

The performances of the *SIMU* are compared to the ones obtained using only *IMU 1*. For this purpose, artificial GNSS-signal outages of several seconds are introduced manually into the data. The loss of the bounding GNSS aid lets the IMU drift away. The examples of Fig. 6 presents two such cases. The first case shows a GNSS interruption of 14 s in a 90° turn. The outage leads to a drift over time. With the single IMU, the absolute error in the horizontal plane is 9 m, whereas the SIMU bounds the error to 7 m with respect to the reference trajectory of the AIRINS (see Fig. 7 left). The second example depicts a 30 s GNSS outage during a double turn. As the outage is twice as long as in the first example, the error growth is even more significant. Here again, the SIMU handles the drift better than the single IMU does (see Fig. 7 right).

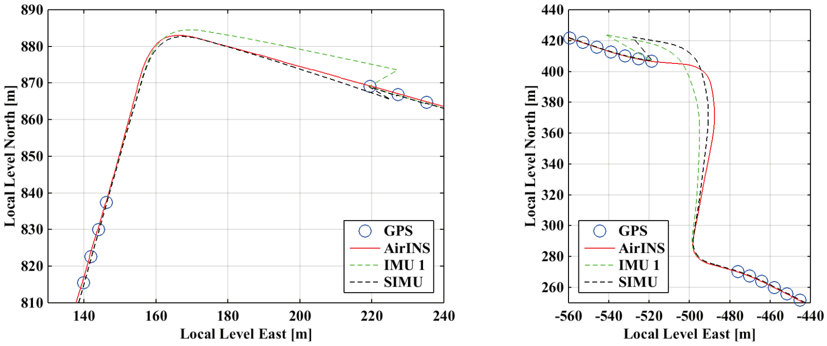

Fig.6. Left: The car turns right without GNSS for 14 s and the IMUs drift away. Right: The car enters an S-shaped curve with a 30 s gap in the GNSS data, where the IMUs drift a lot.

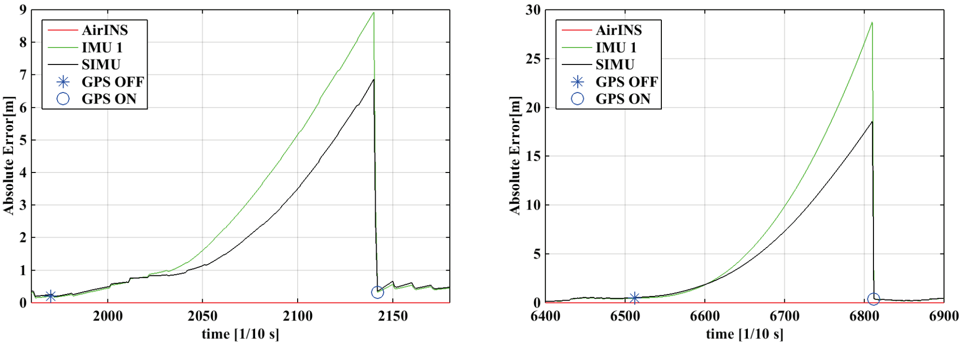

Fig. 7. Left: GNSS outages for 14 s in a right turn; Right: GNSS outage for 30 s in a double curve. The SIMU is performing much better than the single IMU.

The better performance of the SIMU is due to the reduced noise in the fictitious sensor. By adjusting the parameters in the Kalman Filter correctly, the model could keep up even better with the reference trajectory. The creation of the SIMU requires pre-calibration and increases computational demand [9], but once the fusion is achieved, the performances obtained are very promising. Depending on the application, the gaps in the GNSS can be mitigated with this method, while the system redundancy increases.

TOWARD GNSS-BASED TERMINAL SPECIFICATIONS

The next generation of ITS and mobility services should target more efficient and less energy consuming transportation, that would eventually lead to increased capacity, less congestion and improved safety. In this perspective, information, communication and positioning technologies are expected to play a key role in the design and implementation of future ITS. Specifically, mission-critical (e.g. safety-, security-, liability-critical) systems depend heavily on positioning information that primarily relies on GNSS. Moreover, the level of ITS requirements supported by a positioning terminal depends on its quality, and vice-versa. Therefore, the quality of the position output requires a thorough attention to ensure that the Key Performance Indicators of the system remain within requirements.

In the real world, however, the high influence of operational and environmental conditions on GNSS results in a high complexity when defining and assessing its performance in the road sector. In particular, GNSS performance is affected by various error sources that can be attributed to a radio signal, raw measurement (i.e. pseudo-range, Doppler) and receiver output level. Consequently, various initiatives have been recently undertaken to study and develop relevant error models and to propose generic standards and quantified classes of performances in adverse GNSS environments for road transport.

At a standardization level, various initiatives have been launched at national and European level. Noteworthy, ETSI (TC-SES, WG-SCN) and CEN-CENELET (TC-5, WG-1) have been directly mandated by the European Commission to address such performance issues in a coordinated and complementary way [22]. To bring scientific support to these efforts, the COST Action SaPPART (Satellite Positioning Performance for Road Applications) is currently underway, bringing together researchers and stakeholders from the GNSS and ITS world. SaPPART mission is to promote GNSS for ITS applications. The group develops a framework for the definition of service levels for GNSS-based positioning terminals, as well as the associated examination guidelines for certification purposes. In this direction, SaPPART is concerned with the study of error models applying to GNSS position in an effort to translate key performance indicators defined at service level into positioning requirements. A key milestone of this effort is the dissemination of a “White Paper” to explain the key features of GNSS technology in transport and to deliver key messages to the ITS community in a simple and concise way [7].

CONCLUSION

This paper presents a multi-sensor navigation system designed for very demanding road applications. The redundancy of MEMS-based sensors is a clear advantage for the provision of continuous navigation signals under severe environmental conditions. The series of real test scenarios helped to develop a methodology to assess the positioning performance of a navigation terminal for road applications. Recording real datasets is a key advantage for showing the variability of GNSS signals along a vehicle trajectory and the necessity to monitor the positioning accuracy continuously. The evaluation of this redundant IMU platform integrated with GNSS is a first step towards the development of a robust navigation system, which will include dynamic models defined according to the needs of ITS services.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the SaPPART COST Action (TU 1302) for the funding of a short scientific mission to Lausanne (Switzerland), which allowed young researchers to perform valuable navigation tests [23].

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