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High Integrity Reference Trajectory for Benchmarking Land Navigation Data Fusion Methods

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***Abstract*—In the framework of a joint initiative of several French laboratories that investigate land navigation, the authors have designed an architecture and tests protocol for benchmarking altogether data fusion methods applied on a collection of sensors covering the complete range of quality.**

Special attention has been given to sensors data timestamping since the benchmarking is based on the comparison of computed trajectories with the reference trajectory, so called because its computation fuses the most advanced sensors. A device called SensorHub that allows hardware based multi-sensor data timestamping was used.

Real-time but also post-process estimations of the reference trajectory where provided by the combination of kinematic GPS and LandINS, a high precision IMU provided by IXSea. Beyond the precision of these estimated trajectories (that highly depends on how long the roving GPS receiver was masked), the relevance of the computed integrity is emphasized in this article.

I. Introduction

IN the framework of the national project ARCOS (Action de Recherche pour une Conduite Sécurisée) closed in 2004, several French organizations and universities (LCPC-IEF-LIVIC-LASMEA-UTC-EMP-INRIA) joint their effort of research with the aim of improving the localization of vehicles with on-board low-cost sensors. Positioning is actually required for any further development such as map-matching, (ADAS), car-to-car or car-to-infrastructure communications…

For the three years duration of the ARCOS project, many investigations have given birth to multi-sensor fusion algorithms and computing software, as well as hardware development and testing on different prototypes.

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Fig. 1. The LIVIC and LARA vehicles

By the end of 2004, after the project was closed, the researchers involved in this field for ARCOS funded an informal group. François Peyret from the LCPC had the initiative of this group, for which he still have the main role of animation. One direction that the group decided to follow is the edition of a book that relates the best of their experience in data fusion for land navigation.

With respect to this objective, it was decided to collect during a unique experiment a set of data as complete as possible, i.e. with on-board sensors such as those used for the applications demonstrated in ARCOS (collision avoidance, emergency braking, lane keeping, platooning…) and also with an additional INS (Inertial Navigation System) capable of offering a reference onto which one can assess the performance of its positioning solution based on the processing of the collected data.

This was done in November 2005 (see Fig. 1), almost exactly one year after the conclusion of the ARCOS project. Hence, this paper relates both the experimental system and protocol used as well as it depicts the available data offered now to every partner for processing and benchmarking its algorithm. It has been written by a reduced number among the seven associated laboratories particularly in charge of the metrology and sensor instrumentation.

II. State of the Art

A. Fusion of proprioceptive and exteroceptive perceptions for localization

The task of localization, i.e. computing the position and orientation of a mobile in space versus time generally relies on fusion of two kinds of information; this process is sometimes called hybridization. Exteroceptive Information (EI), provides position and orientation with respect to a reference frame. This information is generally extracted by matching sensory landmarks with a spatio-temporal model of

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the position of these landmarks. The nature of landmarks can be various: satellites, as used with GPS system, reflective poles, when a laserscanner is used, or even the urban environment in the case of vision. EI is subjected to limited sampling frequency (1Hz to 30Hz) and the availability is not guaranteed (e.g. GPS satellite outage). EI are thus generally hybridized with Proprioceptive Information (PI). PI provides time derivative information of position and orientation of the mobile, like linear speed, linear acceleration and angular speed. The proprioceptive measurements must be integrated to compute position and heading of the mobile. This information comes mainly from sensors like encoders, gyrometers and accelerometers, able to run at high rate sampling frequency (typically 5 to 500Hz).

B. *Assessment of localization systems with respect to a reference trajectory*

Assessment of localization systems for ADAS is important since the accuracy determines the kind of application a localization system may be used for, from driver information (navigation) to driver assistance or even fully autonomous driving. Key elements determining the performance a localization system are the intrinsic sensor precision, associated modeling and the performance of the fusion method. Characterization of a localization system is of importance in permanent and transient phases. Standard use is permanent phase, when both EI and PI are available and when the system relies solely on PI. During the transient phases PI and sometimes EI are used.

Multi-sensor fusion methods raise the question of the methods for their assessment. First of all, computed trajectories can be compared to road database. This is often done [1]. But this is bounded by the geometrical modeling of the road in the base: for instance, roads are simplified to segments and a round-about is rarely modeled, but its figures as a mode between segments. More difficult, even if the modeling was geometrically more comprehensive, an additional information is required: where am I really on that road, on which I have both longitudinal and lateral degrees of freedom?

Another way of tuning a multi-sensor fusion algorithm for vehicle positioning classically consists in setting artificially outages in exteroceptive data (like satellites navigation solutions) to let the proprioceptive sensors predict the trajectory by their own. The prediction error is computed with respect to the trajectory with no outage at all.

This entails a couple of observations: exteroceptive data are used twice, i.e. in the fusion process and in the reference, which is already subject to criticism. Moreover, these data may be corrupted, particularly during transient phases like during a GPS reacquisition phase after a real mask or in case of GPS multipath... the consequence of which could be locally the inhibition of the reference. Last but not least, these real mask and multipath are interesting to be actually processed through by the filter, since they cause perturbation of the nominal functioning of the fusion process and may produce aberrant data. Therefore, designers have to cope with a paradox. To be completed, the assessment of the capabilities of a data fusion algorithm for vehicle positioning must include tests in the real conditions of use of that vehicle. These are various, and the urban environment will generally cause the most effective perturbations. But these mandatory transient phases also prevent exteroceptive data like GPS solutions to be used as a reliable enough reference.

The computed trajectories given by the fusion algorithm to be assessed have a priori in the case of mass-market automotive applications accuracy of the order of magnitude of a couple of meters (precision of SIRF 2 or 3 GPS receivers: 5-25m CEP / 1-5m DGPS). But once again, future enhanced e-safety applications need the decimeter. The GPS kinematic, in its ambiguities fixed mode, appears to be 10 to 100 times more precise and it naturally provides a reference trajectory… when it works! And this is actually the main problem to be solved when one wishes a relevant benchmark to be made. It actually appears to be very difficult to establish precisely where a vehicle really maneuvers in an environment where masks are so frequent that it is impossible to compute a reliable kinematic GPS solution. The addition of a high quality inertial measurement unit (IMU) brings about the key technological element necessary to solve that problem. The IMU combined with RTK GPS actually enables navigation even during satellites outages. Transient phases always exist and their have to be paid particular attention. Anyway, due to its high quality IMU, the Inertial Navigation System can cope with longer outages, where transient phases may have been included.

In the road safety applications that we investigate, we have to consider different technologies of sensors; from MEMS (Micro-Electro-Mechanical Systems) to FOG (Fiber Optic Gyrometer). If an IMU is used as a reference sensor, its performances must be much higher than those of the other sensors to be fused elsewhere. For example, [2] computes the error of its MEMS based system with respect to the Honeywell HG 1700 output, which is considered to be a reference accurate enough to assess a system whose error will grow up to several hundreds of meters in one minute. In the frame of the experiment reported in this paper, FOG on-board have already the level of accuracy of high-quality IMU, like the KvH e-core gyrometer and the HG 1700. So we chose for its high performances the IMU IXSea 120. Table 1 displays the bias stability, scale factor stability and random walk read in these instruments datasheets.

TABLE I
MAIN SPECIFICATIONS OF GYROMETERS

	bias stability (°/h)	scale factor stability (%)	random walk (°/√h)
KvH e-core	1	0.1	0.1
HG 1700	2	0.015	0.1
IXSea 120	0.001	0.0001	0.001

Note also that kinematic GPS, even with post-process (PPK), has its own limitations as we could already notice during the ARCOS experiment last year [3]. Even if PPK GPS gives more fixed solutions than RTK, it still remains outages with autonomous or in the best case float solutions. During these outages a high quality IMU is actually required.

III. Spatial and Temporal Calibrations

A. Sensors, hardware and software acquisition architecture

The acquisition was done by a prototype called Sensor Hub whose function is logging and timestamping so that the temporal calibration of the complete set of sensors is guaranteed. In order to build an exhaustive sensor database and a high accuracy reference trajectory, different sensors and sensor technologies were used.

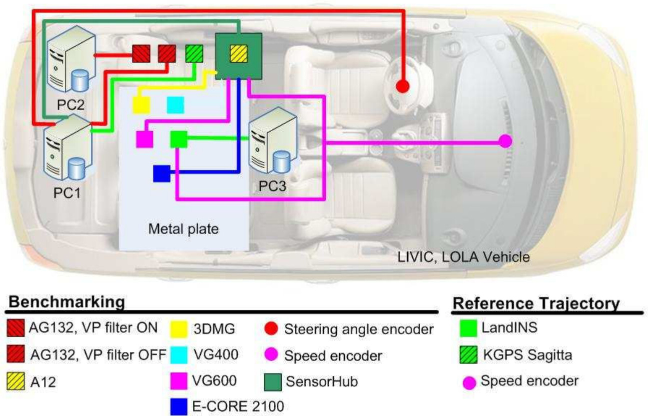

Fig. 2. Multi-sensor acquisition architecture overview

Two groups of sensors were defined (Fig. 2):

- *sensors used in fusion algorithms*. Several inertial sensors were used, from low end based on MEMS (Microstrain 3DM-GX1 and Crossbow VG400 IMUs) to medium and high end products like FOG gyrometers (KVH E-core 2100 vertical FOG and Crossbow VG600 IMU). Similarly, GPS receivers operating in different modes were mounted on-board (Ashtech A12 autonomous, Trimble AG132 EGNOS, PV filter on/off).

- *sensors used for computing the reference trajectory*. IXSea LandINS (that comprises three IXSea FOG 120 and three Honeywell accelerometers) was coupled with both a kinematic GPS Thales receiver and the distance encoder. LandINS is an inertial navigation system derived from IXSea PHINS IMU and dedicated to land positioning.

The hardware and software acquisition architecture called Sensor Hub was designed by INRIA-LARA Joint Research Unit. This is a parallel electronic device based on the FPGA technology to perform data acquisition and timestamping in UTC by mean of an embedded GPS receiver providing Pulse Per Second. The most current protocols used by automotive sensors are available. The precision of the timestamping has been assessed and it is of the order of 1 microsecond [4].

B. Spatial calibration

As highlighted in the state of the art, localization of a mobile in space is usually based on hybridization of proprioceptive data and exteroceptive data. Previously to this fusion step, it is of importance to calibrate each sensor temporally and spatially.

Most sensors generally output their information in their own reference frame, a relative spatial and temporal reference frame. Calibration stage consists in determining the spatial rigid transformations between each sensor reference frame and the reference frame of the mobile. The same approach has to be done to calibrate temporally the sensor (e.g. sensor latency).

The unique GPS antenna that was set-up on the roof of the car during the experiment needs to be located relatively to a metallic base plate fixed on the floor of the car, and onto which the gyro and IMUs, including LandINS, are screwed. The relative location between these sensors is equal to their mechanical offsets (i.e. translations) on the base plate mounting, plus their own characteristics as concerns the location of the center of measurements (internal offsets are to be taken into account here). Moreover, the relative position of the GPS antenna (also called lever arm) has been measured manually as follows (see Fig. 3).

The idea of the measuring process is simple: the base plate is first leveled (by loading or lifting the vehicle once the base plate has been fixed): therefore, its normal direction is directly given by the plumb line. This direction is also the z axis of the LandINS screwed on the base plate (misalignments are not known here but they are identified further in the LandINS navigation process). The z axis intersects the roof of the car at a point that one materializes and from which only plane offsets on that surface have to be measured with a level and a ruler. One estimates that the global accuracy of this process is close to 1cm.

Fig. 3. Relative position of the antenna with the IMU

This calibration of the GPS lever arm can also be confirmed by the automatic procedure provided with LandINS (table 2). This procedure does not require any specific trajectory since the identified parameters (x and y components) are observable in any round about and during any acceleration (which always exist in some part of a usual trajectory). The precision of the lever arm identification by LandINS was 5cm here.

TABLE II
MEASURED / COMPUTED LEVER ARM VALUES

	x (m)	y (m)	y (m)
Measured value	-0.76	0	1.15
Computed value (by LandINS)	-0.74	0.02	not achieved

Lastly, the usual procedure for calibration of the scale factor for odometry has been performed on the circuit, with the measurement of the real distance performed (19.54cm). Once again, LandINS includes a specific algorithm that computes (and confirms) this scale factor (as well as its internal heading misalignment).

The intrinsic calibration consists in determining internal para-meters of the sensors, like scale factors, temperature models, misalignments... It is generally made by manufacturers. IXSea gives these parameters for LandINS, and in real-time LandINS automatically estimates its sensors bias in the navigation process.

IV. TESTS PROTOCOL

The scenarios performed will not be listed completely in this paper. The idea was to perform tests on roads near Versailles (where the LIVIC is based), in and outside the city, on both highways and secondary roads. Natural masks such as trees, buildings, bridges, tunnels, etc… provide a quite complete environment for perturbing the GPS INS tested algorithms.

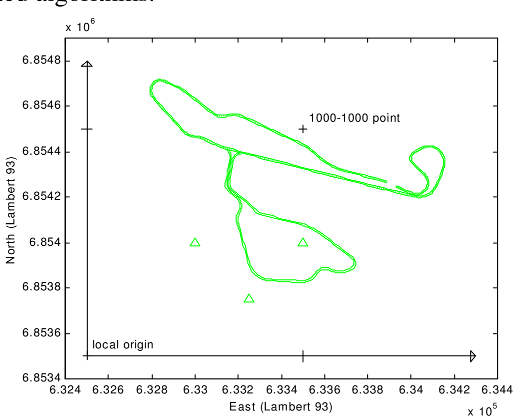

Fig. 4. The tracks in Versailles Satory

Before these tests, a specific experiment has been performed in order to assess the accuracy of the LandINS reference. This was carried out on a private circuit located near Versailles, that is used by LIVIC amongst other public and private users, civil or military. The main track is approximately 3.5km long, with a 2km long additional extension inside a forest where GPS observations are very difficult. Fig. 4 shows a plane projection of the track in French Lambert 93 plane co-ordinates. The accuracy these tracks are surveyed is a couple of cm.

On the main track, RTK fixed mode is almost guaranteed at all time and the a priori working conditions of LandINS are excellent before entering the extension, where natural masks are caused by the tree canopy. During the mask, the driver keeps as well as possible its left wheels on the border of the road that has been surveyed carefully. The survey and the possible deviation from the border due to driving gives a reference of 20cm, to which it is relevant to compare the predicted path given by LandINS.

V. COMPUTATION OF THE REFERENCE TRAJECTORY

A. *Coupling methods available*

Several coupling methods are possible between LandINS raw data and external sensors like GPS and/or odometry. The alternatives are listed below:

- enable/disable LandINS rejection filters for GPS solutions (this is applicable to both real-time and PPK);
- dead-reckoning option (the odometry can be used as an aiding sensor in the IMU integration);
- real-time or post-processed GPS solutions.

The main points that we want to show are:

- the robustness to GPS aberrant navigation solutions (in case of multipath, change in the constellation, change in the GPS functioning mode: standalone, differential, float/fixed);
- the continuity in case of GPS outage;
- the integrity information.

B. *Rejection filter*

An automatic rejection filter that runs in real-time can cope with the situation when GPS rover outputs aberrant navigation solutions. For that purpose, the confidence level of the GPS navigation solutions can be either constant or issued from the receiver itself. First of all, when GPS is used in real-time, it seems to be safe to use constant standard deviations of e.g. 0.3m in fixed mode, 3m in float mode and differential, and 10m in standalone GPS. We actually have to mention that the confidence level (GST NMEA stream) given by roving GPS receivers (including our) may not be reliable.

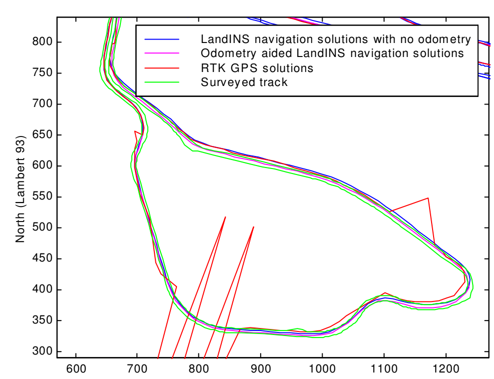

Fig. 5. GPS real-time rejection filter in the forest

Fig. 5 suggests two comments:

- one can see that the south west part of the loop contains RTK aberrant solutions and missing solutions during masks. The LandINS navigation solution, despite these GPS points absent or outside, is included inside the surveyed limits of the circuit.
- in the north part of the circuit, the GPS solutions are globally offset by a few meters. The rejection filter can be optimized by means of the aiding odometry: this additional measurement contributes to reducing the integration error, which also leads to the rejection of the GPS solutions locally biased.

C. *Continuity in case of GPS outage*

This section presents a simulation that will gives us an idea of the performance of LandINS in case of long masks.

We suggest to apply several artificial masks at different parts of the main track where RTK GPS was actually available. The duration of the masks applied to GPS RTK solutions is always 1 minute separated by intervals of minimum 10 seconds, which is enough to reset the filter in good initial conditions before starting another mask (see Fig. 6). During the masks, LandINS navigation solutions are either autonomous or odometry aided, along with the choice of the dead-reckoning option. GPS update of the navigation is done in the separating intervals only.

A comparison of the autonomous LandINS navigation solutions with the RTK GPS solutions (used as a reference in this simulation) is made. The same comparison is possible with the odometry aided LandINS navigation solutions.

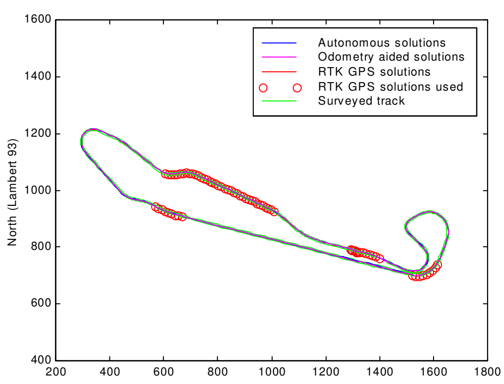

Fig. 6. Simulation of masks

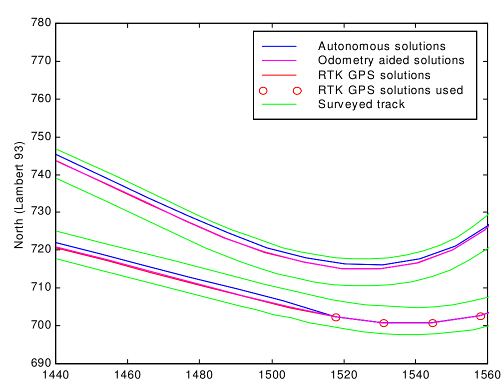

Fig. 7. Zoom at the end of one of the masks

Fig. 7 and 8 illustrate the capability of LandINS to perform continuity in case of GPS outage. The positioning error never exceeds 3m in the autonomous mode of integration and this is improved to less that half a meter in the odometry aided mode.

In autonomous mode (i.e. with no odometry), LandINS works as PHINS, whose specifications give an error of the order of a few meter in 1 minute of integration, increasing with the square of the duration. Hence, with sub-meter error, the odometry proves to be a very efficient aiding sensor.

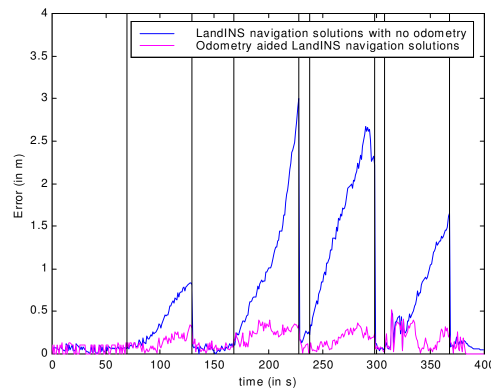

Fig. 8. Positioning error during the simulation

D. *Integrity analysis*

The integrity of the reference provided by LandINS has to be emphasized. Fig. 9 shows navigation solutions (with no odometry) locally at the end of a GPS mask. 95% LandINS predicted CEP are displayed. It is interesting to notice that the fixed GPS solution just after the mask and the LandINS predicted 95% CEP at the same instant are really coherent. This is confirmed on other masks on the circuit, and also in the odometry aided mode of LandINS.

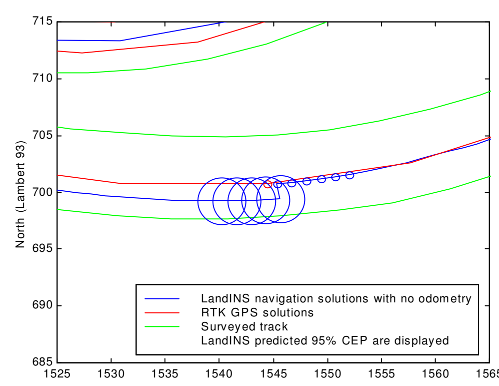

Fig. 9. Integrity analysis at the end of a mask

E. *Use of Post-Processed Kinematic GPS*

The preceding sections typically demonstrate the real-time conditions of use of LandINS. But the IMU raw data (plus the odometry) can be fused with post-processed kinematic GPS instead of RTK GPS solutions. Fig. 10 shows the GPS PPK solutions in the difficult test case inside the forest.

One notices that the offset of RTK GPS solutions in the north part of the loop means floating ambiguities of phase in

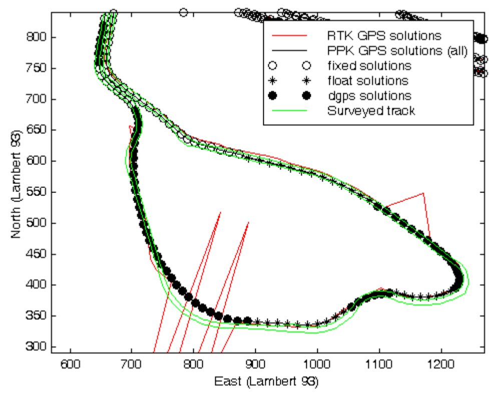

Fig. 10. Post-processed GPS in the forest

real-time, that have been fixed in a backward processing actually possible only in post-process. Nevertheless, some parts of the loop inside the forest remain impossible to be fixed and in that case only differential or standalone GPS solutions will be given. In these parts, LandINS should either reject or eventually use with a low confidence level the GPS solutions available.

F. *Extension of the analysis*

In the tests case of the track inside the forest, the duration of the interruption of fixed GPS solutions is around 2 minutes in post-processing (PPK), i.e. quite shorter than in real-time since the re-initialisation time (typically 30 seconds) is suppressed. We suggest to reject all other GPS solutions during these 2 minutes (standalone, differential, and even float solutions).

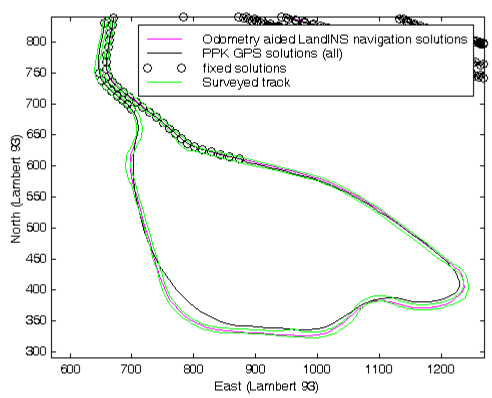

Fig. 11. Long duration mask in the forest

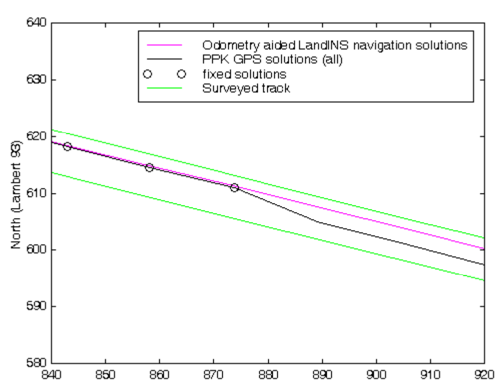

Fig. 12. Zoom at the end of a mask

As shown on Fig. 11 and zoomed in Fig. 12, the positioning error after 2 minutes in LandINS dead-reckoning mode is reduced to a few decimetres on this example (instead of a few meters with PHINS autonomous mode).

G. *Summary*

Based on the analysis on the Versailles Satory circuit, the idea is now to summarize the strategy that is applicable everywhere, particularly in the city of Versailles that the tests protocol addresses.

The main steps of this strategy are:

- post-process GPS raw data
- use fixed PPK GPS solutions only
- link GPS outage by odometry aided LandINS navigation
- fuse forward and backward computations to minimize the error in masks [5].

VI. Conclusion and Perspective

This article gives the description of the architecture used for data collection of the different sensors on-board, including LandINS. This is based on the SensorHub solution.

Moreover, the interest of using LandINS as a reference is also demonstrated. An extract from experiments that were carried out to prove its reliability has been given.

On these experiments, one could improve locally the results of the data fusion with LandINS by locally adjusting the tuning of its parameters and the fusion strategy. Obviously, this is possible only because we specifically have a precise static survey of the circuits.

Practically, once this strategy has been set-up, one will apply it similarly and globally on the entire data set, including long masks in city area.

Further work that aims at studying the consistency of the integrity indicator of LandINS should make the opportunity of another communication soon.

Acknowledgment

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References

[1] J. Wang and C. Wilson, "Integration Challenge Safety at the wheel, Improving KGPS/INS Performance and Reliability", GPS World, May 2003.

[2] Alison K. Brown, Navsys Corp., "Test results of a GPS/inertial navigation system using a low cost MEMS IMU", Integrated Navigation Systems, 2004.

[3] M. Kais, P. Bonnifait, D. Bétaille and F. Peyret, "Development of Loosely-Coupled FOG/DGPS and FOG/RTK Systems for ADAS and a Methodology to Assess their Real-Time Performance", Intelligent Vehicles, 2005.

[4] D. Millescamps, M. Kais, B. Steux and M. Parent, "Time based framework for advance driving systems", European Congress SENSACT, 2005.

[5] D. Bétaille and Philippe Bonnifait, "Vehicles Modeling and Multi-Sensor Smoothing Techniques for Post-Processed Vehicles Localisation", ION (Institute of Navigation) GPS Annual Meeting, Portland, OR, September 2002