COMPARISON OF MULTIPLE IMUs IN AN EXPERIMENTAL FLIGHT TEST.

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Summary

GP-IMU-Bench experiment consists of simultaneous acquisition of data from multiple inertial units under the same dynamic and static conditions. To accomplish those conditions, all the sensors are fixed on a platform that is directly mounted into an airplane. This configuration permits all the inertial units to be able to sense the same movements. The aim of this experiment is to obtain a set of data that allows establishing some comparisons among the IMUs that the IG owns. The results of this experiment are very helpful to evaluate which is the best kind of IMU to be mounted on any remote sensor.
In order to get these datasets, a series of HW and SW modifications were applied on IG's TAG system for acquiring the data from the IMUs simultaneously. Therefore, this paper goes through these modifications made on the system with a more detailed description of the experiment. Some preliminary results of the comparison are shown.

1. Introduction

The Institute of Geomatics (IG) is involved in a large number of projects related with the geodesy and navigation. The integration and test evaluation of new instruments as can be IMUs, GPS receivers or another kind of sensors can be included among this type of projects. For such activities, the IG has its own acquisition system named TAG (Trajectory, Attitude and Gravimetry).

The TAG is an experimental HW/SW system that is composed of a series of functional modules: The Control Unit (CU) that is in charge of the acquisition, storage and processing of the data generated by the sensors; and the Power Unit (PU) which function is to feed the CU and the sensors. The CU is subdivided in a series of modules:

1 GNSS receivers control Unit (GCU) is the unit that manages the SW interface with the GPS receiver.
2 IMU Control Unit (ICU) is in charge of interfacing with the IMUs attached to the CU.
3 Time Synchronization Unit (TSU) is the reference time of the system. It is set up with the GPS time when the acquisition is started and registers the time when an event happens.

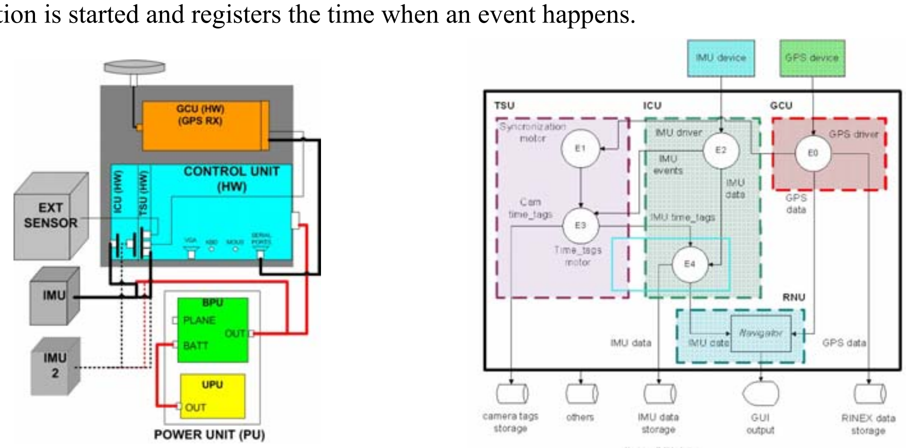


Image 1: Modular structure of the TAG for the HW (left) and the SW (right) [2].

4 Operation Interface Unit (OIU) function is to coordinate all the units described above and interacts with the user through a GUI or a FUI.

5 Real time Navigation Unit (RNU) collects the data generated by the GPS and the IMU through the GCU and the ICU and process them in order to obtain a trajectory that can be used by a device as a stabilized platform or a Flight Management System (FMS).

The PU is composed by the Basic Power Unit (BPU), that switches between an external power supply or a backup battery system; and the Uninterruptible Power Unit (UPU), that is a rechargeable battery system designed to operate with the BPU as an UPS.

The philosophy of this system is to have an experimental platform that is flexible enough to be adapted to the different needs that a project may require thanks to its modular design. That premise makes the TAG a system that is continuously evolving and changing its HW/SW configuration [1, 2].

One of these projects in which the TAG needs to be adapted to its requirements is the GP-IMU-Bench. This project has been funded by the former Spanish Ministry of Science and Technology as a complementary action to the EU project GeoPIE. This project consists of testing all the IMUs that the IG has in a common experiment. The inertial units are attached to the same structure (the bench) and then they are subjected to the same flight dynamics in order to obtain a comparative dataset for each IMU. This dataset is useful for characterizing the behaviour of the lower grade IMUs by comparing its dataset with the higher-grade IMU dataset that is assumed to have a behaviour that is easier to know. The aim of this project is the calibration of the statistical model of the automotive grade IMUs.

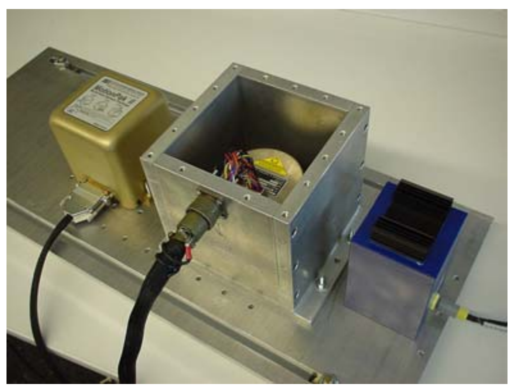


Image 2: IG's IMUs mounted on the bench.

Image 2 shows from left to right the Systron Donner Motion Pack 2, The Northrop Grumman LN-200 inside the protective housing and the iMAR iVRU-SKS-C167 [2].

Important HW and SW changes have been made on the TAG in order to be able to manage, acquire and store the data from the three IMUs. The first part of this paper focuses on the SW structure to support multiples IMUs of different behaviour and the performance of the multiple data acquisition in one HW.

2. Preliminary considerations about SW modelling of the system

It is not the aim of the paper to study in depth the SW engineering procedures used, but to present an understanding framework of how the system was designed and how the problems were solved. The development of a system in terms of SW is not only an engineering task but also a creative activity. The SW engineer must think about the problem and must find a set of solutions. When having this set of possible solutions, the next step is to choose the correct one according to the application.

The SW development of a system implies, in general, a preliminary analysis, a definition of the initial requirements, a design of the system, a design and the writing of the programs, different tests of the system and the maintenance of it. In fact, all of those steps have interrelations between them and most of them have a lot of feedback. As it has been told before, designing a system is to obtain a solution or a set of solutions from some initial requirements. Every design, independently of the type, has a grade of decomposition, thus the system is described as a group of modules or components. First of all, the high level design modules (general features of the system) are defined. Then, it is possible to work in the details of each module in depth. A good design is the one that is modular and has some abstraction levels, some identifying and treatment of the exceptions and some philosophy of predicting and tolerance to the errors. The SW architecture can be defined, using a simple definition, as a schema with modules and their interconnections.

Image 1 (right) shows the basic SW architecture of the TAG. From this basic configuration the modifications for the GP-IMU-Bench experiment were made. In this particular experiment, the system must acquire data from three inertial sensors simultaneously and from a GPS receiver. Some threads techniques and some synchronization objects are used to program the application. The GCU, the TSU and the RNU modules performs the same tasks as in the basic system architecture referred in [1] and [2]. The ICU module is different for every inertial sensor; they are three device drivers that control each sensor. This will be discussed later on the document.

In order to optimize the performance and efficiency of the system, the main requirement for each sensor is the acquisition rate: the IG's Northrop Grumman LN-200 data rate is 400 Hz, the Systron Donner Motion Pack 2 is set to 22 Hz and the iMAR iVRU-SKS-C167 is set to 50 Hz. On the first IMU, the data rate is set by the manufacturer and can not be changed. On the other two the rate can be configured by the user. Those values were chosen because the real time response obtained in the lab tests was good in terms of performance and efficiency [2].

2.1. The sensors

As mentioned before, the GP-IMU-Bench project has the aim of acquiring the data from multiple IMU's: a Northrop Grumman LN-200 unit, a Systron Donner Motion Pack 2 and an iMAR iVRU-SKS-C167 [1]. Every sensor has its own programming methods (device driver), functionalities and problems. It is important to remark that not only the device driver development is hard but also the synchronization effort.

2.1. The device drivers and its synchronization

A device driver is a software routine that provides an interface between the hardware and the operating system (OS). Every sensor has a different device driver that is programmed depending on the application. All the data acquired from the sensors are referred to the system base time that is set up in the TSU module (this is the result of the synchronization). As the target of the project is to make a comparative study of multiple sensors, time synchronization is critical and essential. The TAG includes an event timing controller card. This card is configured with the GPS time when the acquisition is started. When an event occurs in the system, the TSU records the time.

<u>Northrop Grumman LN-200 (LN200)</u>

The data acquisition from this sensor is done through a FASTCOM ESCC-PCI communication card. This is a specific HW associated to this IMU because the communication protocol used by it is the SDLC (*Synchronous Data Link Control*) / HDLC (*High-level Data Link Control*). This tactical grade sensor provides a TTL pulse (*End of Output Data Sampling*) that indicates when the data is received at the card port on the falling edge. In order to synchronize the sensor with respect the system base time, it incorporates an input of 100 Hz that is transmitted by the synchronization card.

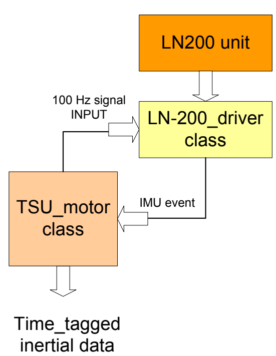


Image 3: LN200 ICU sub modules and their interaction with the TSU module.

Image 3 shows the configuration and interrelations between those sub modules or components. After the initialization of the system, the sensor starts sending data to the system. In that particular IMU, a 100Hz signal is sent to the sensor from the synchronization card. After that, the LN200_driver class manages all the data coming from the inertial sensor. When a raw data arrives to the component, it sends an event signal to the TSU_motor class (synchronization card) to mark the data time. Then, the output data is stored in a file and it may be processed in real time.

Systron Donner Motion Pack 2 (MPK2)

In contrast to the previous IMU, this unit performs all the communications cycle by using the RS-232 standard protocol. However, there is no synchronization signal available (from or toward the IMU) to use with it. Then, the philosophy of the data acquisition changes a little.

The serial port is programmed to send a command to the inertial unit to request some data, after that the sensor sends data and the application catches all that information. The next command it is not sent until the previous reading has been completed.

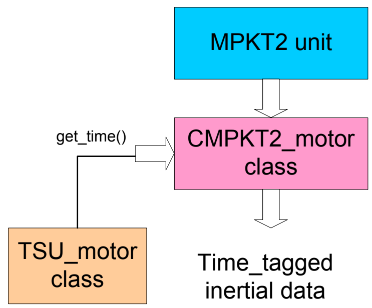


Image 4: MPK2 ICU sub modules and their interaction with the TSU module.

Image 4 shows the interrelation between the sub modules of the ICU written for that inertial sensor. Data transmitted by the inertial unit are managed by the CMPKT2_motor class, marked in time with the TSU_motor class and are also stored in files.

iMAR iVRU-SKS-C167 (SKS)

This inertial unit is configured via a serial interface RS-232 and the data acquisition is done through a CAN (*Controller Area Network*) bus [5][6] (a widely used protocol in the automotive industry). In the case of this IMU, an input/output system of synchronization signals is available. However, in order to evaluate the performance of the unit with low cost acquisition systems, these synchronization signals were not used in this test.

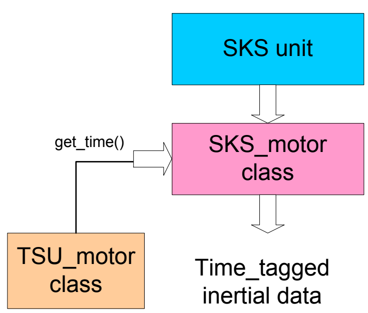


Image 5: SKS ICU sub modules and their interaction with the TSU module.

Image 5 shows, in a high level abstraction, how the inertial unit performs the synchronization task. The working mode in this case is very similar to the MPK2 IMU, but instead of using the RS-232 interface, data are read from the CAN-Bus card.

3. SW modelling of the system

The requirements of the system, as it was commented above, were defined in terms of performance and efficiency. Then when thinking about a solution, it is necessary to take into account some key issues.

The interaction of the system with the user must be minimal. Then it is imperative to have a good method to identify and treat the exceptions and some grade of tolerance to them. As the system can be also ready to integrate a real-time navigation core, the error control was designed to be, as far as possible, strict. It is common to have error sources coming, for example, from the system design, from an inadequate specification, from some interference in the HW devices, and so on.

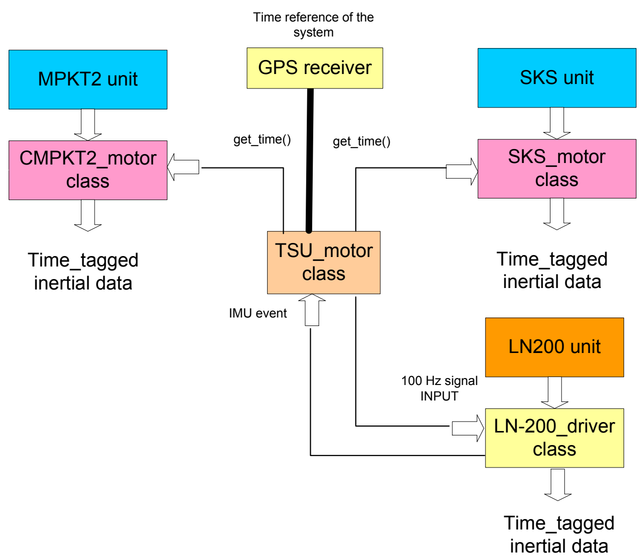


Image 6: Interconnection between the IMU modules.

Every class is controlled by a thread or a couple of threads, depending of the inertial unit. The SW architecture was designed to be implemented in a multithreaded platform, thus allowing concurrent processing.

The interconnections between the modules can be seen in Image 6. It has been added the GPS receiver module that serves as the time basis reference of the system to the synchronization card. RINEX data it is also stored in files for post processing procedures.

When the system first starts-up, a procedure sets the GPS time as the system time base and in order to avoid the clock drift and assure its stability, the PPS signal from the GPS receiver is used. After that step, all the ports are opened and properly initialized. Then the application could receive and process (if working in real time) data coming from the sensors.

Because of the current status of development of the system, the integration of multiple IMU modules was only done with two IMUs (the LN200 and the MPK2) and the integration of the other IMU module (the SKS) was done on a different acquisition system. However, it is expected to improve this performance by means the utilization of more elaborated programming techniques.

4. Flight experiment

In January of 2005, the GP-IMU-Bench flight test was conducted in the area of Sabadell airport. The aim was to test the performance of the inertial sensors as mentioned above. For that purpose, the IMUs were mounted on the bench that was fixed into the airplane, thus they could sense the same forces and turns.

Image 6: Vulcanair P68 Observer 2

Image 7: The TAG inside the airplane with batteries supply for the static data acquisition phase.

Image 6 shows the airplane used at the experiment: a Vulcanair P68 Observer 2 owned by the air services company Mission Air, which has its HQ in the Sabadell airport.

The TAG system was placed at the rear back of the airplane (image 7), where it was properly fixed. Before powering on the propellers of the airplane, there was a static data acquisition of 5 minutes. The same action was repeated after the landing. During the rest of the flight, the airplane supplied 24 volts to operate the TAG system. Battery supply was only used for the static acquisition phase.

At Image 8 it is shown how the IMU bench was installed into the airplane. The platform was put onto some shock vibration absorbers (see Image 14) and then fixed onto the seat rails.

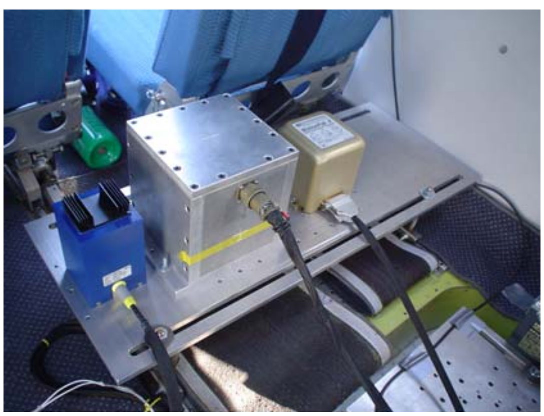


Image 8: The bench with the three IMUs fixed onto the floor rails.

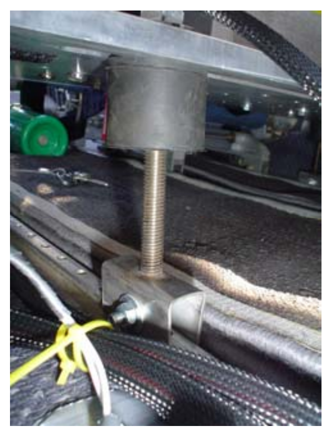
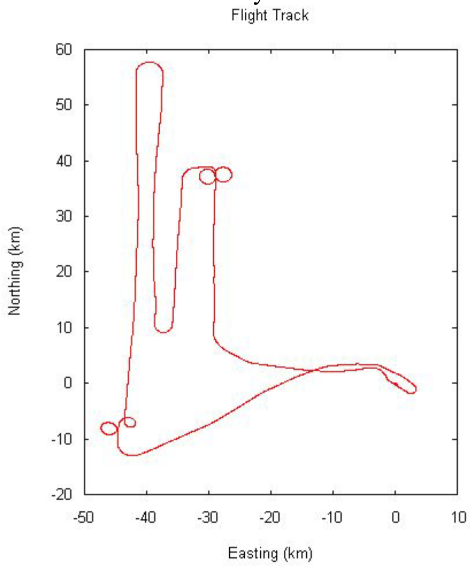


Image 9: Shock vibration absorbers detail.

Because of the current development status of the acquisition SW, the LN200 and the MPK2 were connected to the TAG, while the SKS was connected to an auxiliary acquisition system (used as reserve unit and that is the current prototype of the future mini TAG). By that reason the acquisition was done in two different machines. However this does not invalidates the data acquired in this way. In the results sections it is shown that in spite of being on different machines, the synchronization error is under some tenths of milliseconds that is good enough for the aim of this experiment.

The flight route covered by the airplane consisted of a series of increasing length parallel tracks running along North – South direction (see image 10). The aim of the tracks is to have an estimation of the heading error depending on the length of the track of a typical photogrammetric flight. Two calibrations loops were done during the flight in order to have a reference excitation to calibrate the heading gyro. The flight length was about 260 Km long and lasted about 75 minutes with a mean velocity of 120 knots.



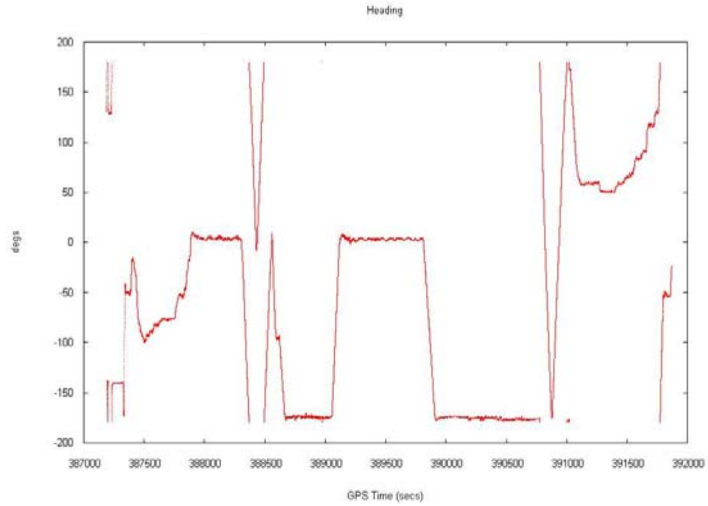
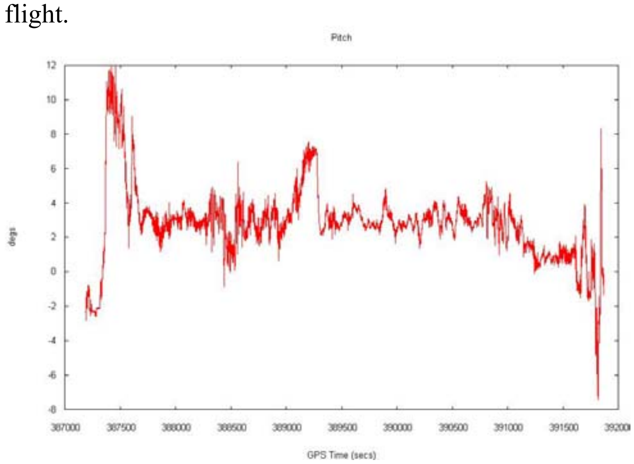


Image 10: Flight track – Easting (Km) - Northing (Km). Image 11: Heading angle.

The LN200 raw data was post-processed and some preliminary results are shown in the following images. Image 9 shows the heading angle, Image 8 the pitch angle and Image 10 the roll angle experimented by the LN200 during the flight.



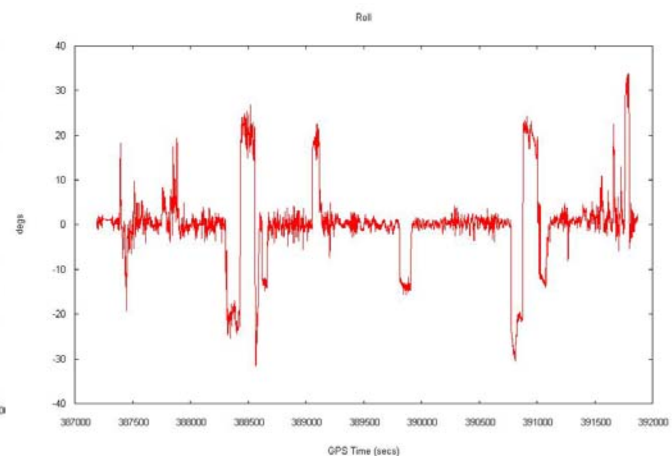


Image 12: Pitch angle. Image 13:, Roll angle.

5. Preliminary Results

5.1 Data Synchronization

First of all a qualitative analysis for each measurement of all IMUs was done. This qualitative analysis is useful to have a first view of the synchronization between the signals and compare their statistical behaviour (noise). A few samples of these signals can be seen in images 15 and 16.

For the gyros, the best comparison is made with *wz* signal. It can be seen that the synchronization is quite good (no delay is observed at first sight). Besides that, it is observed that the signal of the SKS is quite noisier than the other two. This is because the technology used in the LN200 is a FOG that produces little noise. Besides that, it is must be remarked that the signals from the MPK2 and the SKS are averaged.

For the accelerometers, the signal used to perform the comparison is *az*. The determination of the synchronization is not as good as for *wz*, but it can be noticed. It is also noticeable that the signals are noisier than in the case of *wz*. This noisy behaviour is more remarkable for the LN200, which also has an important quantization error.

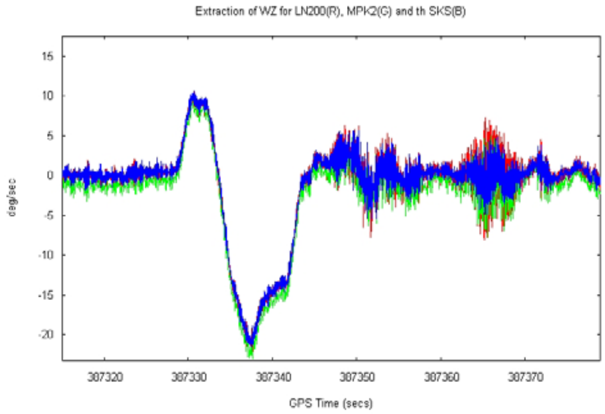


Image 15: Extraction of WZ.

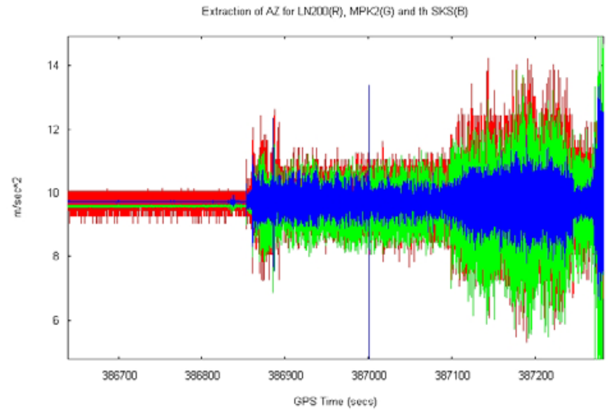


Image 16: Extraction of AZ.

A quantitative analysis of the delay between the signals of the LN200, the MPK2 and the SKS was also done (see Table 1). It is shown that the synchronization between them is quite good. In spite of having the SKS in a different machine from the LN200 and the MPK2 the delay is always below 40 milliseconds. This maximum delay is acceptable for the aims of this experiment.

	Delay (secs)		
Parameter	*LN200-MPK2*	*LN200-SKS*	*SKS-MPK2*
Wx	0.007667	0.041333	-0.032833
Wy	0.007833	0.040667	-0.027333
Wz	0.034667	0.041333	-0.025167
Ax	0.015500	0.037500	-0.022167
Ay	0.022000	0.037667	-0.017500
Az	0.000833	0.017833	-0.003667
Mean	**0.014750**	**0.036056**	**-0.021444**

Table 1: Relative delay between the different IMUs for each parameter and as a mean. The number represents the delay of the second IMU with respect the first for each column. So a negative sign means that the first IMU is delayed respect the second one. These numbers were computed by cross correlating the signal for each parameter in different intervals, and by averaging them.

5.2 Data acquisition performance

Performance is an important factor when having multiple devices working on the same equipment. The following statistics (table 2) shows the preliminary behaviour of every inertial sensor tested in the experiment. It is important to remark that those results are preliminary and a deeper study needs to be taken.

On Image 17, it can be observed that there are some loss of data on the LN200. This loss is equivalent to approximately less than 1% of the total data. On Table 2, it is that shown the frequency of the inertial unit, 395,69 Hz, and the performance is about 99.05 %. Relating to the MPK2, Image 18 shows the performance of the sensor. The equivalent rate is about 23.3 Hz and the performance is about 99.63% (see Table 2).

As it is comented above, the values resulting from the experiment are quite good, despite of the LN200 looses of data. Those looses are due to the current status of the multithreading environment executed under the specific operative system (OS). It is expected to improve these results with more depurated multithreading techniques and some specific processing algorithms (data filters).

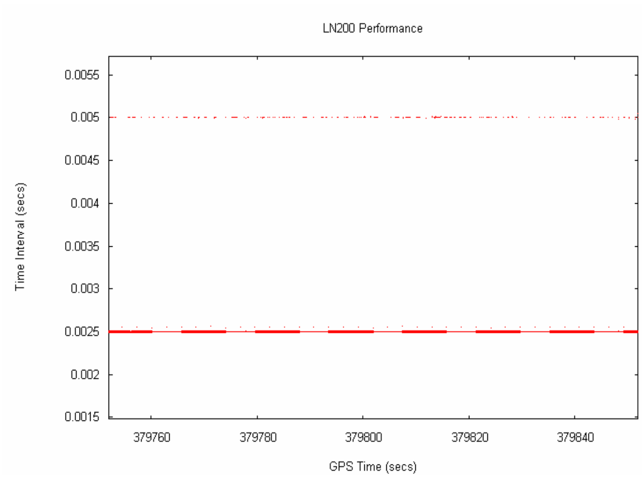


Image 17, LN200 acquisition performance.

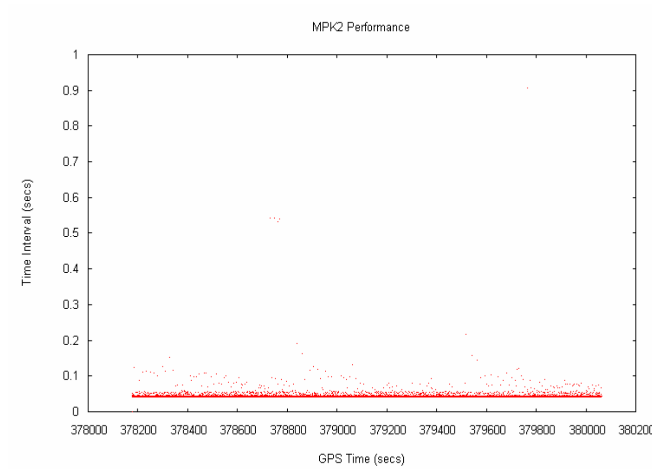


Image 18, MPK2 acquisition performance.

Parameter	*LN200*	*MPK2*	*SKS (Accel)*	*SKS (Gyro)*
Mean (sec)	0.0025313	0.042900	0.0199	0.01997
Std (sec)	0.00034881	0.0070564	0.002156	0.002535
Frequency (Hz)	395.69	23.310	50.074	50.075
Performance (%)	99.05	99.63	99.92	99.886

Table 2, Inertial sensors acquisition performance statistics.

Regarding the SKS IMU, the gyro and the accelerometer data were sent through different ports by the CAN bus. So, the time tag is different for the gyro data and the accelerometer data because the readings at each port in the bus are made at different times (the accelerometer data is transmitted just a few milliseconds after the gyro data). The performances of both channels are very similar between them (see Table 2 and Image 19), and the loss of data is very small. It also can be seen that the difference between the time tags of the gyros and the accelerometers, is one order of magnitude below the deltas of each group of measurements (see Image 20).

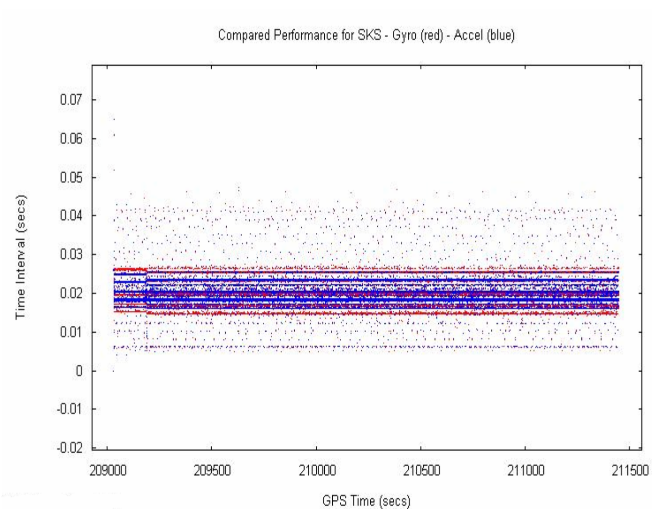


Image 19, Compared performance for SKS.

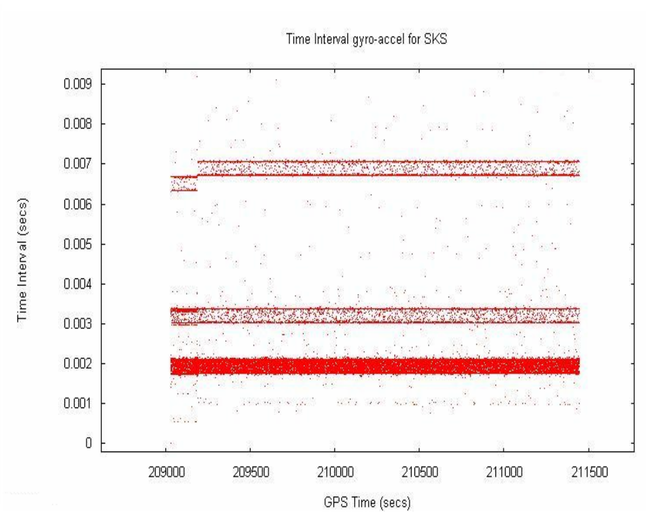


Image 20, Time interval gyro-accel for SKS.

Table 3 shows the mean and the standard deviation values of the interval between the accelerometers and the gyros of the SKS. It is observed that this value is one order of magnitude smaller than the theoretical time interval set for the SKS and the relative delay between the three IMUs.

Parameter	*Interval Accel - Gyro*
Mean (sec)	0.0024228
Std (sec)	0.00139

Table 3, Interval between accelerometer and gyro in the SKS.

6.Conclusions

To meet the aims of the GP-IMU-Bench experiment, the TAG has been adapted in order to acquire data simultaneously from different sensors. The adaptations made implied some HW and SW changes at different levels.

The results of the van experiment show that the data from the three IMU's are synchronized with an error of less than 40 msec, in spite of one of the IMU's is connected to a different machine, as commented before.

This little delay between the IMU's made the data suitable for deeper comparative studies of the parameters of the sensors and for the characterization of the low cost sensors. Those results are preliminary. More complete results will be published in the future.

Regarding to the performance of the data acquisition it can be seen that the loss of data is good enough for the objectives of the experiment. It is expected to improve the performance and to increase the number of sensors controlled by one machine with refined SW techniques and a new design of the SW architecture that will allow more processing capacity and a powerful application.

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