# IMPLEMENTATION OF A SKEWED-REDUNDANT LOW-COST INS IN A FAST-PROTOTYPING ENVIRONMENT

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## BIOGRAPHY

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## ABSTRACT

Low cost inertial navigation systems (INS) are of great interest and many approaches are currently investigated being to cope with their inherent inaccuracy. The approach undertaken in this paper relies on the use of redundant sensor information to enhance the global performance of the navigation system while ensuring the system's integrity. The skewed-redundant set of sensors is structured on a dual-tetraedron, consisting of 8 faces. In addition to the experimental results, this paper addresses the use of a rapid-prototyping approach to design the system integration algorithm and to perform the real-time processing.

The first results show that the structure is suitable to give accurate inertial information given the presence of an external source of information, e.g. GPS fixes. In the case of GPS outage, the navigation solution drifts and further calibration of error should be performed. This last issue is part of the ongoing research effort.

## 1. INTRODUCTION

For many years, low cost inertial navigation systems (INS) have been of interest and many approaches have been investigated in order to mitigate the poor performance of low cost sensors. Among the most common approaches, we can highlight the improvement of the sensor itself, as covered by Kourepenis (1998, 2003) ; the pre-filtering of the sensor outputs, as presented by El-Rabbany (2003) ; the on-line identification of errors and calibration – Leach (1999), Chen (2000), Hide (2002) ; the addition of external sensors - Abbott (1999), Sukkarieh (1999), Ladetto (2000), Grenon (2001), Cho (2003), Rios (2002), Caruso (2003), Kim (2003) ; and the use of a vehicle model to constrain the navigation solution – Koifman (1999), Eck (2000), Cannon (2001), Scherzinger (2003). However, one of the approaches covered by only a few people is the use of redundant low cost sensor information to enhance the global performance of the system while ensuring its integrity.

The area of redundancy management for INS is quite well documented, although most of the work has been done using expensive and accurate sensors. To the author's knowledge, Sukkarieh (1999) were the first to tackle the problem using low cost sensors. Recently, Ray (2002) and Allerton (2002) briefly analyzed the implication of low-cost sensors in the redundancy framework. However, no experimental results have been shown in any of their papers.

This paper address the real-time implementation of a low-cost skewed redundant INS based on a rapid prototyping approach. The first section of the paper presents the Inertial Measurement Unit (IMU) and the data acquisition scheme used in the experimental setup. Second, the navigation algorithm used to process the sensor output will be addressed, together with the fast prototyping environment. Experimental results from a High-Speed Vehicle will be discussed, and a conclusion will highlight the future work.

## 2. HARDWARE

### 2.1 Inertial Measurement Unit

The Tetrad IMU used for the experiment can be seen in Figure 1. The unit is made up of four accelerometers and four gyros, each set of measuring devices arranged in a tetrahedral configuration. The accelerometers used were the QLC 400, chosen for their highly stable bias characteristics over a wide range of operating temperatures. The gyros are British Aerospace Ceramic VSGs which were used due to their low cost, light-weight, small-size and low-power consumption. The specifications and noise characteristics of each of the sensors can be found in Sukkarieh (2000), as reproduced in Tables 1 and 2. The sensors are connected to one another on a truncated tetrahedron constructed from a hollowed block of aluminum.

The angular misalignment of each face of the block was measured in Sukkarieh (2000) using a co-ordinate measurement machine. Also located on the block are temperature sensors and small heating elements that can be used to control the temperature of the IMU. Due to the strong temperature dependence of the biases in the gyros, compensation can be used to maintain the temperature of the unit, keeping the bias drift within a small range.

**Figure 1: IMU and PC104**

**Table 1 – Specifications of British Aerospace Ceramic VSG Gyros**

| | | No.63371 | No.63363 | No.50093 | No.63352 |
|---|---|---|---|---|---|
| Range | °/s | ± 500 | ± 200 | ± 200 | ± 200 |
| Scale Factor | mV/°/s | | | | |
| temperature | +20 | 10.065 | 24.829 | 24.721 | 24.882 |
| | - 30 | 9.656 | 23.862 | 23.719 | 23.956 |
| | +60 | 9.585 | 23.574 | 23.240 | 23.647 |
| Linearity | °/s | | | | |
| temperature | +20 | 0.050 | 0.020 | 0.04 | 0.020 |
| | - 30 | - 0.300 | 0.040 | - 0.82 | - 0.060 |
| | +60 | 0.050 | 0.020 | - 0.08 | 0.040 |
| Bias | °/s | | | | |
| temperature | +20 | 0.041 | - 0.070 | - 0.013 | 0.028 |
| | - 30 | - 1.226 | - 0.912 | 0.04 | 1.241 |
| | +60 | 0.147 | - 0.893 | - 0.08 | 0.441 |
| Bias repeatability | °/s | | | | |
| temperature | +20 | 0.003 | 0.018 | 0.008 | 0.005 |

NOTE: The top row represents the model numbers of the individual sensors.

**Table 2 – Specification of the QLC 400 Accelerometers**

| | | BCAC064 | BCAC083 | BCAC07M | BCAC076N |
|---|---|---|---|---|---|
| Range | | Up to 20g | Up to 20g | Up to 20g | Up to 20g |
| Scale Factor | mA/g | 1.333 | 1.344 | 1.330 | 1.327 |
| Bias | mg | +0.3 | - 0.8 | +3.2 | +3.3 |
| Sensor axis misalignment | mrad | 1.39 | 0.68 | 1.65 | 1.65 |

NOTE: The top row represents the model numbers of the individual sensors.

## 2.2 Data Acquisition / Real-time Processing

Acquisition and processing of data received from the IMU is carried out by the PC104 computer stack as seen in Figure 1. The PC104 consists of five boards ; a 16-bit ADC card, video card, network card, DC-DC power supply module and a CoreModule/P5e using a Pentium 266 MHz processor. The ADC card is used to sample the IMU and temperature sensor measurements between 200 and 400 Hz; the bandwidth of the IMU being 70 Hz, thus avoiding aliasing. IMU data can be displayed via plots in real-time using an external monitor connected via the video card or can be transferred to a host computer for real-time or post processing via the Ethernet network card using a cross-over cable. The DC-DC power supply module receives power from a single 24V input and provides power to the IMU, processor, a floppy disk drive which is used to boot the PC104 and an external GPS receiver. Communication between the PC104 and the GPS receiver is over a serial connection.

An interface board has also been designed to connect to sensors to the acquisition board. This setup was necessary due to the output of the accelerometers being measured by current rather than voltage, the load resistor for the gyrometers, the amplifier stage for the temperature sensors and the DC-DC converter for the sensor's electrical power.

## 3. ALGORITHMS

The integration algorithm used for the processing of the data is developed in the Simulink environment. An earlier paper from Giroux (2003) explains the rationale of such a choice. Figure 2 shows a block diagram of the algorithm.

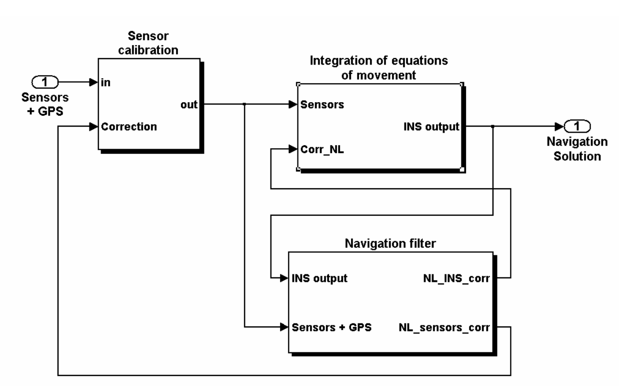


**Figure 2: INS/GPS navigation algorithm**

### 3.1 INS Integration Algorithm

As presented in Giroux (2003), the integration scheme is based on a high order continuous integration scheme, where a new integration block has been created to allow the feedback correction of the navigation solution. Figure 3 shows the dialog box of the new Simulink integration block.

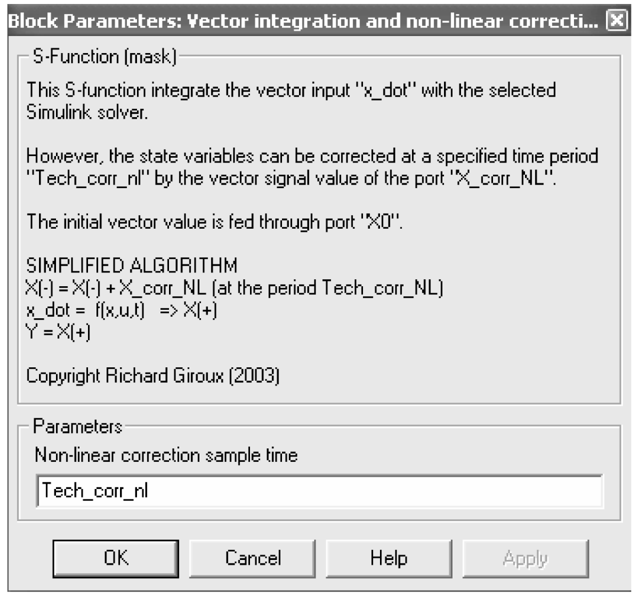


**Figure 3: Dialog box of the new integration block**

### 3.2 Error Model and Navigation Filter Implementation

As shown in Figure 4, the navigation filter is also developed in the Simulink environment and the control of the Kalman filter and the error are performed by a stateflow blockset.

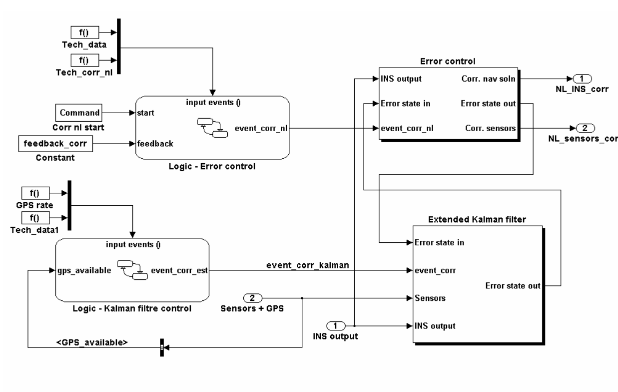


**Figure 4: Navigation filter**

Only one error model applied to the skewed-redundant INS/GPS system will be investigate in this paper. It consists of the standard $\psi$ error model containing 9 state variables.

$$\delta\dot{v}_N = S\left\{ {}^N C_B \left[ {}^I \hat{a}_B \right]_B \right\} \psi_N + {}^N C_B w_a \qquad 3.1$$

$$\delta \dot{r}_N = \delta v_N \qquad 3.2$$

$$\dot{\psi}_N = -{}^N C_B w_\omega \qquad 3.3$$

where S{ • } is the anti-symmetric matrix of the corresponding vector, $\lfloor {}^I \hat{a}_B \rfloor_B$ is the estimated acceleration along the three orthogonal axes based on the 4 skewed accelerometers, $\delta v_N$ is the velocity error in the navigation frame, $\delta r_N$ is the position error and $\psi_N$ is the vector of angular error, as commonly defined. Furthermore, $w_a$ and $w_\omega$ are the noise models of the velocity error propagation and the angular error propagation, respectively.

## 4. RESULTS

The experiments have been conducted using a high-speed vehicle, as shown in Figure 5. The IMU, PC104 and the GPS receiver were fixed in the back trunk of the vehicle as illustrated in Figure 6. The floppy disk drive was necessary due to the use of the conventional xPC Target real-time environment of MathWorks (instead of the option of using a flash disk as available in the complete version of the software). The inertial sensors were sampled at 200 Hz while the GPS fixes were obtained at a 2 Hz rate. Figure 7 shows the number of GPS satellites available to the receiver as a function of the experiment time.

**Figure 5: The High-Speed Vehicle**

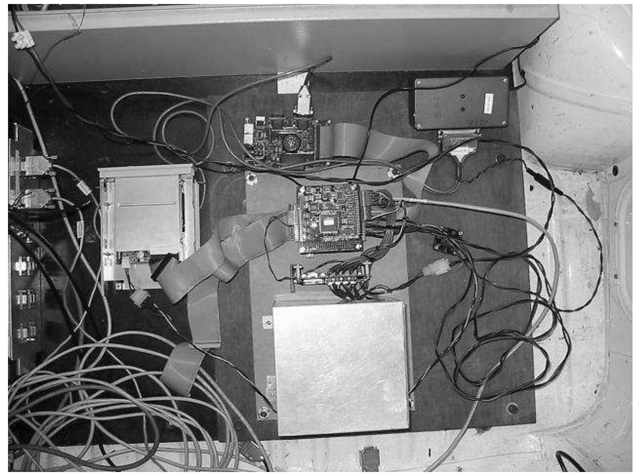

**Figure 6: Experimental setup**

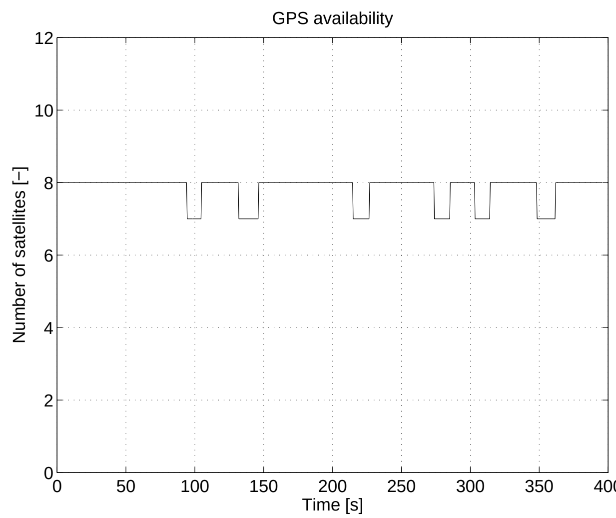


**Figure 7: Satellite coverage**

Figure 8 shows a bird's eye view of the trajectory of the vehicle while Figure 9 represents the vertical position of the vehicle as a function of time. The duration of the experiment is 6.5 minutes.

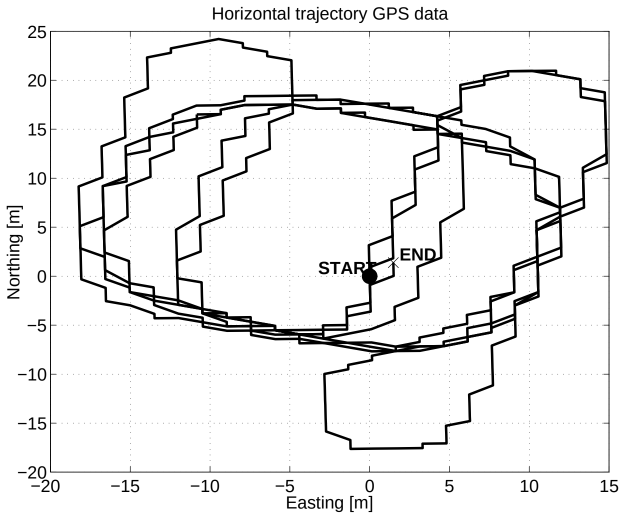


**Figure 8: Horizontal (bird's eye view) trajectory GPS**

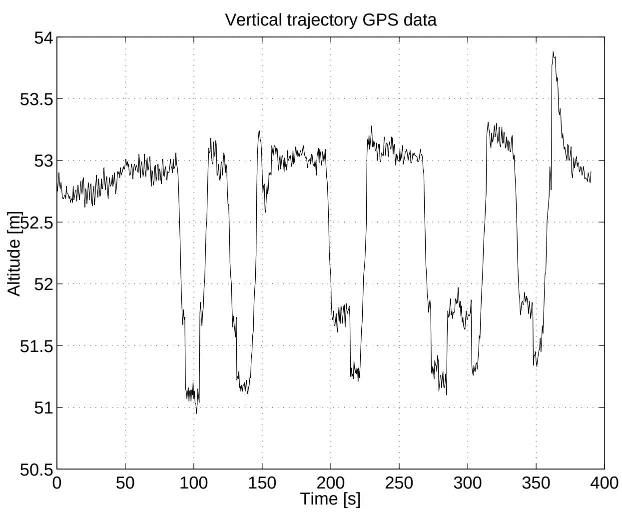


**Figure 9: Vertical trajectory GPS**

The angular rate measurements have been compensated for based on the bias read directly from the sensors at rest. The acceleration measurements are not compensated. Figures 10 and 11 show the orthogonal projection on the body axes of the redundant inertial sensor measurements. We can see that the noises in the gyrometers increase significantly when the vehicle starts moving, due to vibration.

Figure 12 illustrates the navigation solution of the INS/GPS fused system compared to a segment of the GPS solution. A zoom on this particular segment (Figure 13) shows the similarity between solutions. Figure 14 illustrates the altitude solution, whereas Figure 15 shows the error in the solution.

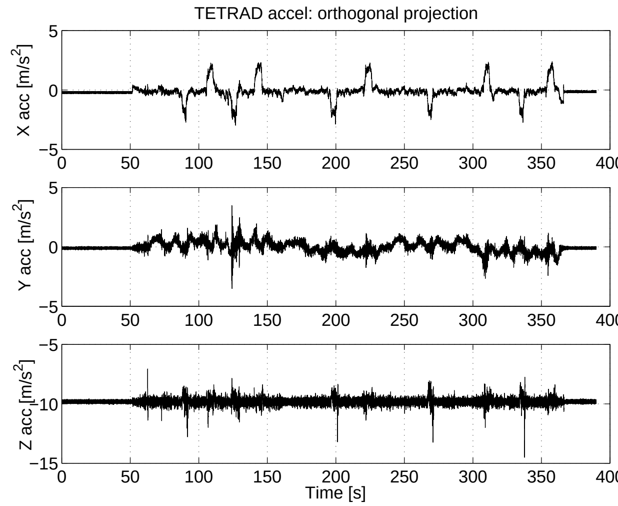


**Figure 10: Accelerometers orthogonal projection**

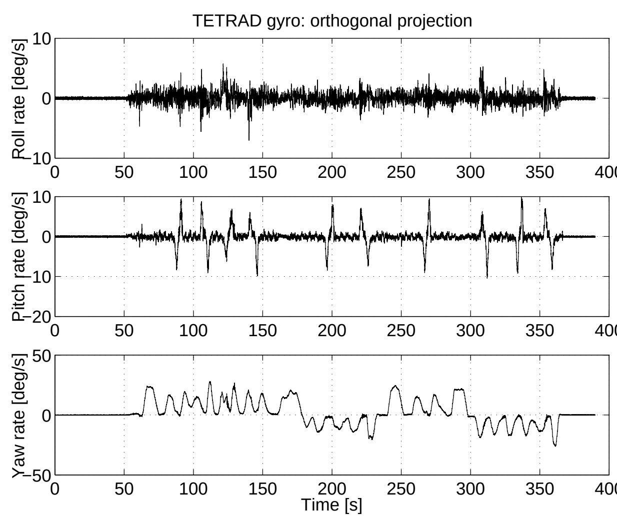


**Figure 11: Angular rate orthogonal projection**

The innovation sequence (Figure 16) of the navigation filter is mostly white noise, implying a well tuned filter. The previous figures have shown that the INS/GPS integration algorithm with redundant low-cost measurement works appropriately when GPS fixes are continuous.

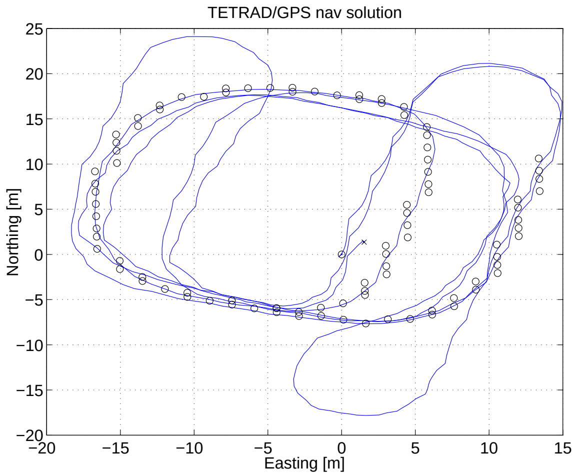


**Figure 12: Navigation solution INS/GPS**

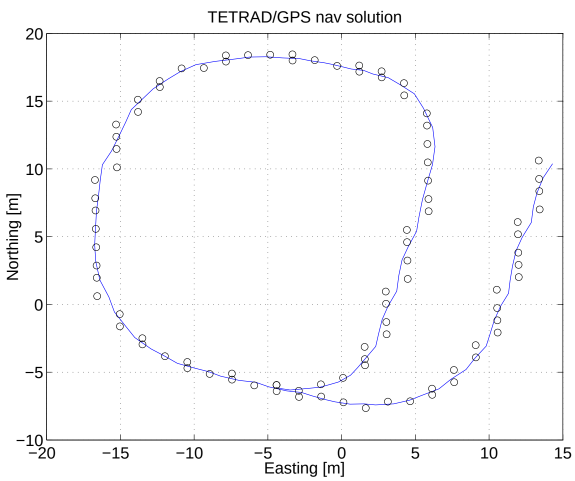


**Figure 13: Navigation solution INS/GPS (zoom)**

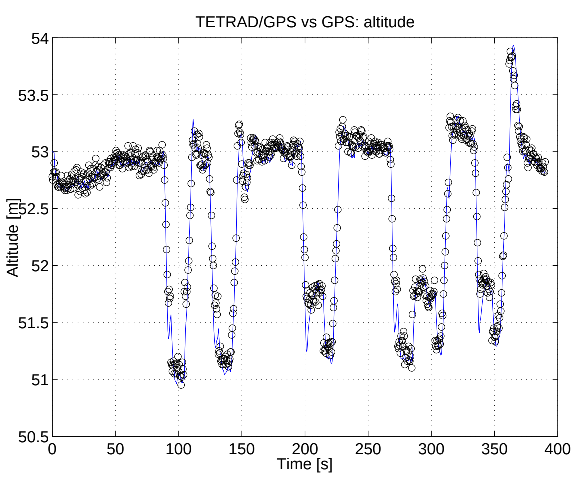


**Figure 14: Navigation solution INS/GPS (altitude)**

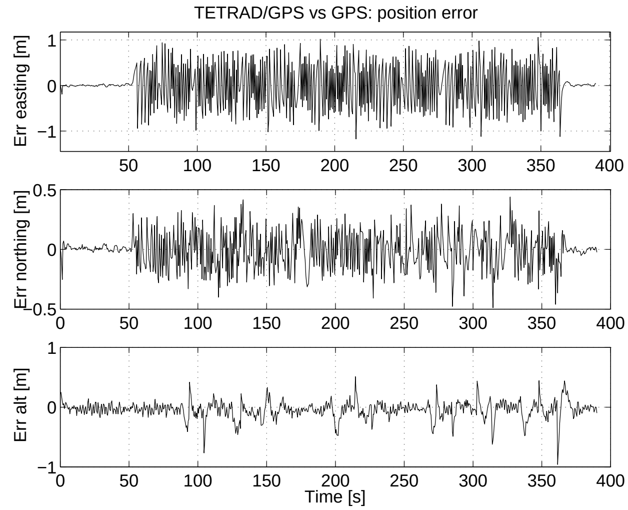


**Figure 15: Navigation solution INS/GPS (error)**

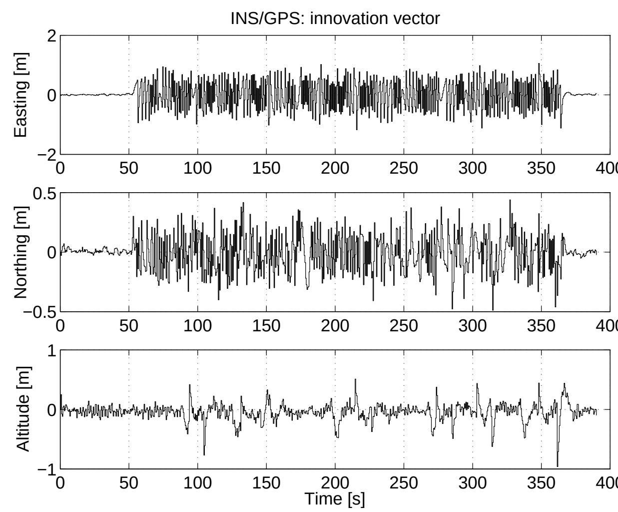


**Figure 16: Innovation (position)**

Figure 17 shows the response of the system to a simulated GPS outage, when the vehicle is turning. The outage is set to 15 seconds, starting at 160 s into the trajectory. The red circles represent GPS fixes that are not available to the INS/GPS integration algorithm. The inaccurate nature of the low-cost sensors makes navigation difficult without GPS fixes. Hence, calibration is a requirement of an accurate navigation system using the available sensors. Only the biases of the gyrometers have been compensated for fixed bias. Further error identification and online calibration should be accomplished in order to navigate without the need for external aiding for a longer period of time.

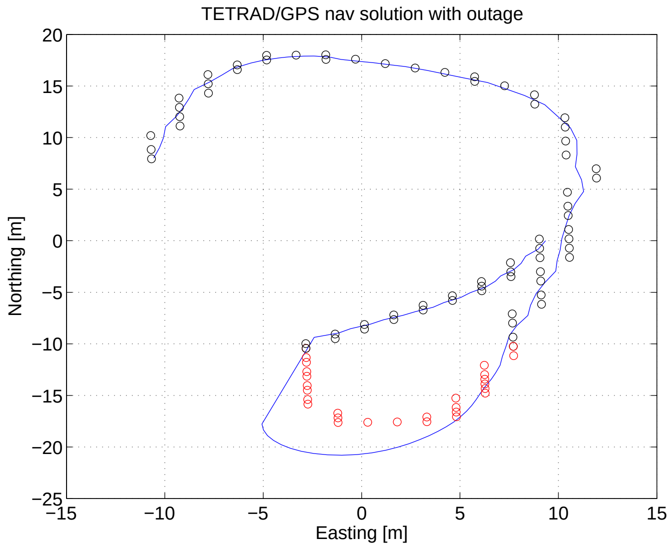


**Figure 17: GPS outage for 15 sec**

## 5. CONCLUSION

This paper has addressed the continuity of a research effort consisting of integrating redundant low-cost sensors into an autonomous navigation system. The rapid-prototyping approach chosen in the implementation has permitted the design of the algorithms and data acquisition scheme in an efficient manner and in a short development time period. It was highlighted that errors in the sensors should be identified and calibrated. To do so, different error models should be investigated, along with the observability issue of such configurations. This last point encompasses the ongoing research effort.


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