Biodiversity monitoring using UAV and 4D monitoring technologies: GeoSUB project.

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Abstract:

The use of Unmanned Aerial Vehicles (UAV) has increased in the last decade, using these technologies for many different topics, such as infrastructure inspection or biodiversity monitoring. The main advantages of these systems are its reduced cost and its ability to navigate on hard-accessible areas, what makes it possible to acquire aerial data with a reduced cost. The new technological developments and the progress in the definition of the regulations applicable to these vehicles have allowed the first BVLOS (Beyond Visual Line of Sight) operations to begin to be carried out at a professional level, which has meant a great advance for the UAV sector. In this field, Telespazio Ibérica SLU is leading a project called GEOSUB, which objective is the development of a UAV integral solution for biodiversity monitoring. The project has two main parts. The first one is the evolution and improvement of a fixed-wing and multicopter UAV, equipped with four different sensors: RGB camera, multispectral camera, thermographic camera, and a LiDAR sensor. The second part focused on the development of a geoinformation processing platform for both the mission planification and monitoring, and the data processing to obtain the final product. This work presents the preliminary results of the project and goes in depth with the developments made.

1. Introduction

In recent years, the use of UAV technology has increased, using these vehicles for many different purposes, such as Infrastructure Inspection and surveillance, biodiversity preservation and monitoring, precision agriculture, cartography or last mile delivery (Hassanalian and Abdelkefi, 2017). The technological advances made has increased its use, increasing fundamental parameters such as their flight endurance, robustness or autonomous navigation capabilities, making it possible to perform new kind of missions in a safe and efficient way.

The other fundamental aspect to consider is the regulations applicable to these vehicles. Globally, the major agencies responsible for the standardization of these vehicles, such as FAA (Federal Aviation Administration) in USA or EASA (European Aviation Safety Agency), have made a great progress in defining the applicable regulations, which historically was one of the main reasons why UAVs were not widely used. In both cases, the definition of this normative for UAVs is still in progress and made in collaboration with the main companies and public national and international agencies in the sector through different organizations, such as JARUS (Joint Authorities for Rulemaking on Unmanned Systems) or EUROCAE (European Organization for Civil Aviation Equipment), what is essential in order to define the safest possible normative taking into account the available technology.

Taking all this into account, the increase in the use of these vehicles for professional purposes can be explained. One example can be found in Spain, where AESA (Agencia Estatal de Seguridad Aérea), which is the NAA (National Aviation Authority) of Spain, has published a study where it is shown the increment of the UAV operators registered in Spain, where they show that in 2023 there were 94.033 registered operators, an increase of 32% over 2022 (AESA, 2024).

In this field, Telespazio Spa, and its extension in Spain, Telespazio Ibérica SLU, are making an important commitment to this sector, developing new technologies that help solve various current problems applying UAVs. Telespazio Ibérica SLU is leading a project called GEOSUB, within the Civil UAVs Initiative, impulsed by the autonomic Galician government through the Galician Innovation Agency (GAIN), Xunta de Galicia (Xunta de Galicia, 2022). GEOSUB is an ambitious project with a total public-private funding of 17.81 M€ that brings together a total of 10 companies and research centres, whose objective is the development of a UAV-based service for different monitoring tasks in Galicia (NW Spain). Within the project many different problematics are faced, such as the forest and coastal monitoring, detection of marine pollution, fire prevention and firefighting or inspection of linear infrastructures such as power lines. Whitin this service, the objective is to develop a 4D monitoring service, making it possible to obtain and process 3D data of large extensions, and also make multi-temporal acquisitions to implement 4D monitoring algorithms.

The project is divided in two main parts: aircraft and avionics systems development, and 4D monitoring algorithms implementation. Regarding the avionics systems and aircraft development, a fixed-wind UAV has been manufactured, with a wing-spam of 3m and a total MTOW (Maximum Take-Off Weight) of more than 25kg, which represent a challenging development. In the remote sensing part of the project, a mission planner has been developed in order to design, validate and execute the flight missions according to the specifications of each problematic, monitor the operation and also a post-process remote sensing software to process all the data taken during the flight to generate the final products, which basically are GIS products that contains all the information needed for supporting the end-user's decision-making.

This work presents the general aspects considered for the UAV and service improvement and goes more in deep with the development made during the project of a positioning solution based on GNSS (Global Navigation Satellite System) and INS (Inertial Navigation System) sensors to support the mission, both calculating the aircraft positioning and its integrity, and using this information to georeferencing the captured data. This positioning system is fundamental for the operation and must be specifically designed for this kind of missions: BVLOS missions with a total flight endurance of more than 6 hours and a distance from the GCS (Ground Control Station) of more than 40 km. Also, it has to be considered that no GCP (Ground Control Points) are going

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to be used in the final service, since the missions are going to cover large extensions, making it fundamental to obtain an accurate and robust position in other to implement correctly photogrammetric algorithms and point cloud reconstruction. Three main aspects have been considered for the development of this systems: current regulatory framework for this type of missions, characteristics of the areas where the system is going to fly (weather conditions, flight altitude, orography) that affect the efficiency of this type of system, and the state of the art of current navigation algorithms.

The positioning system developed uses as input the GNSS raw data from the GNSS sensors (ephemeris data, pseudorange, pseudorange rate, etc) and from the INS sensors (linear and angular accelerations) in order to calculate the attitude of the vehicle, implementing and Extended Kalman Filter (EKF)(Nemra and Aouf, 2010). It also implements different algorithms, such as multipath detection algorithms (Strode and Groves, 2016),to increase the accuracy of the GNSS sensor, and a RAIM (Receiver Autonomous Integrity Monitoring) algorithm (Imtiaz et al., 2019) to calculate the integrity of the calculated position solution, which is fundamental in large flights.

2. Regulatory framework

For the development of the navigation system, the regulatory framework is fundamental, since the system developed has to fulfil all the requirements defined in the regulation in order to make it possible to use it in the desired operation.

In Europe, the entity in charge of the regulatory definition that affects to all the European aerial traffic is EASA (European Aviation Safety Agency). This agency collaborates with different entities, such as EUROCAE (European Organization for Civil Aviation Equipment), JARUS (Joint Authorities for Rulemaking on Unmanned Systems) and all the National Aviation Authorities (NAA) of each country, such as AESA (Agencia Estatal de Seguridad Aérea) as the Spanish NAA.

The main objective of the development of the normative framework is to stablish the necessary conditions to ensure a minimum reliability and robustness of UAVs in aviation and to ensure the safe integration of UAVs in airspace, so that manned and unmanned aircrafts operate safely, to avoid collisions between drones and other aircraft and to mitigate the risk of drone traffic on ground.

In this field, the European Union has published the regulations 2019/947 and 2019/945, where three categories are defined depending on the level of risk of the operation, which are the open, specific and certified categories. The first one covers all the operations with a low operational risk and, as is defined in the regulatory framework, no operational authorisation or declaration by the UAS operator prior to flight is required. This category covers a large percentage of the operations carried out habitually. It is characterised by the fact that UAS shall weigh less than 25 kg and may or may not be class-marked or privately built. They shall not carry dangerous goods or drop items, and operations shall generally be VLOS (Visual Line of Sight), with a maximum altitude of 120m, maintaining a safe horizontal distance from people and not flying over any concentration of people not involved in the operation. This category is also divided in three different categories, which are A1, A2 and A3, depending on the associated risk of the operation.

The specific category covers all the other operations that are not covered in open category and that does not present a high risk (medium risk according to SORA 2.0). Within this category there are three ways to obtain the operational authorisation, which are: by responsible declaration under the conditions of a standard scenario (STS), by operational authorisation for operations described by a predefined risk assessment (PDRA) or after completion of a specific risk assessment (the so-called SORA process), or by holding a light UAS operator's certificate (LUC).

The Standard Scenarios (STS) were defined by EASA to facilitate the processing of certain operations that occur frequently but, due to their risk, cannot be classified as an open category. Within these standard scenarios, EASA defines the requirements that the operator has to fulfil in order to carry out a safe operation. Currently EASA has defined two different standard scenarios, STS-1 and STS-2. The first one (STS-1) covers the VLOS operations with a maximum height of 120m with a maximum distance between the UAV and the remote pilot of 100m, with a MTOW (Maximum Take Off Weight) of 10kg and the UAV must have a parachute. With this standard scenario, it is possible to flight near to people. The second standard scenario (STS-2) covers BVLOS (Beyond Visual Line of Sight) operations in sparsely populated areas, with a maximum distance between the UAV and the remote pilot of 1 km (2 km in the case of flight with ground observers). Also, the aircraft must have a maximum wingspan of 3 m and a maximum weight of 25 kg, as well as the means to programme its trajectory.

The PDRAs are risk assessment documents published by EASA that have to be completed by the UAV operator as if it were a guide or checklist. Then, the operator has to justify the evidence of compliance with the PDRA scenario and request the operational authorisation with the corresponding NAA. They are divided in two groups: PDRA G and PDRA S. The first group are not based on the standard scenarios meanwhile the second one is based on STS but with small changes.

Also, specific category covers all other medium risk operations (according to SORA 2.0) that are not covered by STSs or PDRAs. In this case, the UAV operator has to carry out a risk assessment of the operation, based on its characteristics and the UAS to be used, in order to classify it within a risk group. This risk assessment has to follow the guidelines defined in SORA 2.0 (Specific Operations Risk Assessment), that is a qualitative holistic method composed of ten steps, which objective is to evaluate the risks of the UAV operation and classify them in different risks levels, also known as SAIL (Specific Assurance Integrity Level), resulting from the combination of the ground risk (GRC), air risk (ARC), and the corresponding mitigations applied. There are six different SAIL levels, from SAIL I to SAIL VI, increasing the operational risk and therefore the safety requirements.

The certified category is the most restrictive one, making it mandatory the certification of the UAV by EASA and requiring validations similar to those for manned civil aviation. It covers operations carried out by vehicles with a characteristic dimension of 3 m or more that overflies concentrations of people, carry persons or dangerous materials, or operations with risks assessments that are considered too high to be considered within the specific category.

Within the GEOSUB project, a SORA analysis was carried out using the following operational specifications:

- Large range operations (40 km from GCS) beyond visual line of sight (BVLOS operations).
- The UAV used is a fixed wing with a wing spam ≤ 3m.
- The study areas are sparsely populated (<250ppl/km^2)

- Operational area: 50-100 km^2.
- Mission management through continuous follow-up and monitoring.
- Operations in favourable weather conditions.

Taking all this into account, the result of the SORA analysis classifies the desired operation into the **specific category, SAIL III**. Once the risk level is defined, SORA 2.0 defines the robustness of the Operation Safety Objectives (OSOs), which are a list of 24 requirements that all parties involved in the operation (operator, crew members, maintenance personnel, UAS, external services, etc.) have to comply in order to perform the operation. The level of robustness can be optional, low, medium, or high, and as the level of robustness increases, new and more complex compliance measures are added.

Focusing on the development of the positioning system, many of these OSOs must be taken into account in order to meet all the requirements for the system to be used in SAIL III operations, but the main ones are OSO#05 (*UAS is designed considering system safety and reliability*), OSO#13 (*External services supporting UAS operations are adequate for the operation*) and OSO#24 (*UAS is designed and qualified for adverse environmental conditions*).

The objective of the OSO#05 is to ensure that the equipment, systems and facilities are designed to minimise risks in the event of a malfunctioning or failure of the UAS. In this case, for SAIL III it is not mandatory to carry out a software or hardware certification of the safety critical systems, according to the DO-178 and DO-254 respectively, but a functional risk assessment and a design and installation assessment is needed that shows hazards are minimised. A risk assessment and its mitigations must also be carried out, which can be evaluated by EASA according to acceptable standards, mainly following the ED-280 standard.

OSO#24 is focused on the environmental conditions, and it defines the procedures and environmental test criteria for testing airborne equipment, mainly focused on hardware. It follows the standard DO-160G and the operator is responsible of defining the design assurance level (DAL), from DAL A to DAL E and the applicable fields (humidity, vibration, temperature, temperature variation, sand and dust, etc), depending on the expected weather conditions of the operation and the risk level.

Finally, OSO#13 is focused on ensure that the external services supporting the UAV operation are adequate for the operation. EASA defines *external service* as any service given from an external company or public organization to the UAV operator that is needed to ensure the safety of the operation. In this field, the operator has first to identify the external services for its operation depending on the UAV architecture and the operation specifications. Typically, some of these external services are mobile phone communications (4G or 5G) for the communication between the GCS and the UAV, or GNSS positioning, that uses data from different service providers through their satellite constellations (GPS, Galileo, etc). The UAV operator has to ensure that the level of performance of all the external services is adequate for the operation to be carried out and demonstrate it to the NAA. To do this, the UAV operator has to first define the level of performance needed, identifying the key parameters indicators, or KPIs, that will vary depending on the specific service. Then, the operator has to define the level of performance of the external service needed for a safe operation, using the KPIs. Also, the UAV operator has to ensure an effective communication with the service provider and define the roles and responsibilities. For those external services that are safety critical, the UAV operator has also to define the means of monitoring to ensure that the external service has the performance level needed during the entire operation and define the appropriate actions in case of deterioration of the performance. Finally, in order to obtain the operational authorisation, the UAV operator has to generate evidence, that the external services fulfil all the requirements described before.

The GNSS service is a special case, since the service does not give the UAV its position directly, but provides a series of satellite signals from which the GNSS receiver calculates the position of the system. Therefore, it is hard to evaluate the performance of the service itself, since the accuracy, integrity and other key performance indicators (KPIs) that the UAV operator has to evaluate depends both on the external service and the sensor used. The definition of the minimum performance is done taking into account basically the operative volumes (flight geography and contingency volume) and the contingencies of the operation. For this service, the KPIs identified are:

- **Accuracy**, also know as the Navigation System Error (NSE), divided in two components (vertical and horizontal).
- **Service availability**. The service is defined available when there is enough GNSS information for the receptor on-board to calculate its position. It is divided into two parts: space signal availability (SiS) and GNSS positioning availability.
- **Positioning integrity** defined as the confidence on the positioning and/or a positioning error limit. There are multiple complementary forms to calculate this integrity, such as DOP (Dilution of Precision), number of satellites in view, failure detection, among others.

The regulation for specific operation above SAIL III (SAIL IV to SAIL VI) is not defined yet, but looking at the trend that the regulation is following, as the risk levels increase, so do the requirements related to service availability and integrity. It can be expected that for missions with a risk higher than SAIL III, both the certification of equipment according to the above-mentioned standards and the implementation of integrity algorithms will be mandatory, as is for flight critical systems in manned aircraft.

3. Navigation system

Taking into account the previous section and the mission requirements, the priority in the positioning system is the integrity and robustness of the system, and then the accuracy on the positioning. Also, as the UAV is going to navigate on spare populated areas, so communication with sufficient bandwidth will not be available to send both telemetry data necessary for the safety of the operation and receive data from ground augmentation systems, such as RTK (Real Time Kinematic) corrections. In addition, due to integrity and service availability requirements, the system cannot rely on signals that may lose connection without warning, as is often the case with RTK corrections. Therefore, only satellite data from the constellations in view (GPS, Galileo, Glonass and BeiDou) and from satellite augmentation systems (WAAS, EGNOS) may be used. For the GNSS sensor, a Septentrio Mosaic-X5 was selected. It is a multi-frequency multi-constellation GNSS receiver which also incorporates satellite SBAS corrections.

Also, to improve both the positioning accuracy and its integrity, the positioning system also integrates a IMU (Inertial Measurement Unit). In this case, the VectorNav VN-100 sensor has been selected, which combines 3-axis accelerometers, gyroscopes and magnetometers, and a barometric pressure sensor.

As part of the OSO#05 requirements, the system has to be reliable both at software and hardware level. To comply at the hardware level, the system was designed with sensor redundancy, meaning that both the GNSS receiver and the IMU sensor were duplicated on the system.

Of course, the navigation system also needs a CPU to process all the data received by the sensors, to calculate the final PVT solution and embed all this data into the MAVLink (Micro Aerial Vehicle Link) protocol to be communicated to the autopilot.

With all these requirements, the navigation algorithms were developed. Figure *1* shows the software architecture of the system. It is composed by 4 basic blocks, which are: Filtering and correction algorithms, redundancy filter algorithms, RAIM algorithm and finally an Extended Kalman filter algorithm. As can be seen, the system has three filtering blocks to improve the robustness and accuracy of the system and an integrity calculation block, which makes the final solution robust and also generates integrity calculations for the UAV operator to continuously monitor the availability of the positioning and its level of performance.

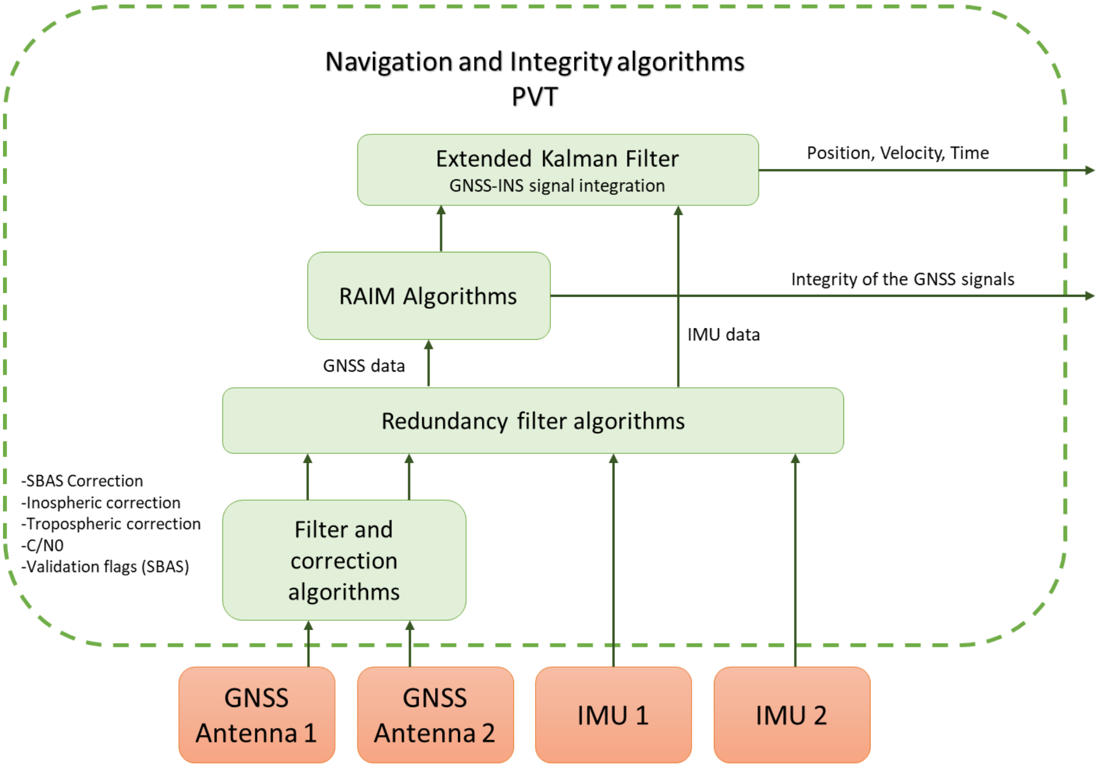

Figure 1:Software architecture of the navigation algorithms.

3.1 Filtering and correction algorithms

This block contains all the algorithms for the GNSS signal filtering and correction, and also the position calculation using this data. The first filter applied is the Ionospheric and tropospheric correction. The first one objective is to eliminate the delay produced during the signal travelling through the ionosphere. As was said before, in the project a multifrequency GNSS receiver is used, so in order to mitigate this error a Inosphere-free combination for dual frequency receivers is used, which basically uses both signals of each satellite (i.e. L1 and L2 for GPS satellites) to eliminate this error (Eq. 1).

$$\Phi_{iono-free} = \frac{f_1^2\,\Phi_{L1} - f_2^2\,\Phi_{L2}}{f_1^2 - f_2^2} \qquad (1)$$

Where:

- Φ_L is the carrier-phase of each signal.
- f is the frequency of each signal
- $\Phi_{iono-free}$ is the Ionosphere free carrier-phase.

In contrast to the ionospheric error, the tropospheric error (also known as the Tropospheric delay) cannot be eliminated using a combination of signals with different frequency. This delay has two main components: hydrostatic component delay and the wet component delay. The first one is caused by the dry gases present on the troposphere, while the second one is caused by the water vapour and condensed water in form of clouds, thence, it depends on the weather conditions, so it is hard to be parametrized. The component which causes the greatest delay is the hydrostatic component. In order to correct the measurements, different approaches or models have been proposed. In this case the model proposed by Collins (Collins, 1999) was applied. Eq. 2 shows how the tropospheric error can be calculated and mitigated.

$$T_r = \int (n-1) dl = 10^{-6} \int N\, dl \qquad (2)$$

Where:

- n is the refractive index of air.
- $N = 10^{-6}\,(n-1)$ is the refractivity.

Other important parameter that has to be considered is the C/N0, which is the equivalent carrier to noise ratio. This parameter is used for measuring the degradation of a desired signal. This can be caused by either the background noise where all the non GNSS signals are included or by another interfering signal of the same or similar nature. This is a parameter that is calculated for each single one of the signals of each (i.e. L1 and L2 in GPS). So, each individual signal has associated a C/N0 value, and it is transmitted to the GNSS receiver. In order to filter those signals with high noise levels, a simple threshold filter has been implemented, so those signals which C/N0 value is higher than the defined threshold are discarded. The value of the threshold depends on the frequency of the signal, so it depends on the specific signal of each constellation.

The system also receives SBAS signals, which basically contains two main data groups, one with information about the state of each satellite (in order to discard those satellites that are not functioning well) and data with the corrected ephemeris data, that is used to improve the accuracy on the satellite positioning, resulting then in a better accuracy of the receiver positioning.

Once the signals are corrected and filtered, discarding those satellites or signals that are not valid, the system calculates the position of the receiver. Before calculating the receiver position, the system calculates the position of each satellite. This is done using the ephemeris data transmitted by each satellite and using the equations facilitated by each constellation operator on the documentation of the system (GPS, n.d.).This is done by means of many equations and parameters which are reflected in these documents and will therefore not be introduced in this paper. Each specific constellation has specific equations, although in the case of GPS, Galileo and BeiDou they are similar, changing small aspects. Glonass, on the other hand, differs both in the ephemeris data and in the calculation of the satellite position. Once the satellite positions are calculated and the pseudorange data is corrected, a least squares algorithm is used in order to calculate the receiver position, using an iterative algorithm in order to reduce the positioning error, reaching the best position solution.

3.2 Redundancy filter algorithm

As was mentioned before, the system was equipped with two GNSS receivers and two IMU sensors. The main objective with this hardware design is to achieve a robust system. If any of the sensors malfunction, either by failing to provide data or by providing erroneous data, the system shall be able to detect it and use the data from the sensor that is functioning correctly.

To do this, an algorithm has been developed that compares the sensor output with the dynamics calculated in the Kalman Filter that will be discussed later. In this way, if a large difference is detected between the sensor output and the expected output, it is compared with the output of the other sensor. If both signals show a large difference, defined by a threshold, the sensor is labelled as faulty and the other sensor is used.

This algorithm and the designed hardware with redundancy on the sensors is used in order to fulfil the requirements of the OSO#05 explained before. There are different ways to fulfil its requirements, but redundancy is the most common way.

3.3 RAIM Algorithm

As was mentioned on section 2. Regulatory framework, for medium or high risk operations, the integrity of the safety critical systems is important. Taking this into account, it is mandatory to calculate the integrity of the PVT solution calculated. In this case, this is done in two steps. First, a RAIM (Receiver Autonomous Integrity Monitoring) algorithm was implemented, which is able to calculate the integrity of the positioning calculated just by the GNSS sensor. As the second step, an Extended Kalman Filter was implemented, which is not really an integrity monitoring algorithm, but it also calculates the estimated error of the PVT final solution, after the GNSS/IMU integration within the Kalman Filter.

The RAIM algorithm is a tool that allow us to measure the integrity of the signals of each one of the satellites used. In this way, it allows us to detect and discard the non-valid signals, signals affected by multipath or any other error over the pseudorange measurement. Typically, RAIM algorithms can be divided in two types, on the one hand we have the RAIM FD (Failure Detection), which basically "measure" the error contained in the signal of each of the satellites to calculate the integrity of the calculated position, and a second option, the RAIM FDE (Failure Detection and Exclusion), where not only this integrity is calculated, but also those satellites whose signal is not valid are discarded, thus increasing the integrity of the signal and the accuracy of the calculated position. A RAIM FDE algorithm was implemented on the navigation system developed (Figure *2*).

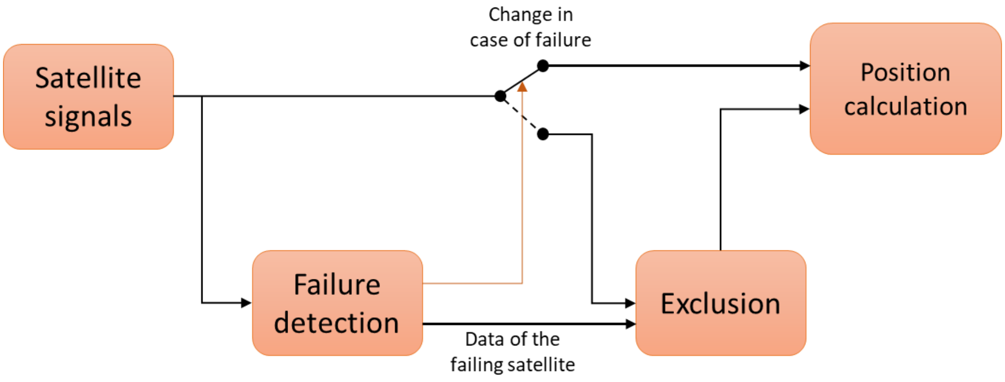

Figure 2: RAIM FDE architecture.

3.4 Extended Kalman Filter

At this point, the data from the GNSS receiver and IMU sensor have been processed and filtered, so the last step to calculate PVT solution is to integrate both signals. This integration between different sensors is done through an Extended Kalman Filter. The main objectives of the implementation are:

- Integrate the measurement of both sensors on a single PVT solution, optimising the final solution.
- Have a second level of integrity in the PVT output.
- Calculate an estimation of the future behaviour of the system, that is used on the redundancy filter algorithm.

During the EKF algorithm implementation, two possible configurations of this algorithm were considered, which are loosely coupled and tightly coupled solutions.

In a loosely coupled architecture, the inputs for the EKF algorithms are the position and velocity calculated using the GNSS receiver and the accelerometer and gyroscope data from the IMU sensor. Meanwhile, in a tightly coupled architecture the inputs from the GNSS receiver are the pseudoranges and the pseudoranges rates. Tightly coupled EKF use to be better in terms of accuracy and robustness than the loosely coupled solution, but is more complex and harder to implement. On the other hand, loosely coupled solutions are more adaptable to be integrated with other positioning systems, such as SLAM (Simultaneous Localization and Mapping) algorithms or with visual odometry solutions. Also, the inputs from the GNSS receiver for the tightly coupled are the pseudoranges and pseudoranges rates instead of the calculated position, so the first level of integrity given by the RAIM algorithms is not used and, therefore, not valid. Taking all this into account, the EKF algorithm implemented uses a loosely coupled architecture (Figure *3*).

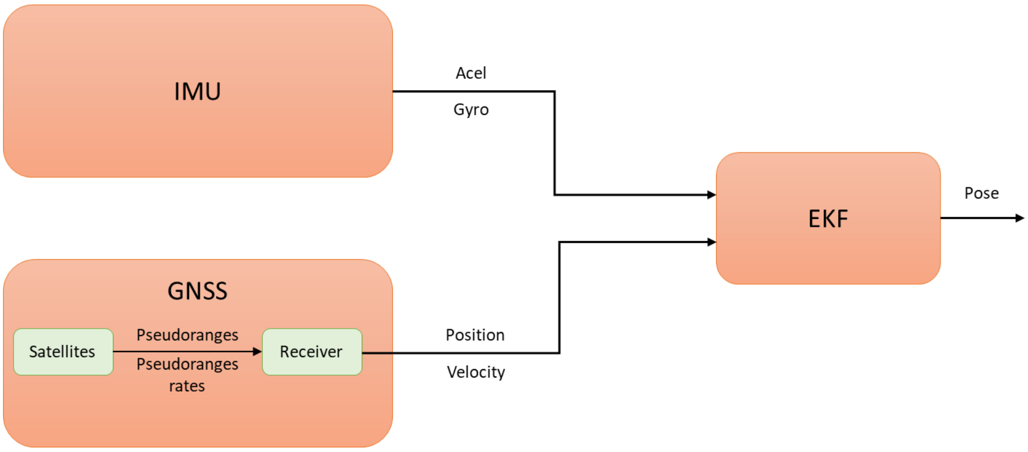

Figure 3: Loosely coupled EKF architecture.

With all these implementations, the mean position error achieved was around 3-4m depending on different factor such as the weather conditions, the obstacles of the environment, the number of satellites in view, among others.

4. Conclusions

This work presents the positioning system developed within the GEOSUB project for SAIL III UAV operations. In this category, as have been showed in section 2. Regulatory framework, the safety critical systems have to fulfil some strong requirements to ensure the integrity of the final solution. With the hardware and software architecture presented, with sensor's redundancy and two levels for integrity calculation, the system developed fulfil these requirements, so it can be used for SAIL III operations.

As future work, the system is going to be certified according to standards DO-178 (software) and DO-254 (hardware), making the system also comply with SAIL IV requirements. Also, the positioning system can be hybridized with other positioning systems based on visual odometry or SLAM algorithms using LiDAR sensors.

Acknowledgments

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