A multi-antenna approach for UAV's attitude determination

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Abstract—**Nowadays, one of the major limits of Unmanned Aerial Vehicles (UAV) is the set of low cost navigator sensors installed on them. They are vulnerable to vibration, high acceleration, high rotation and jerk. Furthermore, magnetometers drift significantly when located close to engines, to electromechanical devices or in areas with strong magnetic fields (for example grid power lines). This document describes an innovative approach using multi GNSS receivers for UAV's attitude determination.**

Keywords—heading, attitude determination, GNSS, accurate positioning, unmanned vehicle control.

I. INTRODUCTION

The GINSEC (Enhanced GNSS-BF-INS Solution for Unmanned Vehicle Control) project aims to design a low-cost, accurate and reliable navigation system for professional (Unmanned Aerial Vehicle) UAV civilian market pre-commercial prototype. The sensors currently installed on UAVs, like inertial sensors, Global Navigation Satellite System (GNSS) receiver and magnetometers, do not always provide with an accurate orientation.

An Inertial Navigation System (INS) is a device that measures and reports the aircraft's velocity and orientation, using a combination of accelerometers and gyroscopes. Low-cost INS use magnetometers to help the determination of the orientation. Traditionally inertial sensors have been used on aircraft to estimate position and orientation in combination with barometers and navigational aids as Very High Frequency Omnidirectional Radio Range (VOR) or Non-Directional Beacons (NDB). More recently, GNSS was incorporated.

GNSS is a constellation of satellites that provide signals on global coverage from space transmitting positioning and timing data. The USA NAVSTAR Global Positioning System (GPS) and Russia's GLObal NAvigation Satellite System (GLONASS) are examples of it. GNSS signals are coming from a 24 satellites constellation orbiting on 6 orbital planes at more than 20.000 km, with two orbits/day.

GNSS, when employed in Differential GNSS (DGNSS) mode, may be used to estimate the three attitude parameters: heading (yaw), pitch, and row. Heading and pitch can be adequately determined using two GNSS antennas. This is similar in theory to the determination of azimuth and elevation in a local coordinate system using relative positioning. Attitude determination is essential for a wide range of navigation, guidance and control tasks.

High quality sensors are expensive and power demanding. The low-cost implementations of these are also vulnerable to vibration, high acceleration, high rotation and jerk. Furthermore, magnetometers used by low-cost IMUs drift significantly when located close to engines, the system is close to electromechanical devices or areas with strong magnetic fields (for example grid power lines); in these cases, the UAV cannot be controlled and crashes down.

Multi-antenna radio tracking and GNSS/Ranging and Integrity Monitoring Stations (GNSS/RINS) techniques, able to provide the necessary parameters with accuracy during the flight, may overcome this problem.

This paper will focus on this multi-antenna component of GINSEC.

II. STATE OF THE ART OF ACTUAL NAVIGATION SYSTEMS AND NEW PERSPECTIVES

The main objective is to implement new ideas and techniques to solve problems in the drones currently present on the market. The solutions has to be a navigation system with size, weight and especially price compatible with the drone market.

One of the problems mentioned above it is the magnetometer, which could cause loss of flight control of the UAV if a strong magnetic field interferes with it. The idea is to control the flight direction through antennas that will be installed directly on the UAV. In that case the antennas interact with the GPS satellites and they are not affected by problems of magnetic fields: the UAV can flight in security conditions (fig. 1). Using three antennas it is possible to determinate all the movements of the drone (yaw, roll, pitch), but since we only need to replace the magnetometer (to know the heading), two antennas are sufficient.

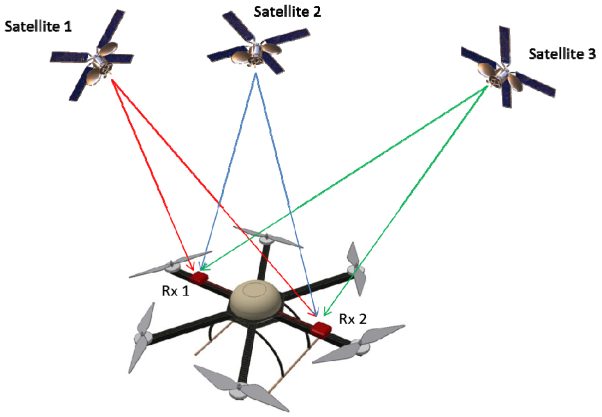

Fig. 1. Short baseline antennas installed on the UAV to estimate the orientation.

At the state of the art, the angular accuracy that could be obtained for the heading (yaw), it is about 2-10 degrees (it depends on the class of the sensor used). An accuracy of 5 degrees or less is the goal to achieve; 1 deg would be the best, but it is not a strictly requirement.

III. THE MULTIANTENNA APPROACH FOR ATTITUDE DETERMINATION

Each GNSS satellite broadcasts a sine wave carrier signal, characterized by a certain phase. At the time of reception, the signal is received by the antenna with another phase but we cannot measure directly the integer number of wavelengths between the satellite and the receiver during the travel time of the signal. This quantity is called «integer ambiguity» (fig. 2). The real ambiguity value is a sum of integer ambiguity and uncalibrated phase delay originating in the satellite and the receiver. Because of that, only the differential positioning between two or more receivers can allow fixing the problem.

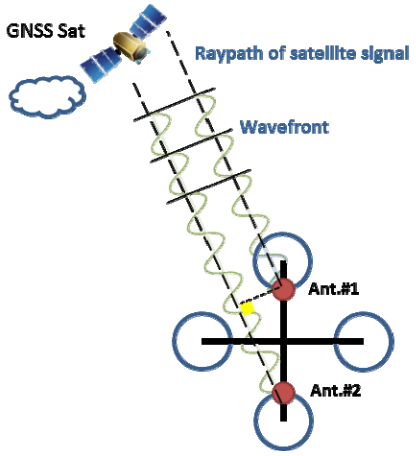

Fig. 2. Receiving waveform from two separated antennas.

By mean of GNSS carrier phase analysis, the heading determination uses two receivers with separated antennas by a given short baseline to estimate the drone orientation. The multi-antenna schematic block is reported in fig. 3.

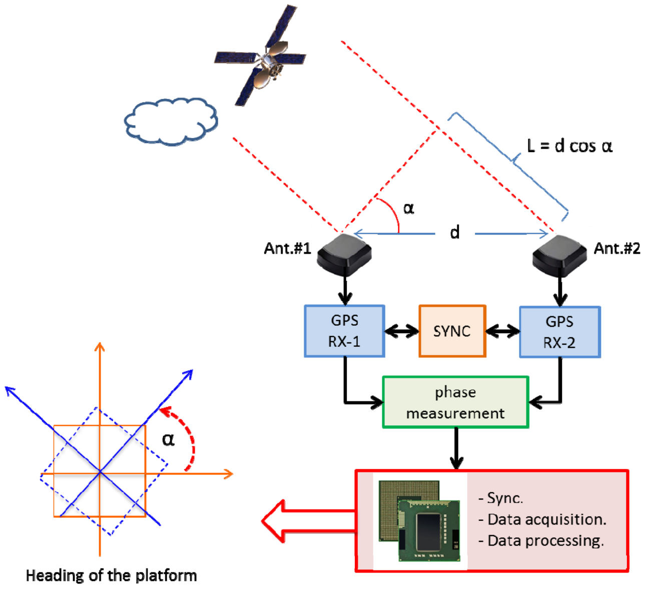

Fig. 3. Multi-antenna schematic block.

In order to obtain an attitude estimation out of GNSS data, the biases present in the system must be removed, thus allowing to estimate the integer cycle ambiguity present in the carrier phase measurement. Signals are digitally modulated with different codes from one satellite to the other but located at the same frequency (L1, L2 or L5). The Binary-Phase-Shift-Keying (BPSK) method, with instantaneous phase changes of 0° and 180°, is the digital modulation technique used in all GPS signals. The signal modulated on the GPS carrier is a Pseudo Random Noise (PRN) code. The L1 signal is modulated by two PRN codes, the precise P-code and coarse-acquisition C/A code. The L2 carrier, on the other hand, only carries the P-code signal. Ranging determination is made possible through a very precise time delay measurement. It compares a receiver-replicated code vs the satellite-transmitted code received by an antenna using an auto-correlation method. To define the position for a given receiver, a three-dimensional position vector and a bias in the receiver clock offset must be estimated, requiring pseudoranges to a minimum of four satellites at any given instant. In particular, the combination of two or more receivers' measurements may be used to mitigate the biases introduced by the atmospheric effects and the receivers and the satellites clock offsets from GPS time.

Theoretically the antenna would need to receive signals from the whole sky, as the main applications require, and the "position" reported from the GNSS is that one of the phase centre of the antenna. In this way the phase centre needs to be dimensionally very stable and independent of the direction of arrival of the signals from the constellation. Unfortunately, Radio Frequency Interferences (RFIs) coming form man made activities and/or multipath signals, introduce errors in the definition of the position of the phase centre. Since the antenna is aiming its primary beam to the sky, it comes out the necessity to mitigate RFI and/or multipath signals coming from low elevation angles (approximately 5 or 10 degree).

High accuracy positioning and navigation, therefore, requires a better and finer GNSS observable in certain applications including attitude determination. GNSS carrier phase is a more precise observable than its pseudorange code counterpart and therefore it becomes the primary observable in high accuracy applications. It is possible to improve the accuracy of GPS up to five orders of magnitude. With Differential GPS (DGPS), where the users have the chance to use one or more GPS receivers placed to known and fixed locations, the related positioning accuracy could be improved to the sub-centimeter level. Attitude determination of sub-degree accuracy usually requires the relative vector of the antenna pair(s) to be determined at a sub-centimeter level.

By determining the precise relative positions of at least two points in space, two of the three attitude parameters of the platform associated with these points can be computed. If two or more GNSS antennas are properly mounted on a platform and the measurements are simultaneously collected, the baseline vector from the primary antenna to other secondary antenna can be determined. The orientation of the antenna platform defined by these antennas can then be computed from the derived baseline vector. Usually, the baseline vector of the antennas obtained by GPS is in the World Geodetic System 1984 (WGS84). Then, the baseline vector is transformed into the local level coordinate system with the origin at the primary antenna.

Several positioning techniques have been developed: Single Point Positioning (SPP) is the default form of GNSS positioning. This form only requires a GNSS receiver without any extra infrastructure. The accuracy of method is quite low due to limitations of the format and the widely spaced update time; Differential positioning method is based on that many of the error sources affecting the range measurements between the receiver and the satellite are spatially correlated. Using one or more reference stations at known positions, the errors affecting measurements at the movable receiver (rover) can be corrected for. All relative positioning methods need at least one simultaneously observing reference station, and for real-time applications, a data link. Three common forms of relative positioning exist: Differential GNSS (DGNSS), Real-Time Kinematic (RTK) and Network RTK; Precise Point Positioning (PPP). Zumberge [9] introduced the technique of PPP using undifferenced code and carrier phase observations from dual frequency receivers. Rather than using differences between receivers and satellites to reduce the error budget, PPP uses external correction products and models for the error sources.

IV. GINSEC METHODS FOR DRONE HEADING

The methods selected for the GINSEC project are Post processing Kinematics (PPK) and PPP. PPK is the most extended post-processing technique and relies on differential corrections from a reference base station.

As referred in the previous section one option to get cm level accuracy with GNSS is through the usage of Continuously Operating Reference Stations (CORS) that provide reference measurement allowing for error and bias correction at the rover. This defines as referred in the previous section RTK. In this method, the reference station set on accurate known point, and the rover receives correctors from the reference station. The positions are known in real time (no need for post processing) and the correctors are sent via radio or cell phone, and therefore a communication link is required. The main advantage is that we are able to achieve cm level accuracy in real-time, while the obvious disadvantage is that if there is no radio link availability no correction is possible.

The solution to cope with this limitation is PPK that allows positioning without radios or cell coverage. As the name indicates post-processed is a method in which data is collected in the field and data processing occurs at the later stage, using proprietary or commercial software. GNSS measurements are made with two receivers, one which is fixed (base station) located over a known fixed point and one which may be moved around (the rover), and which is made for the actual positioning measurements. The data collected by the rover may be processed and corrected after the measurements have been made, post-processing, to achieve very high precision (1cm±1ppm) identical to RTK.

This correction is possible because the base station is located over a stationary point with known coordinates and any deviations from this position can be considered noise and can be removed. The difference in coordinates between the base station may then be analyzed together with data from the rover to obtain an accurate positioning of the rover relative to the base station. In practice, measurements are made by installing the base station over a known fixed point and setting up the rover anywhere desirable. The rover must remain perfectly still on the ground for 15–20 minutes to gather enough data to make the differential correction possible in the post-processing stage. This is referred to as initialization. Once initialization has been achieved, the rover may be moved around to make position measurements while the base station remains fixed over the known fixed point. The GNSS system controls sampling so PPK requires a base set on an accurately known position within 10km of the rover, and requires simultaneous data received by the base and rover. It also requires that the rover to be locked on to 5 or more satellites and maintaining lock to these satellites while moving.

Precise point positioning (PPP) stands out as an optimal approach for providing global augmentation services using current and coming GNSS constellations. Combining the precise satellite positions and clocks with a dual-frequency GNSS receiver, PPP is able to provide position solutions at centimetre to decimetre level. PPP requires fewer reference stations globally distributed rather than classic differential approaches (e.g. RTK), also one set of precise orbit and clock data (computed by a processing centre) is valid for all users everywhere, and the solution is largely unaffected by individual reference-station failures.

There are always many reference stations observing the same satellite because the precise orbits and clocks are calculated from a global network of reference stations. As a result, PPP gives a highly redundant and robust position solution. The starting point for PPP is orbit and clock products accurate to within a few centimeters. It is shown that it is possible to reduce the error budget sufficiently to enable centimeter accurate static positioning by using code combinations and observables phase, along with models for predominant error sources.

The PPP technique has clearly the advantage over differential methods in that only a single receiver is needed (at the user's position), removing the need for the user to establish their own local reference station or to have access to observations from one (or more) reference station(s) operated by others. Consequently, the spatial operating range limit of differential techniques is overcome, as well as the need for simultaneous observations at both user and reference receivers.

V. SIMULATIONS AND FIRST RESULTS

In order to test the multi-antenna concept, some measures on the field have been carried out. In particular, we arranged 3 GNSS receivers with different baselines, from tens of meters down to sub-meter distance (fig. 4). Initially starting from a MATLAB toolbox [10], we evaluated the basic performance by means of Double Differencing. In particular, starting from 3 RINEX files obtained from 3 GNSS receivers, an accurate computation of attitude parameters (Yaw, Pitch and Roll) as well as their accuracy were obtained.

Obviously, the best accuracy is obtained with large distances between the antennas, while the error is increased reducing the baseline. Some problems occurred while trying to simulate «drone sized» arrays, from example with baselines under 1 m, but we had encouraging results with baseline of 10 m.

At present, simulations have been done using real data acquired from GNSS platform where 3 receivers were installed with baseline of several meters. With a baseline of 10 m, the heading accuracy was better than 2 degrees with a standard deviation of about 0.4 degree.

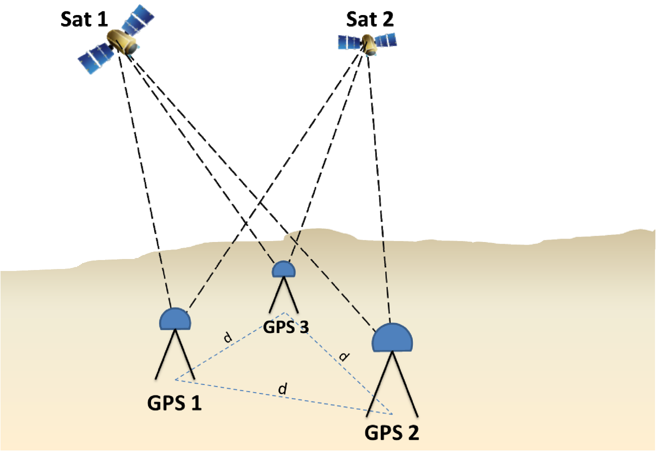

Fig. 4. Basic test bed used for the tests.

Shorter baselines showed some decreased accuracy, that may be related to the receivers' clock noise and to the lack of a coherent clock reference; the consortium is currently investigating the situation and working on its improvement.

VI. CONCLUSION

At present, simulations have been done using real data acquired from GNSS platform where 3 receivers were installed with baseline of several meters and results are encouraging. As a second step, some simulations allowed studying the geometry of a small drone size baseline with 2 GNSS receivers (placed at a distance 60 cm); evaluation of results is ongoing. This phase will be followed by models based on real data which will allow developing the necessary algorithms to be implemented on the prototype test beds and furthermore on real UAVs for their final validation. The objective of the activity is to find a solid definition and quantification of trade-off between cost effectiveness and accuracy. At this level we have not yet terminated the activity, but we are confident to obtained very valuable results.

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