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HIL System With 3-axis Gimbal For UAV's Autopilot Tests

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Abstract. *This paper describes the development of a system to speed up UAV's Autopilot development in general, and specifically test Inertial Measurement Unit (IMU). The system is composed of a three axis gimbal, controlled by an embedded control board. To realize the communication between the simulated aircraft and the gimbal control board it was developed data conversion software. Results acquired with the gimbal being automatically positioned with the simulated aircraft attitude are presented.*

Keywords: *unmanned aircraft systems, airspace control, hardware-in-the-loop.*

1. INTRODUCTION

The design of an autopilot (AP) for autonomous vehicle needs several test and validation stages. Bench tests are desirable and should be used before missions in field. Field tests need a complex structure involving people, equipment and adequate physical space, which makes these tests expensive (Lu and Geng, 2011) (Bittar *et al.*, 2014). Hardware in the Loop (HIL) is an important test bench, because it minimizes error detection costs and reduces the risks of field testing (Chudy *et al.*, 2012) (Carter and Ali, 2008).

X-Plane is a flight simulator that has accurate commercial aircraft models. Besides that, it has an input/output module, which allows the software simulator to send flight data via UDP (User Datagram Protocol) to other processors during the simulation (RESEARCH, 2014).

The use of a robust professional and expensive tool for test bench entails three problems: the high cost of using the equipment; the time between the project and its experimental trials; and the fact that most of these equipments are in restricted areas, which makes it difficult to access this type of technology (Valavanis, 2008). These problems lead to a long design time, due the large number of tests necessary and the necessary time between them: time to fix the problems found added to the time to access the professional tool (Santos and Oliveira, 2009).

This paper describes the development of a HIL platform with a gimbal structure controlled by the X-Plane flight simulator suitable for restricted budget academic AP projects. The gimbal has three-axis and is capable to follow the attitude orientation on flight. The orientation imposed to the gimbal and the attitude read by an attached sensor can be compared. The platform allows HIL tests of guidance algorithms, Inertial Measurement Unit (IMU) and AP control loops.

2. METHODOLOGY

To develop the proposed system, it was necessary to integrate three-separated system, X-Plane flight simulator, IMU and gimbal. Each system was studied to understand their characteristics and functioning. Very briefly describing, the attitude of an airplane in simulated flight is sent to the gimbal. The gimbal set their axis to the airplane attitude. The IMU attached to the gimbal estimates the attitude. So, the data flow among these system must be properly done.

2.1 X-PLANE AND GIMBAL

The flight simulator X-Plane allows flight data flow with another software or even with another computer. It is possible to get the aircraft state in simulation, for instance, its airspeed, altitude, angular velocity. These characteristics allow the use of this simulator in several tests related to AP development (Çetin and Kutay, 2016) (Ribeiro and Oliveira, 2010).

The simulator also has an already native autopilot module, so there is no need to worry about stabilizing the aircraft during the tests. Another form to control the aircraft is through the data entry module. This module allows the insertion of parameters in a way similar to those that a pilot modifies during the flight, therefore, it also makes possible the insertion of an external autopilot (Ribeiro and Oliveira, 2010).

The gimbal used in developed HIL platform is a three axis freedom gimbal. The angular position of each axis can be commanded by electrical signal. Unlike the step motors used by (Carter and Ali, 2008), the gimbal motors are brushless which have smoother movements. A computer/processor may generate these signals and the gimbal angular orientation can be automatically done.

With the use of an electronic gimbal it becomes possible to build a system that accompanies movements predicted by a computer system as an autopilot or an inertial measurement system.

Therefore the complete system is composed by integrating gimbal, imu and simulator, fixing the imu on the gimbal table. In this way, by making the simulator impose to the axes of the gimbal the attitude of the aircraft, it is possible to emulate in a bench a PA where the attitude of the aircraft is estimated from the readings of sensors in the IMU.

This tool allows the mechanical calibration as in (Sahawneh and Jarrah, 2008), where a table with accuracy of $\pm 0.5^\circ$ was prepared for the calibration of IMU's. For this calibration, a table was made with a counterweight capable of being aligned with such accuracy.

For the table alignment, a digital level with a resolution of 0.05° and a precision of $\pm 0.1^\circ$ was used. For the adjustment of the heading angle an analogue compass was used. After the mechanical calibration is done the system is energized and the signal for the calibration of the accelerometers and gyrometers is sent to the microcontroller. These accelerometers and gyrometers are responsible for estimating the attitude of the gimbal to close the loop with attitude control. After the alignment with tangent plane of the earth it is possible to obtain other angles for the validation of the system.

2.2 DEVELOPED SYSTEM

The complete system shown in Fig. 1 can be described as formed by three blocks:

- The computer with the simulator and software that converts the information from the simulator to the serial port;
- The microcontroller that receives the information via serial and converts it into PWM signals;
- Gimbal that has an embedded electronics circuit that converts the PWM signal into control signals into the feedback loop of the platform angles.

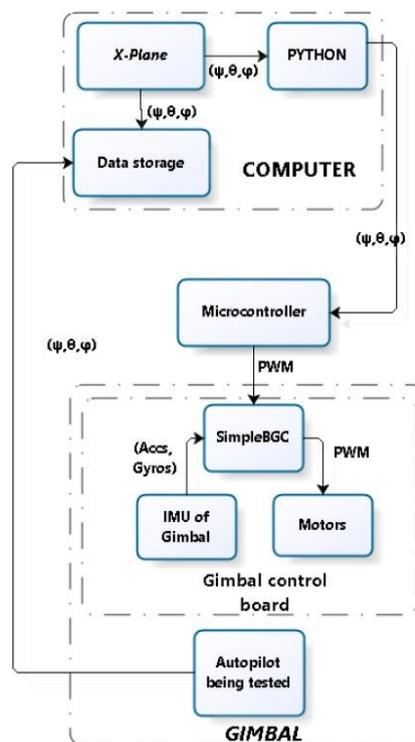


Figure 1. HIL Platform: Aircraft simulator commanding the gimbal orientation

Dataflow in Fig. 1 starting in the computer running the X-Plane can be described as: The data is collected from the simulator X-Plane through UDP connection, which sends the parameters of aircraft guidance to the embedded electronics system. This system, in turn, controls the gimbal engines to position the table according to the movement of the simulated aircraft. The IMU attached to the gimbal table serves to stabilize the table position by closing the gimbal control loop. This test IMU must be placed on the gimbal table and its response is stored on a computer along with the information from the simulator, which will be compared for compatibility check of the data. The control loop was closed with information coming from the simulator, such as speeds, to determine the position of the aircraft.

3. RESULTS AND DISCUSSION

To implement the system it was necessary to work with software components, as developer and as user; it was also necessary to work with hardware components, designing and building mechanic parts for the system. After the integration of all components, the result comparing a reference trajectory with a trajectory generated using the estimated information acquired by the developed system is presented.

3.1 SOFTWARE

A UDP socket was created using Python to receive the simulation data. Figure 2 shows the screen of the simulator with the developed software screen, which allows the flow of data to / from the simulator. The developed software is responsible for converting the data packet received from the simulator, sends it through the serial to the microcontroller that generates the PWM to control the gimbal.



Figure 2. X-Plane screen, with some available aircraft data (left); Data flow in the developed software during the simulation (right)

3.2 GIMBAL CONTROL BOARD

To obtain the simulator data it is necessary to unpack the UDP and generate the control signals. A Python software was made that unpacks the UDP and sends the reference signals to a microcontroller. This microcontroller generates the PWM signal from the reference and sends it to the control board. The control board receives the reference signal and passes through controllers to generate the signal to the motors.

3.2.1 MICROCONTROLLER

The control board receives the angular position to be commanded to the gimbal axis and converts it in adequate PWM signals, with 16 bits resolution and 500 Hz. The proportionality between the angle and PWM is given jointly between software written in Python and the gimbal software available for users. The maximum angles have been set at $\pm 90^\circ$ for roll and pitch and 0° to 360° for heading. The PWM signal ranges from 0 to 100% for these values.

Figure 3 shows the PWM signal for three roll angles: -90° , 0 and 90° . It is possible to see two dead zones in the signal, one in the beginning until near the 50% and another one after the 99%. The behavior of the PWM was mapped by making the value variation and observing the output.

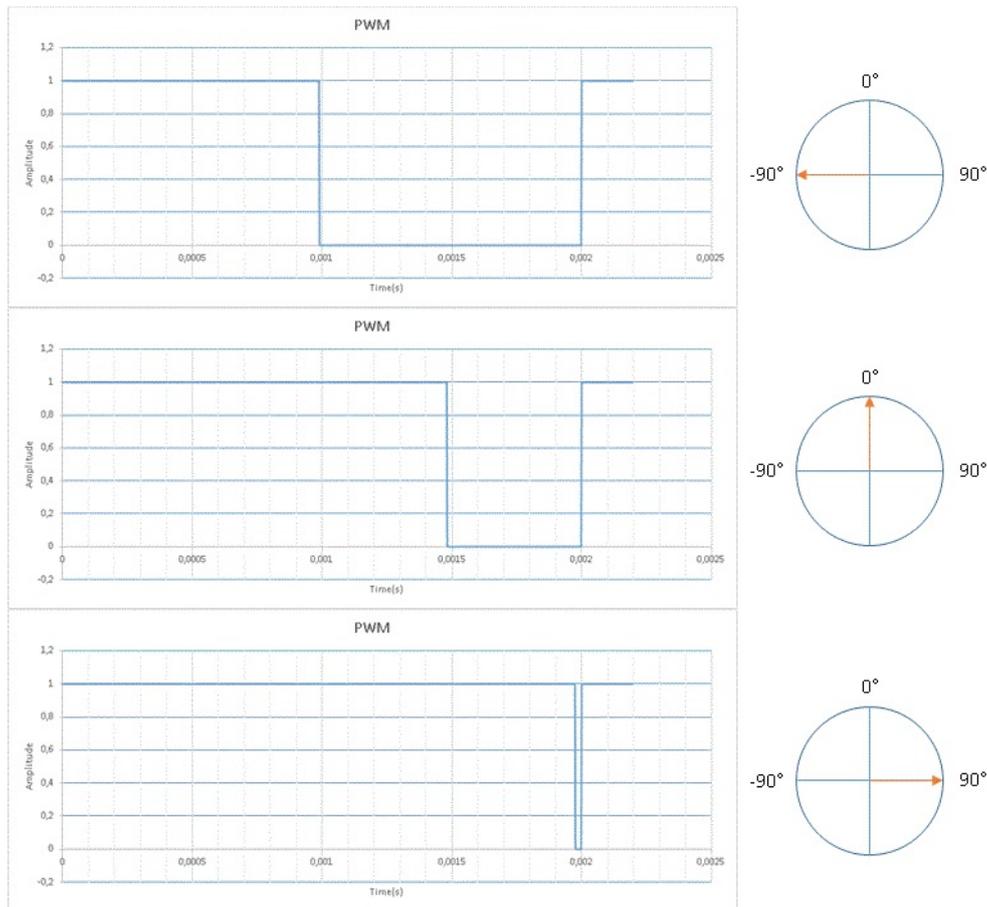


Figure 3. PWM signal to roll by varying its value from one end to another. It is possible to verify two dead zones obtained experimentally

3.2.2 SOFTWARE SIMPLEBGC

For the settings of the gimbal controllers there is a software called SimpleBGC available free download on (Eletronics, 2016).

PID gains were adjusted for rapid table stabilization. For a ± 10 degree of perturbation in a pre setted angle, the accomodation time to return to the reference position was chosen as 2 s., these were the gains stored in the system. Figure 4 shows the program screen, which is the gimbal configuration interface.

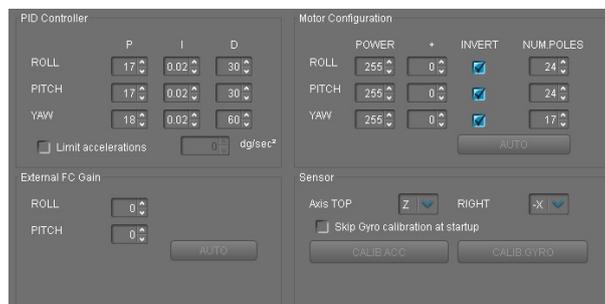


Figure 4. Screen of configuration of the PID gains of the three axes

The adjustment of the gains of the PIDs was done by trial and error in order to achieve a smooth response without oscillations. This smooth dynamics was chosen because the simulated aircraft has the slow dynamics. Therefore if the aircraft is changed to one that has a dynamics very different from the one chosen, the gains must be readjusted.

3.3 CONSTRUCTION OF THE STRUCTURE

For the construction of the system was designed a table that has two purposes, enable the insertion of the equipment that will be tested and mechanically align the system with the plane tangent to the ground at its initialization. This alignment is used to determine the pitch and roll angles with the value 0° . This calibration must be done every time the system is energized. From this, the electronic system is able to force the table to a certain attitude. This makes it possible to test in IMU's and AP's.

The development of the desk design was carried out in computer software design, where the mechanical constraints of the system were considered. The table should allow the insertion of the gimbal IMU in the middle of rotation of the three axes of the system in order to reduce alignment errors as shown in the Fig. 5. Also considered was the need for an apparatus that allows the change of the center of gravity of the system table to make its alignment with the plane tangent to the ground as you can see in the Fig. 6.

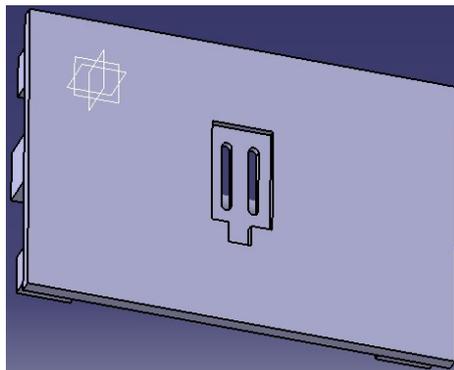


Figure 5. Vision of the insertion chamfer of the inertial measurement unit on the gimbal table

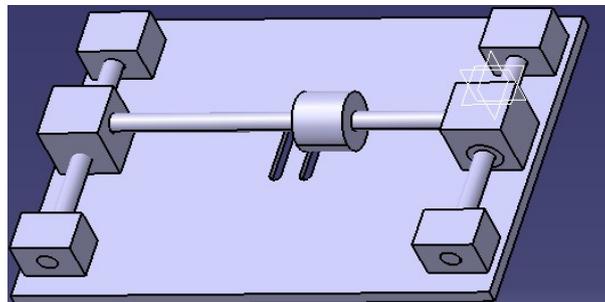


Figure 6. View of the movable counterweight system to change the position of the center of gravity of the table for alignment with the plane tangent to the ground

Figure 7 shows the complete table incorporated in the gimbal system where all aspects of the design can be seen as the counterweight and the chamfer with the system IMU in its proper place.



Figure 7. Complete table with the positioning system of the center of gravity and IMU in the center of rotation of the three axes of the system

Figure 8 shows the alignment in the two axes of the system, for the third axis a compass was used for alignment with the north.

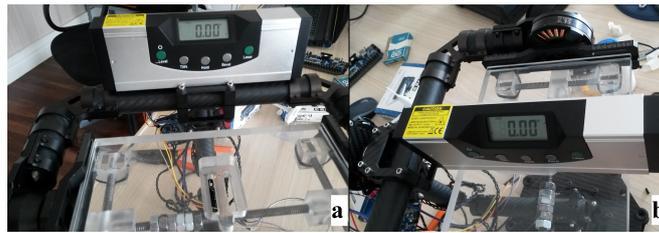


Figure 8. Alignment of the table with the tangent plane. (a) Alignment for scrolling. (b) Alignment for pitching

Thus, when the tangent plane is aligned, the signal for the calibration is sent to the software in order to guarantee certainty of the accuracy of the measurements made in the test IMU.

Without the table, in preliminary tests, the calibration measures had a discrepancy of $\pm 2^\circ$, which would lead to an uncertainty in the measures that should be considered in the use of the equipment. This is due to the fact that the alignment is done by visual means. The insertion of the calibration table avoids this problem, since the system is mechanically balanced.

3.4 TEST

For functional testing, a IMU and microcontroller were placed on the gimbal table. The microcontroller, as already said, is responsible for estimating the Euler angles based in the IMU data. The experiment was performed during a takeoff generated in the simulator; simulation data was stored on the hard disk of the computer. After the acquisition the data were taken to Matlab[®] to generate a graph for the comparison of trajectories.

For the acquisition of the angles from the IMU, the DCM matrix technique was used. This algorithm is embedded in the microcontroller that in conjunction with the velocity values coming from the simulator it is possible to determine the position of the aircraft in space.

For the acquisition of the angles from the IMU, the DCM matrix technique was used. This algorithm is embedded in the microcontroller that in conjunction with the velocity values coming from the simulator it is possible to determine the position of the aircraft in space. The microcontroller sends the euler angles to the Matlab[®] for position determination.

Matlab[®] uses the Dead-Reckoning (DR) (Farrell, 1999) algorithm to estimate the position of the aircraft during the in-flight mission. The DR had a small change because in the simulator there is no output of accelerometers, so the speed readings were used. Figure 9 shows the diagram of the form in which DR was used.

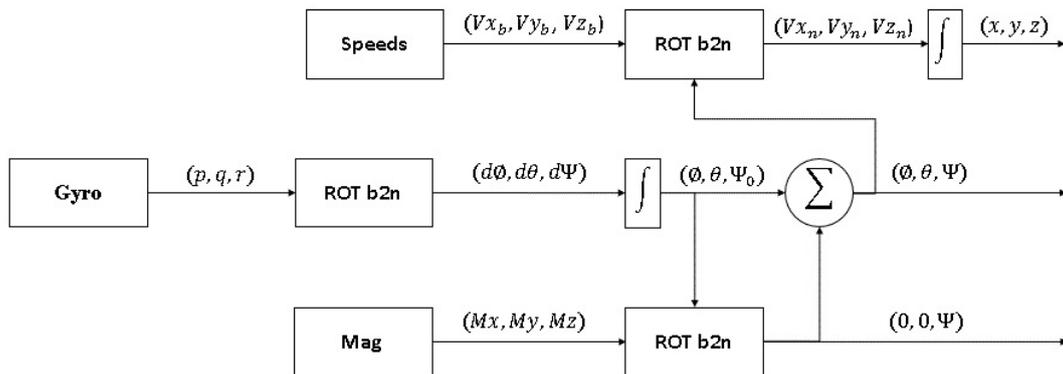


Figure 9. Modified Dead-Reckoning algorithm for the use of velocities instead of accelerometers

In our experiment, we plotted the trajectories of the aircraft in the simulator and the estimated trajectory using the Eulers angles obtained from the IMU readings and the velocities obtained from the X-Plane. Figure 10 shows the trajectory generated by the simulator in green and the trajectory generated by the acquisition of the data from the IMU allocated on the gimbal table in red. There was a deviation in the position possibly linked to integration errors. This may be connected to the step used during integration.

To compare the information between the simulation and the gimbal setup, it was used the Matlab[®] to generate the graphs. Using the gimbal attitude, a DR algorithm generates the trajectory of the "gimbal attached aircraft". In Fig. 10 we can see the trajectory generated by the simulator in green and the trajectory generated by the acquisition of the data from the IMU attached on the table of gimbal in red.

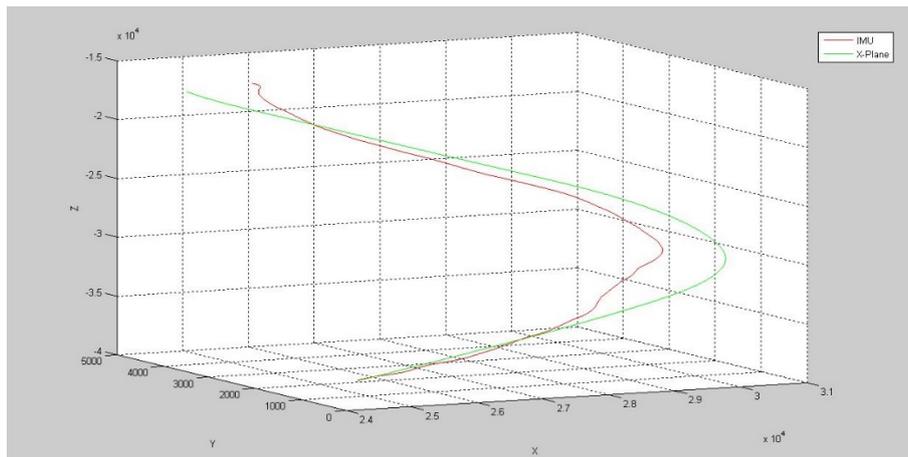


Figure 10. Trajectories: Green, from the X-Plane; Red, generated using the IMU attached in gimbal as input to a Dead-Reckoning algorithm. Note an accredited deviation to a cumulative error connected to the integration step

4. CONCLUSIONS

A HIL platform with a controlled 3-axis gimbal was developed and tested. The objective of such system is to allow tests as real as possible, allowing the test of attitude sensors to be embedded and also allowing several AP algorithms tests. These kinds of tests can spare time and money compared to field tests.

The construction of the calibration table made possible the mechanical calibration of the system, reducing the number of errors related to electrical interference and accelerating the calibration process. Once the system is stabilized, it is only necessary to start the software calibration. For the prototyping of the table pieces were used the laboratories of the University of Brasilia with the support of the technicians responsible for them. The table was manufactured in an acrylic sheet, because due to the measures of cuts and chamfers and tooling restrictions, other plastic materials such as polyacetal would damage both the material and the tool, causing a waste of time and material.

The setup development was successful. Each gimbal axis assumed the commanded orientation. Tests using the sensed attitude data given by the IMU attached in the gimbal compared with the X-Plane information were presented. However, the system tests are still preliminary. A very useful application to this system, yet to be explored, is its use in IMU calibration.

As we were interested in a HIL platform, we presented the result of the integrated IMU, Xplane and microcontroller. However, a work that will be done next is the comparison of the values of Euler angles estimated with the IMU and Euler angles imposed on the axes of the gimbal. For this way it is possible to verify the accuracy in each axis and propose new solutions.

5. ACKNOWLEDGEMENTS

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