Control Algorithm for the Inertial Stabilization of UAVs

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A Abstract—**The UAVs (Unmanned Aerial Vehicles) are aircraft used in applications that requires great capacities to operate in harsh environments. They include efficient tools to support the development, security and defense of a country. To guide the navigation while generating the route and stabilization of these vehicles, a control algorithm is applied in order to direct and stabilize the aircraft. A generic control system to drive the aircraft is used which considers electronic, mechanical and aeronautical aspects for their operation.**

The unmanned aircrafts need a navigation system that must be designed using variant or invariant time control methods that must be efficient in their operation. This work shows the results of the application of a control algorithm that includes an inertial platform with a GPS actualization to navigate and control the unmanned aircraft. The designed system was tested considering different weather conditions in the free space, which shows satisfactory results that predicts their future use. The hardware and software of the stabilization system of the aircraft is a result of the Ecuadorian researchers team work.

Index Terms — **Control Algorithm, Inertial Stabilization, unmanned aircrafts, GPS actualization, aircraft control.**

I. INTRODUCTION

The instrument navigation based in generic technologies differs from sensor dependent and open technologies navigation systems. Inertial navigation uses measuring instruments like accelerometers, gyroscopes and magnetometers, they allow aircraft navigation to support the stabilization, guiding and control of the system [1].

The inertial or estimating navigation needs the real time response of the aircraft by using the real time measurement in the place where the UAV is operating. This situation needs a fine driving of the actuators which are guided by the variables that shows the situation of the aircraft .

The functions of the control module include a great degree of the aircraft's operating regulation that need to consider the speed of the aircraft and the control's memory. The program that processes the aircraft speed uses more than 20000 instructions per second and requires a minimum system memory of 500 kBytes that is one of the strengths of the system. Due to the fast response required of the UAVs, it is necessary to use processors that must work simultaneously to distribute the processing load that the sensors and the systems variables use. The selected method for operation is the inertial navigation system that includes different instruments like speed meters, altimeters, GPS and others [2].

One of the main problems related to this kind of navigation is the position and the distance that runs the aircraft, therefore the information that the sensor presents is used to calculate and determine the position which is related with the GPS updating of the UAV. The dead time can be eliminated by introducing a predictive model considering a route where the aircraft must be directed [3].

Inertial navigation is an alternative method to navigate using a GPS. This method has the advantage of being more precise but requires additional time to process the data. The processing is more complex when the conditions include disturbance problems, which in many situations could be disastrous.

Related work to this research is done in [4] where a procedure for certifying the effects of noise in an Aircraft and predicting the full scale over-flight noise of a propeller is done. This work's testing considers measurements using a small scale propeller in an acoustic wind tunnel. Data manipulations are discussed considering the simulation of the flight distance.

In [5] there is a study about a target tracking control of a Quadroto UAV using vision sensor, [6] considers the hovering capture and load stability of an air system, [7] presents the autonomous indoor aerial using a quadrotor, [8] shows the mechanical design of a manipulation system for unmanned aerial vehicles and [9] presents a hybrid pose / wrench control framework for quadrotor helicopters.

This work presents the results of the application of the control algorithm, used to stabilize the aircraft considering the mechanical plant that is invariant in time and the control criteria.

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II. UAV STABILIZATION

However, it is important to consider that any aircraft is able to navigate in a predetermined route while arriving at the specified targeted point. The aircraft must navigate in a stable mode following predefined patterns to assure that the airship doesn't make any roll or can get loss of compensation [10]. This work uses an UAV with a 3m wing span, 80 km/h of cruise speed, 10 pounds of load, 12000 ft. of maximum height, a 25km of maximum distance and 30 minutes of autonomy.

A. *UAV stabilization as function of the inertial platform*

The general scheme for the aircraft stabilization is done by considering the required speed and accuracy of the movement of the aircraft planes as shown in Figure 1.

Input and output data are used to identify the system plant. The plant can take different characteristics according to the planned control, for this reason the parameters of the plant (Flight Planes) are taken as independent and they are linked whenever a navigation is done. The model is considered as invariant in time to simplify the design of the controller.

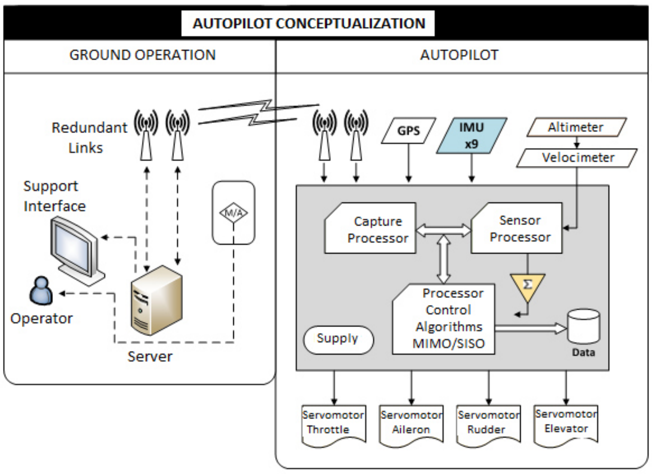

Figure 1. General scheme of an UAV

For inertial navigation, stability is included considering a linear reference point for every sampling period, which involves the reference point monitoring as a direct function of the gyroscopes. Because the GPS information can be updated every time period, it must be considered a control policy between each time interval in which data updating is no available so the data that generates the GPS can update the set points at each sampling period, [11] therefore the control is treated as LTI [12]. The stabilization system acts during the time that the waypoints and references are not updated [13].

B. *Control implementation for aircraft stabilization*

The control system used to guide the aircraft considers the plant output to drive the aileron and rudder servomotor. This control takes into account the spoiler that aims to put the waypoints far enough apart considering internal navigation angles greater than 120 degrees. Control systems can be provided by several control laws as SISO [14] or MIMO [15]; all depends on the desired control level, control heading is SISO type while a MIMO control type was selected for controlling the aircraft height. The monitored variables are height, angle of attack, speed of the aircraft and engine acceleration.

C. *Heading control with azimuth.*

Due to the type of navigation applied to automatic flights, the usage of the GPS update is required during the period in which no continuous GPS data update is handled, stability is very important in this situation [16]. The stability control has its variable reference for specific times and the flight plant acts according to the waypoints where the aircraft must navigate.

Stability can be implemented under any control type as it takes into account the fact that when integral actions are used, it should consider the saturation error criteria. The proposed solution includes a PID control [17] with a pole increased by a saturation feedback due to the integral section. The solution to this control should be considered because the moving planes of an aircraft must respond at the right time even when the system has been carrying long time errors due to disturbances. This could be more complex in bad weather conditions.

Figure 2 shows the control structure for the stability of the aircraft's moving plane. In this specific case we apply it to the heading control [18], the feedback is given by the inertial platform and its variable set point is given by the result of the azimuth calculation according to the Havrsine law.

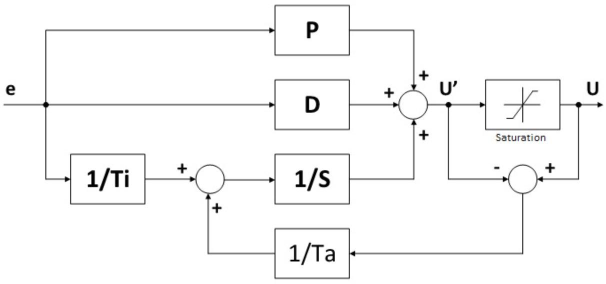

Figure 2. Control Heading Diagram

Moreover, the additional pole that was introduced in the system develops a delay due to the integrated action of the controller, the included pole doesn't affect the stabilization because the response of the system it is not fast. The technique of increasing a pole in the integral part of a PID control is known as Anti Windup [19] and changes the type of the control related to the conventional parameters. Calculations are shown below for the response of the controller.

$$A = e_y(t)$$
$$B = e_s(t)$$
$$v(t) = kp\left[A + \frac{\int A dt}{T_i} + T_d\left(\frac{d}{dt}A\right)\right] + \frac{\int B dt}{T_i} \tag{1}$$
$$C = e_y(k)$$
$$D = e_y(k-1)$$
$$E = e_s(k)$$

$$v(k) = kp\left[C + \frac{T(\sum C)}{T_i} + \frac{T_d(C-D)}{T}\right] + \frac{T(\sum E)}{T_i} \quad (2)$$

$$F = v(k-1)$$

$$v(k) - F = kp\left[C - D + \frac{T * D}{T_i} + \cdots\right] + \frac{T * E}{T_i} \quad (3)$$

$$e_s(k) = u(k) - v(k) \quad (4)$$

$$G = 1 + \frac{T}{T_i}$$

$$H = \frac{T_d}{T}$$

$$Gv(k) - F = kp[G + H]C - kp[1 + 2H]D + \cdots \quad (5)$$

$$\frac{V(z)}{E(z)} = \frac{q_0 z^2 + q_1 z + q_2}{z(z-1)} \quad (6)$$

$$J = q_0 z^2 + q_1 z + q_2$$

$$K = P_0 P_{00} z^2$$

$$(z)[z(z - p_{00})] = p_{00}(J)E(z) + KU(z) \quad (7)$$

Where:

$$q_0 = Kp\left[1 + \frac{T}{T_i} + \frac{T_d}{T}\right] \quad (8)$$

$$q_1 = -Kp\left[1 + \frac{2T_d}{T}\right] \quad (9)$$

$$q_2 = \frac{KpT_d}{T} \quad (10)$$

$$P_0 = \frac{1}{T_i} \quad (11)$$

$$P_{00} = \frac{1}{1 + P_0} \quad (12)$$

$Kp = Proportional\ Gain$

$T_i = Integral\ Time$

$T_d = Derivative\ Time$

$T = Sampling\ Time$

$T_a = Settling\ Time$

$e_s = Saturation\ Error$

$e_y = Control\ Error$

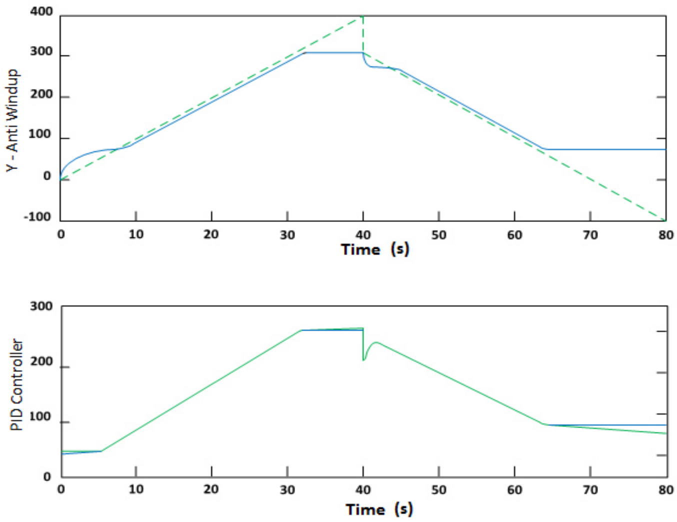

Figure 3.Control response of the integral section of the PID controller for the disturbance and saturation for heading.

The additional control element sets new calibration parameters that should be tuned only when the aircraft is in flight. Figure 3 shows the saturation time that was removed using a PID controller that includes an anti-windup control.

Calibration depends on the dynamics of the plant because an aircraft do not have similar response to others. The calculus of the azimuth angle between two points is done according the Haversine formula which is used to update the reference point of the aircraft that is given by equation 13 which shows that values between $-\pi$ and π.

$$P = \sin(\delta long)\cos(lat2)$$

$$Q = \cos(lat1)\sin(lat2)$$

$$R = \sin(lat1)\cos(lat2)\cos(\delta long)$$

$$\theta = atan2(P, Q - R) \quad (13)$$

Where:

θ: Azimuth between two geographical points.

δlong: Length variation between two points.

lat1: Latitude of the source point.

Lat2: Latitude of the destiny point.

It is necessary to get the angle in which the UAV is positioned. An inertial platform that shows the UAV reference point relative to magnetic north is used. The control scheme is simple because the system has one input and one output, it should be considered that the error is an angle and the output is a pulse width modulated signal (PWM). The output vector control is considered as a linear transformation.

D. State Variables for aircraft height control using nonzero integration and balance states

In this case we consider a multi-variate system whose reference input is the height, and the feedback variables are the height, pitch angle and engine acceleration. We have to consider that the sampling period should be as fast as possible, consequently:

$$T_S = \frac{1000\ ms}{50\ samples} \quad (14)$$

The control requires the knowledge of the plant and therefore a MINO system is identified as shown in figure 4. Figure 5 shows the response of the system identification with accuracies of 84.83% and 61.52%.

To identify the plant we use the Matlab software libraries that makes use of recursive algorithms, considering predefined input and output conditions applied to the plant. From this we get the matrix 16, 17, 18 and 19:

$$x(k+1) = Gx(k) + Hu(k) \quad (15)$$

$$\mathrm{y(k)} = Cx(k)$$

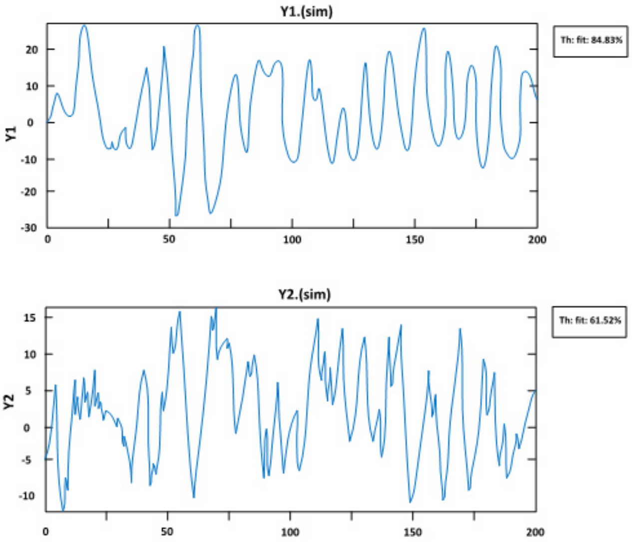

Figure 4.MIMO system identification.

$$G = \begin{bmatrix} -0.15729 & 0.78568 & -0.18824 \\ -0.83481 & 0.030596 & -0.20251 \\ 0.33926 & -0.10915 & -0.56345 \end{bmatrix} \tag{16}$$

$$H = \begin{bmatrix} -0.0068318 & -0.016443 & 0.031459 \\ 0.0096626 & 0.0060729 & -0.04607 \\ 0.017302 & 0.0093034 & 0.0068943 \end{bmatrix} \tag{17}$$

$$C' = \begin{bmatrix} 17.328 & 15.579 & -33.482 \\ -33.002 & -80.805 & 21.848 \end{bmatrix} \tag{18}$$

$$D' = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \tag{19}$$

Figure 6 shows the dynamic response of the plan, this reason makes the control can be implemented using state space.

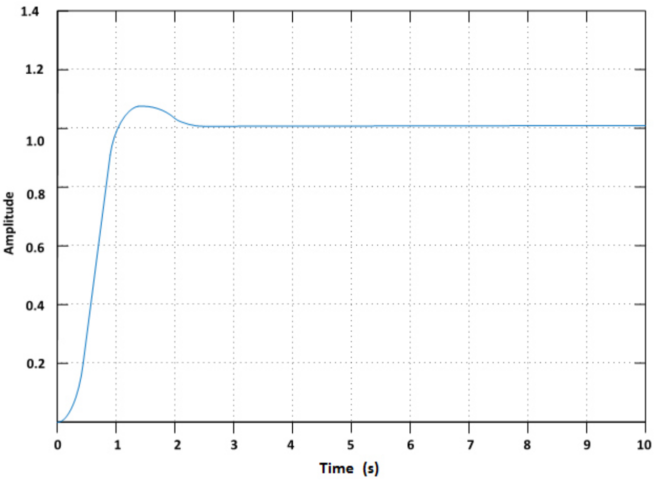

Figure 5. Dynamics of the plant (aircraft height)

After the implementation of the system using a state space control, the parameters and the maximum settling peak time must be calculated using the Bessel polynomials.

TABLE I

CONTROLLER BESSEL POLYNOMIALS

N	Polynomials
1	$s+1$
2	s^2+3s+3
3	$s^3+6s^2+15s+15$
4	$s^4+10s^3+45s^2+105s+105$
5	$s^5+15s^4+105s^3+420s^2+945s+945$
6	$s^6+21s^5+210s^4+1260s^3+4725s^2+10395s+10395$

Once the calibration parameters had been set, it is necessary to calculate the control matrix according to Ackerman [20]:

$$k = [-0.2320 \quad 0.7555 \quad 0.7555] \tag{20}$$

The control diagram is established as shown in figure 6 which considers the aircraft height as the output variable.

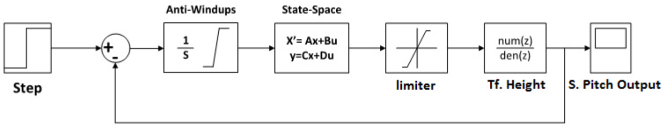

Figure 6. Aircraft height control system

Figure 7 shows the three reference signals which enter to the MIMO control so they converge to the control system to be controlled. Aircraft height is taken as the output variable.

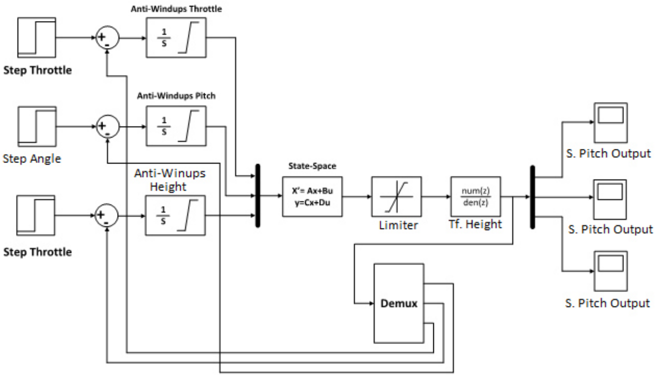

Figure 7. Aircraft height control system

Figure 8 shows the system response which correctly acts against an introduced disturbance when the system is stable, the system follows the aircraft height reference.

The designed control follows the reference with a peak of 7.4% and 2.6 s. as the stabilization time, enough time to control the aircraft height variable.

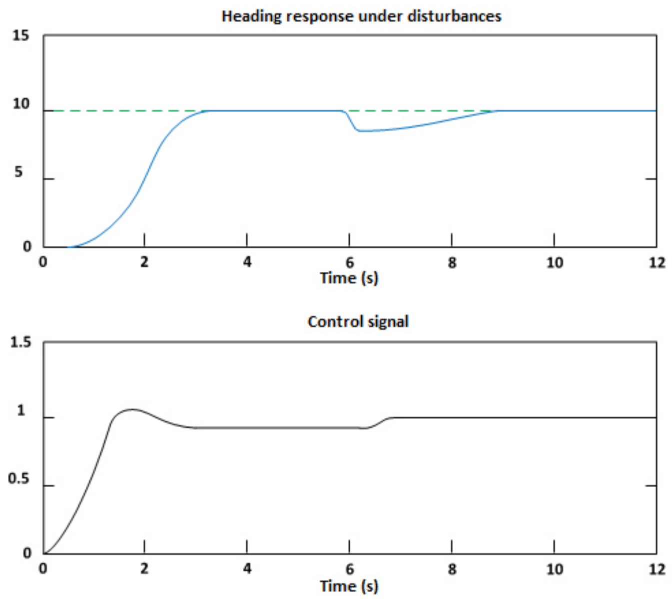

Figure 8. State Space response for the height control.

E. Waypoint Access verification

To get the optimum condition to assure that the UAV reaches the specified waypoint, we need to verify that the radius point approach is higher than that specified by the calculations. It should be calculated the distance as function of the geographical coordinates taking into account the radius of the Earth.

$$d1 = \sin\left(\frac{1}{2}\delta lat\right)^2 + \cos(lat_1)\cos(lat_2)\sin\left(\frac{1}{2}\delta long\right)^2$$

$$d2 = 1 - \sin\left(\frac{1}{2}\delta lat\right)^2 + \cos(lat_1)\cos(lat_2)\sin\left(\frac{1}{2}\delta long\right)^2$$

$$d = 2R\ atan2\left(\sqrt{d1}, \sqrt{d2}\right) \qquad (21)$$

It is necessary to consider whether the aircraft goes to the waypoint to an specified height when it have reached the specific geographical point, if necessary, the aircraft can take a repeated action until getting the desired height or jumping to the next.

Once the UAV has passed through the programmed point, it finds the next waypoint, these navigation conditions are considered to stabilize the aircraft because it depends in the reference changes during navigation, especially when heading is changing continuously. Figure 9 shows direction changes that must be done when the UAV is in position P1 and should reach position P2.

To get the optimal direction of the aircraft flight, we select the absolute differential angle that depends of the point's angle (α) and the angle obtained from the inertial platform (β). It is known that the relative angle γ should be between -180 ° and + 180 °, if the sign of this angle is negative, then the UAV must turn right and left in the other case, as shown in Figure 10.

$$\gamma = \alpha - \beta \qquad (22)$$

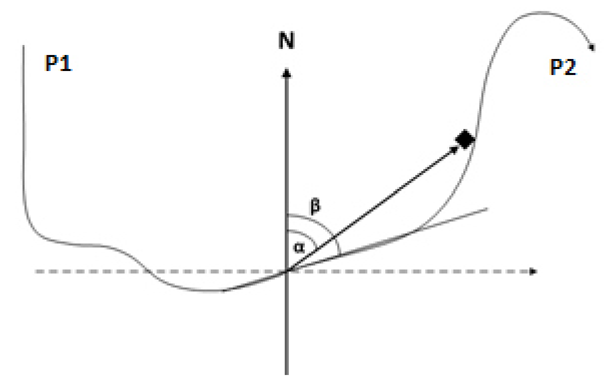

Figure 9. Changes in the aircraft flight direction from position P1 to P2

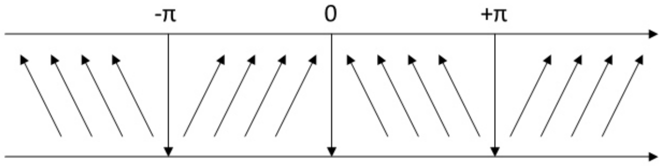

Figure 10. Optimal rotation decision for correcting the heading angle of navigation

The rudder and aileron plane must rotate in the proper direction, leaving its equilibrium position to enter a new position where the dynamic equilibrium is reached according to the sampling period. The values of the width of the PWM pulse of each plane is directly proportional to an electronically estimated value and to the maximum value of the rotation of the servomotor. The heading control of the aircraft system is done by the ailerons having a 100% of free rotation, while the helm adds a 20% value to rotation.

F. Kalman Filter for the reference signals.

Acquired signals need to be digitalized to enter the control system. If the incoming signals do not satisfy the necessary conditions they will not satisfy the requirement of the controller. Equations 22 and 23 determine the status of the altimeter and speedometer sensors. The filter was implemented using 22 and 23.

$$X(k) = X_{esy}(1-k) + kZ(k) \qquad (22)$$

$$X_{est} = 2X(k-1) - X(k-2) \qquad (23)$$

The Kalman filter acts as filter and data predictor. Figure 11 show that data, besides being corrected, predicts the next data information. This variant of the Kalman filter is valid for this kind of system when the aircraft speed exceeds GPS data updating. If it is required to take a control action, the controller has to wait for one second to give a new control response. This action can be developed by the Kalman filter’s response if it does a properly weighting.

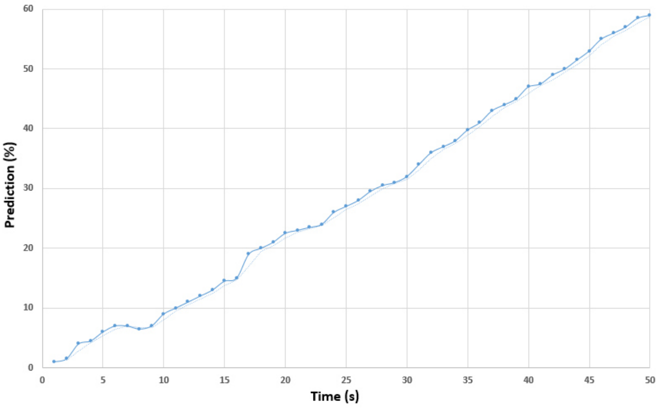

Figure 11. Kalman filter response for the control input signals.

III. CONCLUSIONS

The flight of an aircraft must be considered as an integral system that includes independent elements. There are many variables that affect the moving planes of the aircraft during a flight. The control systems need to be linked together, when making a turn, the aircraft must control all servomotors to make a clean turn. A clean spin involves fine control in stabilizing the aircraft in terms of disturbances, because these may become uncontrollable as they depend on weather conditions in every instant of the flight.

The proposed solution is effective from the viewpoint of linear control because it considers the plant is invariant in time and the signals saturation is controlled with the integrator section of the PID controller.

Moreover, calibration can’t be done on ground and because it is not possible to calibrate the system by varying the feedback signals instead of changing the reference. The calibration of the system parameters must be done in flight.

Future work includes the research to control the unmanned aerial vehicles to be used in very harsh environmental regions, where the height of the places is higher than the sea level. The knowledge and understanding of the conditions where the UAV must flight will help to develop better systems to control the aircraft.

Finally, stabilizing the aircraft is not indispensable to use PID controller because it is possible to get similar effects by implementing other controllers like a fuzzy PID, control state variables, optimal control and even with a neural network, as long as is taken into account the above criteria.

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REFERENCES

[1] D. Tazartes. “An Historical Perspective on Inertial Navigation Systems” In ISISS, 2014. Laguna Beach, CA, USA. Proceedings of International Symposium on Inertial Sensor and Systems, 2014.

[2] A. K. Brown and Y. Lu. “Performance test results of an integrated GPS/MEMS inertial navigation package”. In Proceedings of the ION GNSS 2004, Long Beach, CA, USA, 21–24 September 2004; pp. 825–832.

[3] Q. Zhong and L. Mirkin. “Control of integral processes with dead time” Part 2: Quantitative analysis. IEE Proceedings Control, Theory and Applications, 149(4), 291–296, 2002.

[4] J. Ryi, W. Rhee and J. Choi. "Effective Perceived Noise Level Prediction for a Propeller driven UAV by using Wind Tunnel Test Data", Journal of Korean Society for Aeronautical & Space Science, No. 41(1), pp. 10-16, Jan. 2013.

[5] M. Goo and S. Hong, "Target Tracking Control of Quadroto UAV using Vision Sensor", Jour-nal of Korean Society for Aeronautical & Space Science, No. 40(2), pp. 118-128, 2012.

[6] P.E.I.Pounds, D.R.Bersak, and A.M.Dollar, "Grasping from the air: Hovering capture and load stability"; in Proc.IEEE Int Robotics and Automation (lCRA) Conf, 2011, pp.2491-2498.

[7] Y.Ghadiok, 1.Goldin, and W.Ren, "Autonomous indoor aerial 2g0ri1p1p ing using a quadrotor," in Intelligent Robots and Systems (IROS), lEEElRSJ International Coriference on, sept.2011, pp.4645-4651.

[8] A.Keemink, M.Fumagalli, S.Stramigioli, and R.Carloni, "Mechanical design of a manipulation system for unmanned aerial vehicles", in Robotics and Automation (ICRA), 2012 IEEE International Conference on, may 2012, pp.3147-3152.

[9] S.Bellens, 1.De Schutter, and H.Bruyninckx, "A hybrid pose / wrench control framework for quadrotor helicopters", in Robotics and Automation (ICRA), 2012 IEEE International Conference on, may 2012, pp.2269-2274.

[10] L. Fei, H. Yingdong, X. Zhihua and W. Jingchun, “Stability Margin Analysis of Multivariable Aircraft Control System under Single Loop Perturbation”, 2013 32nd Chinese Control Conference, July 2013, pp. 2292-2927.

[11] K. Sailan and D. Kuhner, “Speed Control of Unmanned Ground Vehicle for Non Autonomous Operation” International Journal of Materials Science and Engineering Vol. 3, No. 1 March 2015, pp. 44-48.

[12] E. Hartley, “A Tutorial on Model Predictive Control for Spacecraft Rendezvous”, 2015 European Control Conference (ECC), July 2015, pp. 1355 – 1361.

[13] E. Oland and R. Kristiansen, “Adaptive flight control with constrained actuation”, 2014 American Control Conference, June 2014, pp. 3065 – 3070.

[14] L. Romero, D. Pozo and J. Rosales, “Quadcopter stabilization by using PID controllers” MASKANA, I+D+ingeniería 2014, 2014, pp. 175-186.

[15] C. Johnson, "A General Theory of Set-Point Regulation for MIMO Linear Dynamical Systems; “The Case of State Set-Point Regulation”, Proc. of the 38th Southeastern Symposium on System Theory, Tenn. Tech. Univ.; Cookeville, TN., Mar 5-7, 2006, pp 27-32.

[16] G. Enzner, “Analysis and optimal control of LMS-type adaptive filtering for continuous-azimuth acquisition of head related impulse responses”, 2008 IEEE International Conference on Acoustics, Speech and Signal Processing, 2008, pp. 393-396.

[17] J. Park, W. Chung and J. Yuh, “Nonlinear and optimal PID control of autonomous underwater vehicles”, Underwater Technology, 2000. UT 00. Proceedings of the 2000 International Symposium, 2000, pp. 193-198.

[18] A. J. Parente and P. Paglione, “Design of a flight control system based on the total heading control system philosophy”, 19th International Congress of Mechanical Engineering, Proceedings of COBEM 2007, november 2007, pp. 1-10.

[19] G. Grimma, A. Teelb and L. Zaccarian, “The l2 anti-windup problem for discrete-time linear systems: Definition and solutions” Systems & Control Letters, 2008, pp. 356-364.

[20] G. Yang, J. Wang and Y. Soh, “Guaranteed cost control for discrete-time linear systems under controller gain perturbations”, Linear Algebra and its Applications, Volume 312, Issues 1–3, June 2000, pp. 161–180.