# STUDY OF FLIGHT CONTROLS MODIFICATION TO ADAPT A REGIONAL AIRCRAFT TO UNMANNED AIR VEHICLE CONFIGURATION

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***Abstract.*** *Nowadays it is observed a strong tendency of growing in the unmanned aerial vehicles market, for military or civilian purposes, however they still present a low reliability and high tax of accident that appears as a big obstacle for this kind of aircraft. This is in a large amount due to fact that these aircraft do not have regulations and certification process so severe than passenger's aircraft. Taking this reality into account the present work has as objective to propose a sequence of development to make it possible to transform a regional aircraft, with high reliability, into an unmanned aerial vehicle controlled by totally automatic systems. For that intention, the main characteristics of a regional aircraft regarding to flight control systems were detached, and basing on them, it is proposed the development of system that increase the aircraft automatism, finally leading to an aircraft that should be totally able to control itself without an on board crew. The development of the automatic flight control system was performed based on the definition of criteria for stability, command response and disturb rejection, with the objective of making the system modification process more simple and with guaranteed results. The methodology used is based on gain optimization for particular operational conditions, followed by linear regression of the points obtained in order to generate gain schedule functions that contain the entire required operation interval. This process makes easy the utilization of existent architectures and the task of adaptation to a new aircraft configuration becomes clear, standardized and with good expectation of success*

***Keywords****: UAV, optimization, AFCS, stability criteria, linear regression.*

## 1. INTRODUCTION

The most common definition for Unmanned Aerial Vehicles (UAVs) was given by USA Department of Defense, according to this definition:

"A powered, aerial vehicle that does not carry a human operator uses aerodynamic forces to provide vehicle lift, can fly autonomously or be piloted remotely, can be expendable or recoverable, and can carry a lethal or non-lethal payload. Ballistic or semi ballistic vehicles, cruise missiles, and artillery projectiles are not considered unmanned aerial vehicles."

Although its use is recent the research on UAV were initiated in the World War I and had continued in Germany during the Second War generating the V-1 "flying bomb", an embryo of modern UAVs. However its use only has initiated in the 1970s during the Vietnam War with AQM-34 Firebee from U.S.A. The developments of Israeli Air Force, as the Pioneer, have stimulated the use of UAVs in the end of 70s and during 80s, typically in regional conflicts as the success of UAVs in Lebanon operations in 1982 (Bone and Bolkom, 2003).

With the evolution of avionics systems a larger aircraft automatism become possible for civil and military use, so more UAVs development projects have been initiated, with bigger capacity of load, endurance, range and that are capable to perform more complex missions.

The UAVs had emerged as an important source of tactical level information of the theater of operation. The American Air Force used this type of aircraft in its more recent conflicts as:

- Gulf War - Pioneer,
- Conflict in the Balkans - Predator,
- Afghanistan and Iraq - Global Hawk.

The traditional uses of UAVs are for Intelligence, Recognition, Monitoring and Target Acquisition. These aircraft acquire real time images from the terrain that can be used to direct bombers and fighters, to monitor movement in controlled area or to lead troops. This kind of work when made for manned aircraft can be considered a three "D" job (dull, dirty and dangerous) and is this niche of market where the UAVs takes greater advantage.

At U.S.A. the governmental budget planned to research and development of UAVs for the years 2001 and 2004, went from US$ 667 million to US$ 1.39 billion (Bone and Bolkom, 2003), and is foreseen to arrive at US$ 3 billion per year from 2008, according to U.S.A Department of Defense. In Europe, the United Kingdom, France, Germany and Italy also intend to invest heavily in UAVs. The European budget foresees for investment in UAVs around € 5.5 billion up to 2012 (Spacedaily, 2004).

In the panorama of civil aircraft, although the use of UAVs is still incipient the prediction for next years is promising. The American aviation regulatory agency (FAA) formed a committee to establish criteria which the UAVs of civil use will have to comply with, in an indication of the concern over this subject.

However the development of new projects of UAV always faced the problem of low reliability, its tax of accident is 100 times bigger than for manned aircraft (Bone and Bolkom, 2003), in part for the fact that these aircraft are developed from research programs, but also for the lack of requirements that can assure an acceptable level of safety for this kind of vehicles.

In this point passenger's aircraft take advantage in relation to the UAVs, because the concern with safety took the projects to a high level of reliability and robustness to fail. It is this fact that makes interesting the adaptation of a platform originally conceived as a manned aircraft for passengers transport in an unmanned air vehicle.

## 2. PROPOSAL OF LINE OF EVOLUTION

To transform a manned aircraft into a completely independent UAV, a line of evolution is proposed aiming initially to provide the manned aircraft with automatic systems for piloting functions, in the sequence to develop automatic systems of protection and fault management, and finally to reconfigure the aircraft removing all the systems designed to interface with the crew.

Taking into account this approach the following line of evolution is considered:

1. Development of an automatic Thrust Control System;
2. Development of Vertical and Lateral Navigation System;
3. Development of Automatic Approach, Flare and Landing;
4. Development of Automatic Take-off;
5. Development of Automatic Landing Gear Deployment and Automatic Brake;
6. Development of Automatic Control of Flaps and Spoilers;
7. Development of a System for Communication with Ground and remote Flight Plan Reconfiguration;
8. Make Compatible the Automatic Flight Control System with Protection and Failure Warning Systems;
9. Reconfiguration of flight command chains with the removal of the flight control devices;
10. Reconfiguration of pilot cabin with the removal of human being interface devices.

These steps may be divided in four groups according to the kind of methodology required to develop the functionality.

The first group containing the initial six steps is related to piloting and navigation actions and their functions consist on controlling the dynamical behavior of the aircraft in the entire operational envelope. The methodology proposed in this work is related to this group and it will be taken as example the development of an adapted automatic approach system.

The second group is formed by the step seven and is related to the communication function that any aircraft must have, including a UAV. For traffic control, treatment of unexpected cases and other situations that require external human assistance it is necessary that UAV has a system of communication that allows data exchange and even remote adjustments made in the aircraft.

The third group is composed by protection and warning systems and has still a long way to become a mature system. For a UAV all the messages that require a pilot action shall be substituted by automatic procedures to avoid the loss of aircraft control and have to take into account a degraded state of the aircraft.

The last group consists on reconfigurations of the aircraft to eliminate all the devices that are related to a presence of a human pilot, like the control devices, displays, buttons, seat, etc. This last task is intended to eliminate weight and is one of the main advantages of modifying an aircraft to a UAV.

## 3. PROPOSAL OF METHODOLOGY

Automatic pilot systems are currently manufactured by companies specialized in avionics, since these systems involve software programming and hardware implementation that requires a specific technology of development and manufacture. The aircraft manufacturer role is specifying the characteristics of the system and integrates it into the aircraft. Does not exist any reason so that it should be different in the case of the development of an unmanned aircraft.

Taking this idea and for the aircraft manufacturer point of view, the project of an automatic flight control system is made by the specification of the functional characteristics, the required performance and the characteristics related to reliability and system malfunction.

With regard to flight characteristics, the most relevant subject is the specification of required performance for each autopilot mode, since it will be based on these requirements that the controllers will be designed. In this work therefore will be given emphasis to specification of criteria that guarantees a good flight characteristic, which will translate the required performance.

The starting point to adapt a control law for a slightly different aircraft configuration is to define the criteria to be used in order to maintain or enhance the flight performance. Traditionally it is used a set of stability criteria, command response criteria and disturbance rejection criteria. These criteria will be used as restrictions to the simulation program that will establish the gains for the controller.

The method consists in building a computer model of the aircraft and of the controller architecture, where the gains of the control law are parameters that have its values attributed externally.

For the calculation of the gains an optimization routine shall be conceived to use the models to simulate the behavior of the aircraft after specific commands and thus to minimize a cost function related to the aircraft response. This optimization routine uses as restrictions the defined criteria.

The same process of calculation must be repeated for several conditions of altitude and speed, generating a gain matrix that shall be condensed by linear regression in gain scheduling functions.

With the gain scheduling functions the simulations shall be run again to validate the process in the whole altitude and speed envelope. If the gain function does not pass in the criteria after the validation step it can indicate that the criteria are too restrictive or that the current architecture can not achieve the desired flight performance. In this point the designer has to decide between a change in the criteria that can reduce the flight performance or a change in the architecture that can lead to the development of a new controller.

Summarizing the methodology steps are as follow:

- Define criteria to achieve the desired flight performance
- Obtain a computer model of the baseline architecture
- Generate a computer model for the new configuration aircraft
- Define a set of operational conditions (speed, altitude, …)
- Calculate optimized gains for each operational condition using the aircraft and controller models, for the optimization define cost functions and restrictions based on the chosen criteria.
- Build a table with the conditions and the calculated gains
- Calculate a function for each gain that relates the gains to the operational conditions (gain scheduling)
- Validate the obtained gain function by running the simulation with this gains for the entire aircraft envelop of operation
- Modify the criteria if the gain function is not validated and if the flight performance is affected study modifications in the controller architecture.

### 2.2. Example of Lateral and Vertical Approach

To show an example of the methodology it will be presented the definition of the gains for lateral and vertical approach of existent control law architecture. The control law for lateral approach chosen as an example is a simply architecture that uses the lateral distance and lateral velocity as input for the roll command.

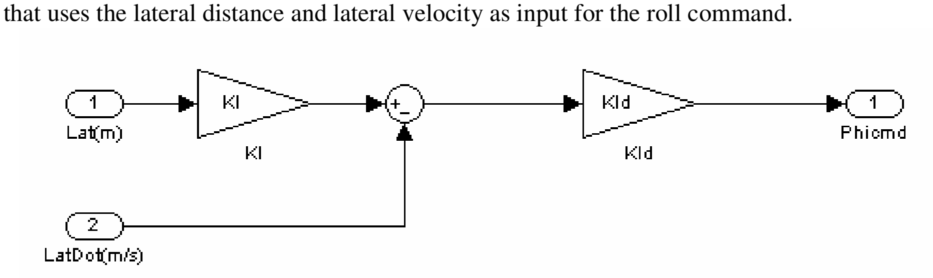


Figure 1 - Lateral Approach Control Law

Using a Matlab® routine of optimization with the original aircraft gain as initial values:

```
[x, fval] = fmincon(@objfun,x0,[1 0 ;0 1 ;-1 0;0 -1],[20; 20; 0; 0],[],[],[],[],@confun);
```

Where the objective function calculates the sum of the lateral distance from the aircraft to the runway axis, this function initiates assigning gain values to the model and in the sequence simulates the aircraft behavior using these gains:

```
function f = objfun(x)

assignin('base','Kl',x(1));
assignin('base','Kld',x(2));

sim('uav_loc',500)

f = sum(abs(lat.signals.values));
```

The constraint function contains the criteria defined to assure a good flight quality to the aircraft:

```
function [c,ceq] = confun(x)
```

```
[aa,bb,cc,dd] = linmod('uav_loc');
syss = ss(aa,bb,cc,dd);
[MG MF wcg wcp] = margin(syss);
MG = 20*log10(MG);
MF = mod(MF,360);

sim('uav_loc',500)
T = lat.time;
Yd = 1 - lat.signals.values/lat.signals.values(1);
[Mp100,tp,tr,ts2,Mp] = stepchar(T,Yd);

c = [ 6 - MG; % MG >= 6 dB
     45 - MF; % MF >= 45º
    Mp100 - 15; % Mp100 <= 15%
    ts2 - 500 % ts2 <=500
];
ceq = [];
```

This example shows as restrictions to the runway axis capture an overshoot of 15 % and a settling time of 500 s, in addition to gain margin of 6 dB and phase margin of 45 º. Following this routine it will be obtained the optimum gain set for a particular initial condition. The next step is to modify the initial condition of speed, altitude and intercept angle and obtain a gain matrix. This gain matrix will be used to extract a gain scheduling function according to speed and altitude using a data analysis tool that calculates linear regression. The functions obtained are similar to the example:

**Kl = 0.007468 - 3.2e-6*ALT + 5.08e-5*VEL**
**Kld = 0.2854 – 1.8e-4*ALT + 0.001328*VEL**

Table 1 – Gain Matrix for Particular Optimization

| ALTITUDE (FT) | AIRSPEED (KTS) | INTERCEPT ANGLE (º) | Kl | Kld | OVERSHOOT (%) | SETTLING TIME (s) |
|---|---|---|---|---|---|---|
| 1500 | 120 | 90 | 0.0058 | 0.1336 | 0.83 | 210.26 |
| 1500 | 170 | 90 | 0.0094 | 0.2036 | 0.42 | 145.51 |
| 1500 | 220 | 90 | 0.0146 | 0.1249 | 14.43 | 277.78 |
| 1500 | 270 | 90 | 0.0245 | 0.1248 | 22.8 | 340.19 |
| 1500 | 320 | 90 | 0.0176 | 0.2915 | 3.22 | 147.6 |
| 1500 | 370 | 90 | 0.0206 | 1.3781 | 0 | 112.43 |
| 2000 | 120 | 90 | 0.0071 | 0.1683 | 0.73 | 193.41 |
| 2000 | 170 | 90 | 0.0049 | 0.1296 | 0.97 | 169.75 |
| 2000 | 220 | 90 | 0.0148 | 0.1813 | 7.51 | 235.19 |
| 2000 | 270 | 90 | 0.0002 | 0.1098 | 12.55 | 157.76 |
| 2000 | 320 | 90 | 0.0245 | 0.338 | 8.07 | 145.57 |
| 2000 | 370 | 90 | 0.0209 | 0.1266 | 26 | 342.33 |
| 2500 | 120 | 90 | 0.0068 | 0.1865 | 0.23 | 212.05 |
| 2500 | 170 | 90 | 0.0099 | 0.2069 | 0.83 | 135.83 |
| 2500 | 220 | 90 | 0.0128 | 0.2558 | 0.93 | 103.98 |
| 2500 | 270 | 90 | 0.0245 | 0.1249 | 22.74 | 340.12 |
| 2500 | 320 | 90 | 0.0002 | 0.1225 | 16.03 | 142.09 |
| 2500 | 370 | 90 | 0.0223 | 0.336 | 5.52 | 136.82 |

Table 2 – Gain Matrix after Linear Regression

| ALTITUDE (FT) | AIRSPEED (KTS) | INTERCEPT ANGLE (º) | Kl | Kld | OVERSHOOT (%) | SETTLING TIME (s) |
|---|---|---|---|---|---|---|
| 1500 | 120 | 90 | 0.008764 | 0.17476 | 2.390275 | 306.63 |
| 1500 | 170 | 90 | 0.011304 | 0.24116 | 1.696687 | 140.63 |
| 1500 | 220 | 90 | 0.013844 | 0.30756 | 2.382643 | 187.8 |
| 1500 | 270 | 90 | 0.016384 | 0.37396 | 3.229285 | 173.07 |

| | | | | | | |
|---|---|---|---|---|---|---|
| 1500 | 320 | 90 | 0.018924 | 0.44036 | 4.04056 | 156.47 |
| 1500 | 370 | 90 | 0.021464 | 0.50676 | 6.553229 | 148.7 |
| 2000 | 120 | 90 | 0.007164 | 0.08476 | 1.783386 | 202.89 |
| 2000 | 170 | 90 | 0.009704 | 0.15116 | 1.212059 | 153.83 |
| 2000 | 220 | 90 | 0.012244 | 0.21756 | 2.033304 | 179.51 |
| 2000 | 270 | 90 | 0.014784 | 0.28396 | 3.009848 | 178.04 |
| 2000 | 320 | 90 | 0.017324 | 0.35036 | 3.926005 | 162.32 |
| 2000 | 370 | 90 | 0.019864 | 0.41676 | 5.580663 | 150.81 |
| 2500 | 120 | 90 | 0.005564 | -0.00524 | 2.236246 | 366.21 |
| 2500 | 170 | 90 | 0.008104 | 0.06116 | 1.009876 | 165.98 |
| 2500 | 220 | 90 | 0.010644 | 0.12756 | 1.850499 | 121.02 |
| 2500 | 270 | 90 | 0.013184 | 0.19396 | 2.91393 | 184.96 |
| 2500 | 320 | 90 | 0.015724 | 0.26036 | 3.913183 | 169.24 |
| 2500 | 370 | 90 | 0.018264 | 0.32676 | 5.091854 | 154.61 |

The final step is validating this gain scheduling function, simulating again all the conditions using the gains according to the function.

This methodology has shown a good level of efficiency as some conditions in the particular optimization procedure do not comply with the restrictions, but when the linear regression is performed the outlier points disappear from the gain function that homogenizes the response for all the conditions.

For the vertical approach the same methodology was used but in this case the criteria for a good aircraft performance were chosen to be related to the aircraft behavior under wind conditions. So the simulations have as input variables not only altitude and aircraft speed but also wind speed value.

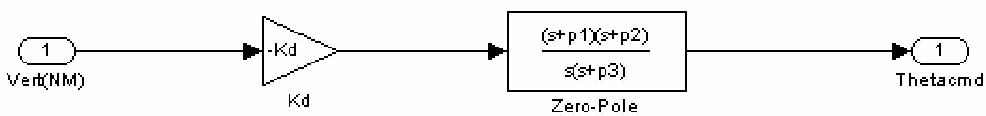


Figure 2 - Vertical Approach Control Law

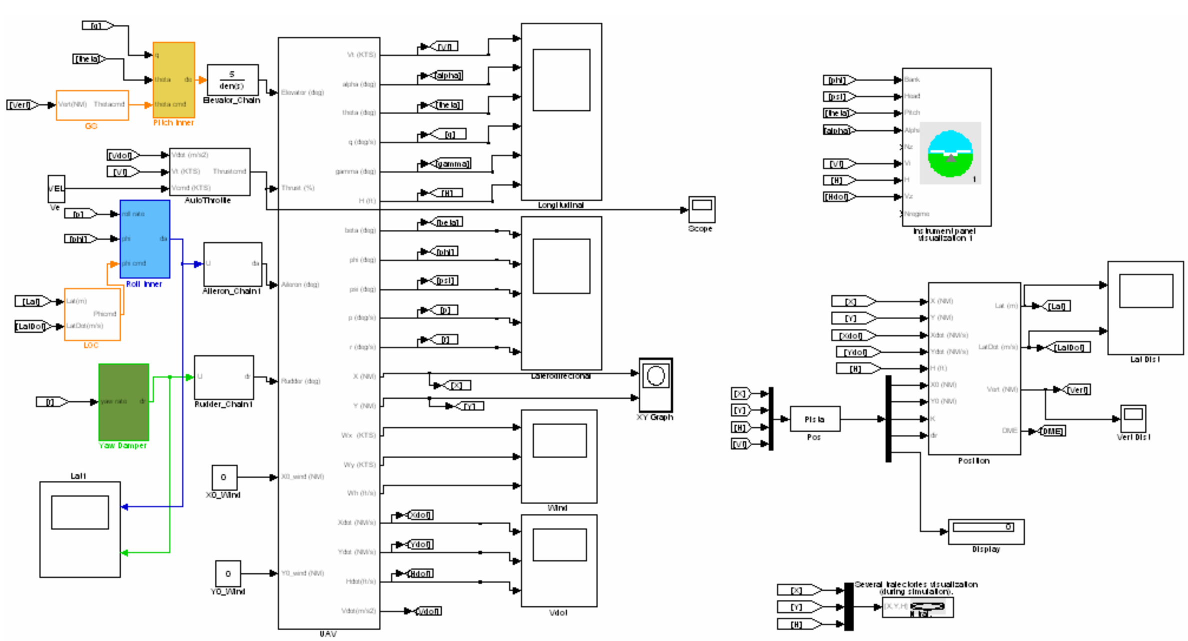


Figure 3 – Simulation Tool Overview

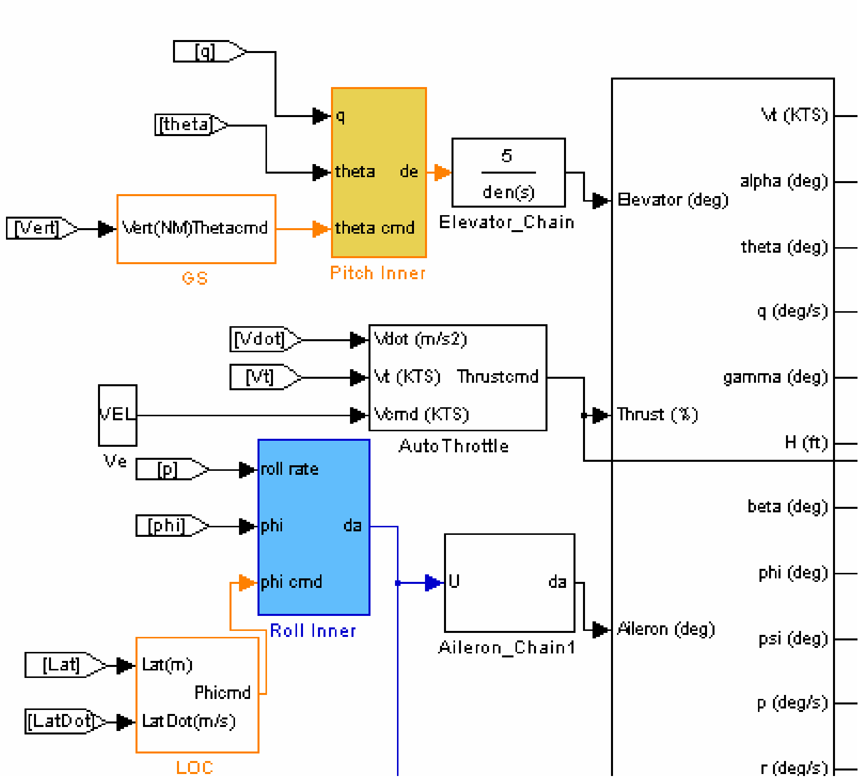


Figure 4 –Simulation Tool - Lateral and Vertical Approach

### 2.3. Results

With the control law gains obtained using linear models the whole approach was simulated using a non-linear model of the aircraft. This validation is necessary to analyze the behavior of the controller in a more representative environment. However an unsatisfactory result may not lead to a gain adjustment but to a re-evaluation of the criteria adopted, increasing the margins and improving the performance required. The process of making the criteria more restrictive can invalidate the controller architecture and demand for some changes in this architecture or the development of a new one.

Below it is shown the results for a simulated approach with 45 º of intercept angle at 3000 ft (914.4 m), where the first segment is the lateral approach and the second is the vertical approach.

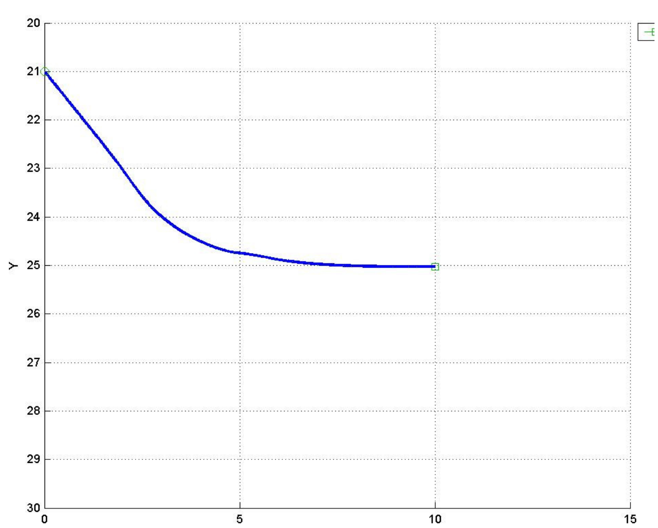


Figure 5 – Lateral Approach

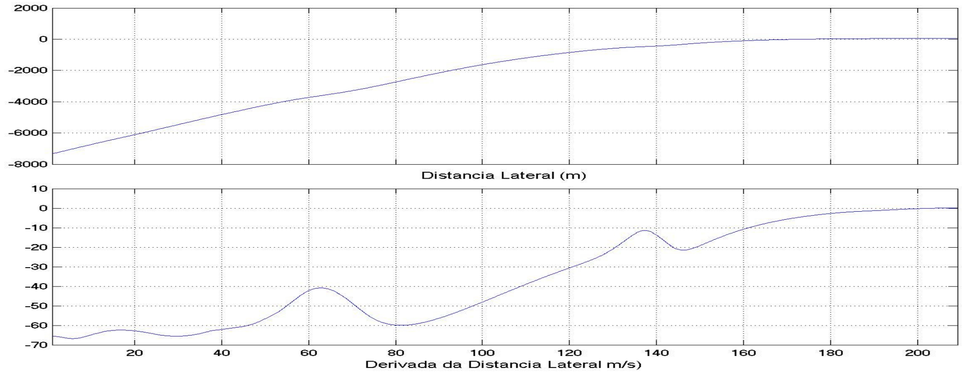


Figure 6 – Lateral Distance and Lateral Speed


Figure 7 – Vertical Approach

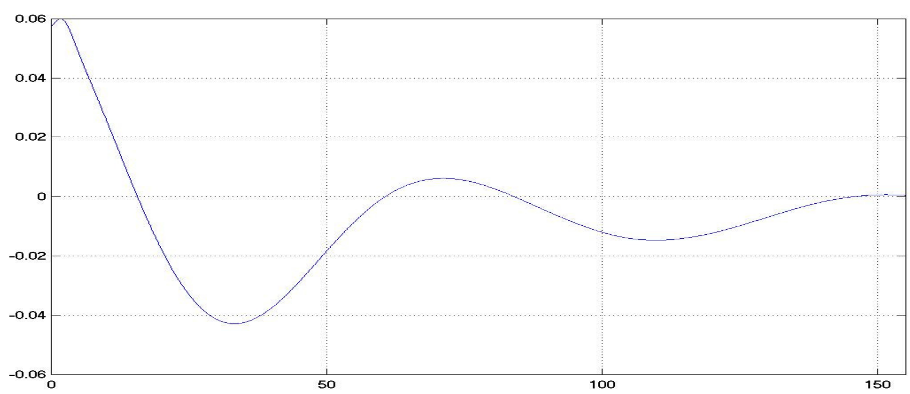


Figure 8 – Vertical Distance

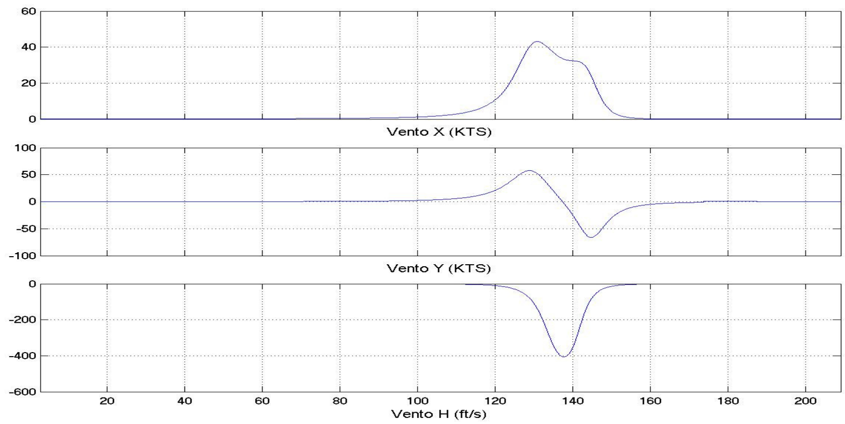


Figure 9 – Wind Speeds (X, Y, H)

## 2.3. Conclusion

The idea of adapt a manned regional aircraft to a UAV configuration may be in an initial view a difficult and not advantageous task. However if a sequential approach is taken with the objective of increasing the automatism in a step by step way, such development can provide a profitable and self sustainable path to a UAV. The concept of unmanned aircraft is currently associated to small aircraft, however the concept of increasing automatism is associated with large aircraft for commercial operations. The steps to be followed in development terms do not involve creation of total new systems that already do not exist in certain scale, however it foresees an effort of adaptation to the reality of absence of the human element controlling or monitoring the actions. The intermediate developments will already be products with an associated value that would pay for their own development.

In relation to the design of controllers, the methodology described makes easy the use of existing architectures, in this manner the task of adapting the baseline architecture of controller to the a new configuration of aircraft can be made in a clear and standardized form, generating quantifiable requirements that may be used to evaluate suppliers proposals and decide for the proposal that better accomplish with the desired performance.

The gain adjustment task is specific for each aircraft configuration and without a higher level quantifiable requirement a configuration modification may lead to serious reduction of quality in the aircraft behavior under automatic control. The use of a methodology that focus in the definition of higher level requirements not in gain adjustments is more appropriate to aircraft variations where UAVs are only examples, but that can be applied also to aircraft family designs and modernized versions of existing aircraft.

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