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CLIMB-OPTIMIZED AUTO TAKEOFF CONTROLLER DESIGN USING FIXED-STRUCTURE H-INFINITY CONTROL TECHNIQUES

Rafael Marin Herrera
EMBRAER, Av. Brig. Faria Lima, n 2170, Putim, São José dos Campos, SP - Brasil
rafael.herrera@embraer.com.br
Pedro Paglione
ITA, Praça Mal.-do-ar Eduardo Gomes, n 50, Vila das Acácias, São José dos Campos, SP - Brasil
paglione@ita.br,

Abstract. *The purpose of this paper is to present the design of controllers for an AutoPilot in the takeoff phase of flight (Auto Takeoff) using Fixed-Structure H∞ based control techniques. This Auto Takeoff System is considered to have a previously known climb-optimized pitch angle for each aircraft height for a given aircraft configuration.*
The following control techniques were explored: SISTUNE and H∞ STATIC OUTPUT FEEDBACK.
A complete rigid body mathematical model with other aircraft systems modeled (such as flight controls, landing gear and hydraulic system) of a commercial aircraft with the capacity of carrying about 100 passengers was used to extract the linear models necessary for the controllers design and used for the non-linear time domain simulations as well.
This work defines controller design goals suitable to the real application, shows the design procedure used and shows simulations of the Auto Takeoff with optimized pitch angle curves.

Keywords: *Auto Takeoff, Autopilot, Systune, H-Infinity Control, Robust Control*

1. INTRODUCTION

Joining the need of Automatic Flight Control Systems in modern aircraft and the market pushing aircraft manufacturers to develop better systems, we find a scenario where automation is present in all fight phases providing flight envelope protection, enhancement of aircraft inherent dynamic characteristics, weight savings, reduction of pilot's workload, smoother aircraft movements and hence improved levels of comfort and safety.

Although AutoPilot is well accepted and widely used in most of the flight phases, the takeoff phase is one of the few where AutoPilot is still not fully present in commercial aviation. Some systems have engine-out protection providing automatic rudder compensation in case of engine failure during takeoff, some have automatic tail strike protection in case the takeoff rotation is too strong and some have pitch or speed hold AutoPilot after a certain altitude still during takeoff after the lift-off. But the rotation and initial lateral and longitudinal control is mostly still under pilot's hands.

Besides of the difficulties of the ground-air transition to design a proper controller, the absence of it is not a technical limitation. Industry is still striving to find reasons to automate this flight phase as it is very expensive to design and certify an Auto Takeoff system. It is also under discussion the operational gain of having such system and the payback of it.

Recent works show that there are advantages of an Auto Takeoff system. Automating takeoff allows pilots on board to be more available to monitor the system, helping crew to recognize and react faster to a failure as the workload is reduced (Genova, 2011). This increases the level of safety of the takeoff procedure. It also creates a trajectory pattern reducing the variation of manual control of each pilot. This optimization reduces fuel burn during takeoff but it is not a big gain as the savings are small comparing to overall fuel consumption. On the other hand, this non-optimal behavior leads aircraft manufacturers to design the takeoff procedures conservatively, which either reduces the takeoff weight for a given air field length or limits the operation in smaller airports (Anjos, 2013).

Commercial aviation industry already shows interest in designing an Auto Takeoff System. (Villaumè and Jeanneau, 2007) depicts an study from Airbus presenting an Auto Takeoff system architecture for their airliners and the results of a control law design validated in Flight Simulators. Embraer also has a high level of automation in their commercial jets with AutoPilot for most phases of flight but Takeoff initial guidance still does not have automatic control. Embraer shows interest in automating takeoff due to its patent: Climb-Optimized Auto Takeoff System (Embraer, 2012).

The primary objective of the research presented in this paper was to develop controllers for an AutoPilot for the takeoff phase of flight (Auto Takeoff) using Fixed-Structure H_∞-based control techniques with previously known climb-optimized pitch angle trajectory and optimized takeoff speeds for a given takeoff configuration. The optimized pitch angle trajectory and speeds were not in the scope of this work and the ones calculated in (Anjos, 2013) were used as reference.

This kind of Auto Takeoff system is protected by the Embraer's owned patent Climb-Optimized Auto Takeoff System (Embraer, 2012). As the studies in this work are part of a professional master program sponsored by Embraer, the content of the patent is used as reference.

2. STATEMENT OF THE AUTO TAKEOFF PROBLEM

The engineering problem explored in this work is to design a control law for the Auto Takeoff system that is robust regarding operating conditions variation. Using the analogy of Fig. (1) extracted from (Embraer, 2012), the goal is to design a *Pitch Control Subsystem* to a known optimized *Pitch Guidance Subsystem*. To achieve that, the control law shall have good tracking characteristics.

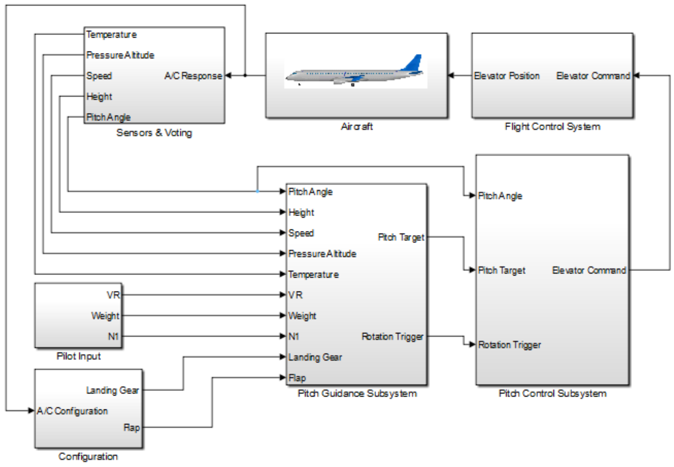

Figure 1. Auto Takeoff system diagram from (Embraer, 2012)

Although the Auto Takeoff system must comply with all applicable certification requirements of Title 14 of CFR part 25 (or any other certification requirements from a certification authority other than FAA) and geometrical limitations, they are already covered by the restrictions of the optimization from (Anjos, 2013), which is used as reference for the *Pitch Guidance Subsystem*. As this work uses the optimum curves from (Anjos, 2013), all requirements are inherent from the controller reference curve.

The control architecture chosen for the Auto Takeoff is depicted in Fig. (2).

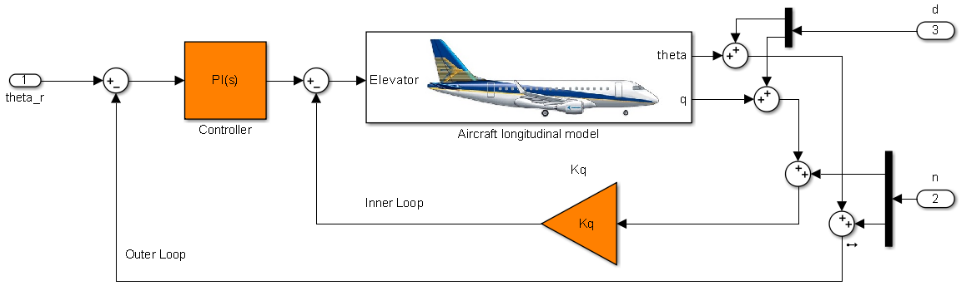

Figure 2. Auto Takeoff control architecture

A classical control architecture was selected with a pitch rate feedback with gain K_q as inner loop and a theta feedback as outer loop with a PI controller to the error between current pitch angle Θ and desired pitch angle Θ_{ref}. The pitch rate feedback improves the rotation characteristics avoiding strong rotations.

The overall architecture may be regarded as a standard PID system since the pitch rate q is the derivative of Θ but the difference is that the measured pitch rate is provided to the system instead of calculating it at the controller from the measured value of Θ. The inner loop stability needs to be guaranteed to allow robustness of the system in case of a failure in the outer loop path.

3. AIRCRAFT MODEL AND LINEARIZATION POINT

The aircraft model is one of the most important pieces of the control system design. Any inaccuracy in the model may lead to a controller that makes no sense in the real world application.

The model used in this work was adapted from a model extensively explored in previous works such as (Oliveira, 2011) and (Anjos, 2013). It is comprised of a rigid body aerodynamic aircraft model of a commercial aircraft with the capacity of carrying about 100 passengers validated using wind tunnel simulation and includes ground effect model, complete flight controls models, landing gear model, engine models and atmospheric model as well. This complete model was taken as a black box and details about it were not in the scope of this work.

As important as the non-linear model used are the linearization points considered for the design of the control law. It is very hard to choose a linearization point for the takeoff because many non-linear variables are present in the ground-air transition and a linear model considers only one operating point as representing the complete movement. As an academic exercise, this work focuses its efforts in a set of linear models when aircraft is around 15 ft above ground. Other linearization points should be considered for a more complete assessment.

4. H_∞-BASED CONTROL TECHNIQUES

Fixed-structure techniques were chosen instead of unstructured matrix feedback in order to keep the controller easy to understand just by looking at the designed gains. With fixed structure controllers, it is possible to have a feeling on how good the design is just by looking at the gains. For instance, it is possible to see at a glance that if the proportional gain is too big, an oscillatory behavior is to be expected in the simulation; or if the integral gain is too small, a steady-state error is to be expected.

Other methods based on Algebraic Riccati Equations (AREs) or Linear Matrix Inequalities (LMIs) would lead to a complex matrix feedback that does not have a straightforward understanding, requiring lots of simulation for validation of the quality of the design.

This work explored two control techniques, namely, *SYSTUNE* and *H_∞ Static Output Feedback*. *SYSTUNE* is a powerful modern control tool available for MATLAB in the *Robust* Control System Toolbox version 4.2 and later versions. *H_∞ Static Output Feedback* is the technique detailed in (Gadewadikar, *el al.*, 2006).

5. H_∞-BASED CONTROL TECHNIQUES

The design goals are detailed in section 5.1 and the actual design using *SYSTUNE* and *H_∞ Static Output Feedback* are depicted in sections 5.2 and 5.3.

5.1 Controller design goals

As the Auto Takeoff main objective is to follow an optimized pitch angle curve, the first design goal is good tracking performance. This goal is described in terms of the cut-off frequency of the open loop system:

Goal 1: The cut-off frequency of the open loop system needs to be around 50% bigger than the short period frequency of the aircraft longitudinal model.

Another concern is to avoid the feedback of the structural oscillatory modes of the aircraft. It is assumed that around 2.5 rad/sec is a good frequency value to attenuate this feedback:

Goal 2: Open loop frequency bandwidth around 2.5 rad/sec.

A design goal aimed to guarantee passenger comfort is the maximum load factor limit:

Goal 3: Maximum vertical load factor (n_z) during takeoff rotation limited to 1.2 as defined in (Oliveira, *et al.*, 2010).

For the stability margins (gain and phase margins) the reference values are the ones recommended by (United States, 2008). This recommendation is made for all the AFCS closed loop paths:

Goal 4: Gain margin of 6 db and phase margin of 45 degrees for either the inner loop when the outer loop is open and the outer loop when the inner loop is open.

5.2 Controller design using *SYSTUNE*

SYSTUNE needs a set of SOFT and HARD requirements written using the MATLAB *TuningGoal* classes and its algorithm uses a multi-objective constrained optimization problem of the form of Eq. (1) (Apkarian and Noll, 2014).

$$\begin{aligned} &\textbf{minimize} \quad && f(x) = \max_{k_s \in SOFT} \left\| T^{k_s}_{w_i z_i} \right\|_\infty \\ &\textbf{subject to} \quad && g(x) = \max_{k_h \in HARD} \left\| T^{k_h}_{w_j z_j} \right\|_\infty \leq 1 \end{aligned} \tag{1}$$

Where $T^k_{w_i z_i}$ is the *i*-th closed-loop robustness or performance function of channel $w_i \rightarrow z_i$ for the *k*-th plant model, since it may be defined for different plant models. All T functions are Linear Fractional Transformations depending on the structured controller to be designed. The *T* functions are not written by the user, but MATLAB constructs them from the *TuningGoal* classes and the Simulink model.

Not all of the design goals of section 5.1 were explicitly set as *TuningGoal* requirements in this SYSTUNE design because the more constraints *SYSTUNE* has the more complicated the solution becomes to the algorithm. An iterative process was developed to build a proper controller using requirements that indirectly enforced system's desired goals.

First step was to set some *HARD* and *SOFT* requirements to see if *SYSTUNE* was able to meet them or to see in which frequency range they were not met. If the requirements were not completely met, an analysis was done to see if it was acceptable to relax some requirements. Second step was to evaluate the controller gains to see if they seemed to be suitable. As the controller has a fixed PID-like structure, a quick look at the gains provides a felling on how good the design was before any simulation. Last step was to run frequency domain and time domain analysis and simulations to validate the designed controller against the design goals.

Another concern of this design is the robustness over operating conditions variation. To account for such variations, the design was made for 9 different weight conditions. Therefore, 9 different linear models were used and the final controller is the average gain of the controller designed for each condition. It was possible to notice only a small gain variation between controllers designed with different weight conditions.

The controller designed used the following *HARD* requirements:

Hard Req. 1: 6 db of gain margin and 45 degrees of phase margin for the outer loop using the *TuningGoal.Margins* class;

Hard Req. 2: 6 db of gain margin and 45 degrees of phase margin for the inner loop using the *TuningGoal.Margins* class;

Hard Req. 3: Maximum gain as a function of frequency allowed for the closed loop function using the *TuningGoal.Gain*;

And the following *SOFT* Requirement:

Soft Req. 1: Maximum tracking error allowed as a function of frequency using the *TuningGoal.Tracking*;

Note: More details about how those functions were built using *TuningGoal* are available in (Herrera, 2014).

The average designed gains (mean gain value for all 9 different operating conditions) with the *SYSTUNE* design are:

$K_P = -11.7444$, $K_I = -9.3078$ and $K_q = -5.4464$.

Frequency and time domain simulations show that all design goals are met with this design.

5.3 Controller design using H_∞ *Static Output Feedback*

For this design, the challenge is to select the suitable values for γ (system L2 gain), Q (state weighting matrix) and R (control weighting matrix).

Several values were tested always seeking to meet the design requirements of section 5.1. An exhaustive trial and error process led to the following values: $\gamma = 0.01$, $Q = H_a^T * H_a$; $Q(n_s; n_s) = 5$ and $R = 0.1$. Where H_a is the performance output matrix augmented with the controller dynamics as defined in (Lewis and Stevens, 1992), n_s is the number of augmented state variables, or the number of columns of H_a in other words ($H_a = [0\ 0\ 0\ 1\ 0\ 0\ 0]$). Q ends up being a n_s by n_s matrix with zeros in all positions except for the position related to the state Θ, which has a value 1, and for the last position $Q(n_s; n_s)$, which has the value 5. This last value is to weight the integrator state of the controller.

The average designed gains (mean gain value for all 9 different operating conditions) with the H_∞ *Static Output Feedback* design are:

$K_P = -9.2226$, $K_I = -7.6031$ and $K_q = -3.5168$.

Frequency and time domain simulations show that all design goals are met with this design.

6. TIME DOMAIN SIMULATIONS WITH NON-LINEAR MODEL

After the controllers were designed using the H_∞-based Control Techniques, a final verification of the quality of the designed controllers was done in the application it was designed for, the Climb-optimized Auto Takeoff System.

Matlab Release 2010b with Simulink and a non-linear model of the same aircraft used to extract the linear models were used.

Optimum “theta versus height” curves adapted from (Anjos, 2013) were used as reference. This curve for the medium weight considered in the design is depicted in Fig. (3).

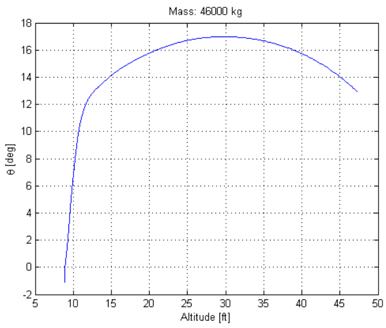

Figure 3. Theta versus altitude reference curve

The optimized speeds V_1 *(decision speed)* and V_r (rotation speed) were also obtained from (Anjos, 2013) for each aircraft weight configuration. Throttle position is set to full throttle until the decision speed V_1 is achieved. After it, an engine failure is simulated and the throttles are put in a medium position where the aircraft engine power is reduced to 50% of the full takeoff power. This simulation is done by reducing both engines to half power instead of actually failing one of them because this work is focused only in the aircraft longitudinal behavior and the lateral compensation is not relevant. The rotation starts when the rotation speed V_r is achieved.

6.1 Auto Takeoff simulations with *SYSTUNE* design

The simulations were made for different aircraft weights, but only the simulation for the medium weight configuration is depicted in this paper. The results are shown in Fig. (4) to Fig. (6). The first figure is the theta (Θ) versus time figure, where it is shown how the aircraft with Auto Takeoff tracks the theta target. It is also depicted in this figure the rotation trigger when the rotation starts (after V_r is achieved). The second figure contains the aircraft indicated airspeed KIAS, the angle of attack α, the CG Height Above Ground Level, the flight path angle γ, the pitch rate q and again Θ to make it easier to compare with the other variables. The third figure shows the control inputs column position and throttle lever angle (TLA), the vertical load factor n_z and the elevator position. In this last figure it is possible to see when V_1 was achieved by looking at the TLA position dropping.

This results show that the controller has good tracking characteristics for this operating conditions. However, a higher than expected overshoot is seen around the time 32 seconds in Fig. (4), but this is due to the fact that the theta target changes abruptly when the altitude is near the final simulation altitude of 35 ft AGL. A reanalysis of this optimum curve would need to be done to see if it is possible to make it smoother at the very end. This abrupt change is very hard to be tracked by a controller.

Another interesting point to note is in Fig. (6) where it is possible to see the column position and the elevator position. Right before 30 seconds, a non-expected change in the commands is noticed. They change from soft nose up direction to nose down direction for a while. After this change, system compensates itself and does what it is supposed to do trying to track the optimum theta curve. This effect does not seem to be caused by the controller. In fact, when the linearized model used for the design is run, this behavior in not present. After further analysis, it was seen that this point is right after the WOW signal goes from 1 to 0, meaning this is near the point where the aircraft actually lifted off. Near the ground, there is the important presence of the ground effect, which is very hard to model and not in the scope of this work. This change in command is most likely related to the non-linearities of the ground-air transition present in the model or due to the dynamic coupling of the ground effect and the designed controller.

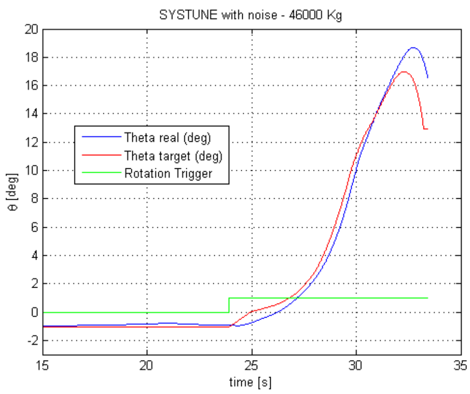

Figure 4. *SYSTUNE* Design - Theta Tracking with 46000 Kg

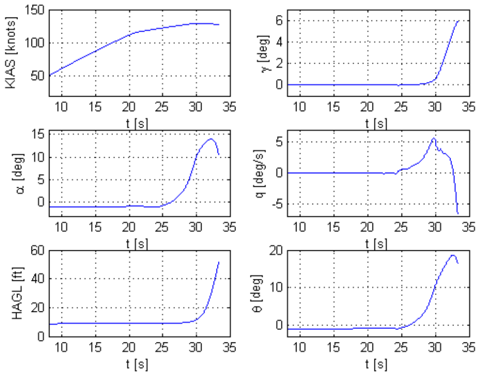

Figure 5. *SYSTUNE* Design – Monitoring Variables with 46000 Kg

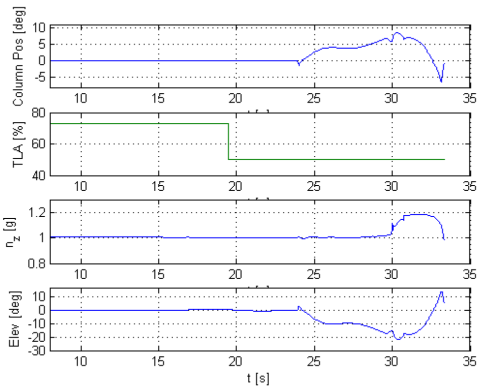

Figure 6. *SYSTUNE* Design - Control Inputs and n_z with 46000 Kg

6.2 Auto Takeoff simulations with H_∞ *Static Output Feedback*

The simulations in the same conditions of section 6.1 but with the H∞ Static Output Feedback are depicted in Fig. (7) to (9).

The same comments of previous section apply.

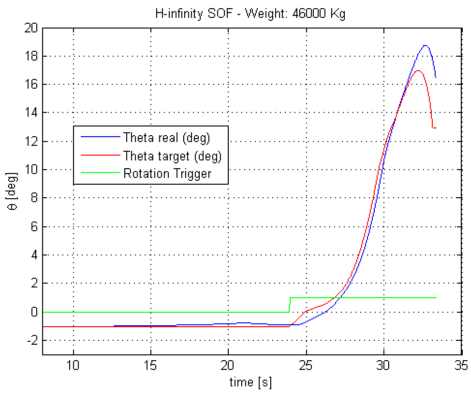

Figure 7. H_∞ *SOF* Design - Theta Tracking with 46000 Kg

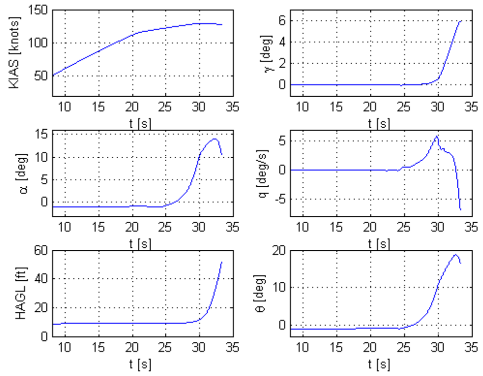

Figure 8. H_∞ *SOF* Design - Monitoring Variables with 46000 Kg

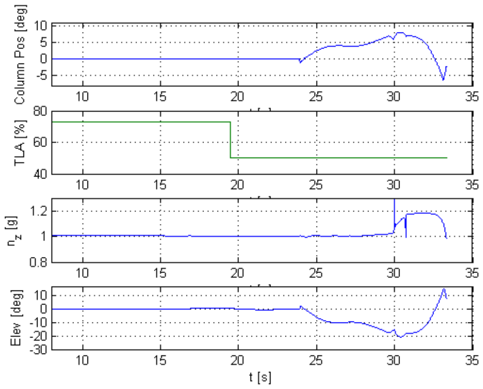

Figure 9. H_∞ *SOF* Design - Control Inputs and nz with 46000 Kg

7. CONCLUSIONS

The primary assumption of this work is that an optimum theta as a function of the altitude was previously calculated and that the control law designed would have great tracking characteristics that guarantee an optimum AutoTakeoff system that reduces the airfield length and that provides the gain aimed by the Climb-Optimized Auto Takeoff System. As this work was being developed, it was noticed that it is very hard to design a robust controller with great tracking performance while keeping all other design goals. The tradeoff makes a good control law in an average aspect but that might not have good tracking in all operating conditions.

Results of the non-linear simulations show that the aircraft theta deviates from the optimum theta and a reanalysis of this response would need to be done to see if the complete AutoTakeoff system with the designed controller indeed provided the expected optimization detailed in (Anjos, 2013).

The approach of having a previously calculated reference curve for the control law without considering the control law dynamics might not be the best one for this system. However, this work has a major contribution in providing an initial control law design that could be added to the optimization of (Anjos, 2013) to get to another optimum trajectory in an iterative process that would lead to a system with real performance improvement.

Regardless of the performance improvement that are not in the scope of this work, the controllers designed are good start points for a real implementation of this system. It is a start point that requires a fine tuning after lots of validation through flight tests in many different aircraft configurations and different atmosphere conditions such as high and low temperatures, strong wind conditions, etc. Pilot's feedback is also an important tool to adjust the control law to design a safe system with soft response, especially in the situation where something goes wrong and that pilot needs to take the controls to recover an unsafe maneuver.

The controllers designed presented good and robust characteristics. The robust part is very important because as in any model-based simulation and design it is impossible to take into account all model variations and even more challenging in the takeoff where the non-linearities of the ground effect and the wheels friction are very hard to be modelled.

The model uncertainties also account for the rigid body aerodynamic simplification and many other small simplifications because it is impossible to model it all. Again, flight tests are required as a final validation of the design but unfortunately it is very expensive and this is one of the reasons why companies are still being careful in implementing an AutoTakeoff system.

SYSTUNE proved to be a very powerful and easy to use tool that could be easily incorporated to real control law design in aviation. In this work, the algorithm almost always converged to a good solution or it was easy to see where the requirements needed to be relaxed in order to get a better design.

H_∞ *Static Output Feedback* technique also had a good controller designed with similar characteristics of the *SYSTUNE* controller, but it is a little harder to achieve a design with the desired characteristics in the frequency domain by the selection of the system L2 gain, the state weighting matrix Q and the control weighting matrix R, which makes this technique less practical in real engineering applications.

The control law part of the AutoTakeoff system explored in this work is only one piece of this system, which is complex and needs to have protections against abnormal operation and proper failure and operation indication in te cockpit, otherwise it will never be certified in any commercial aircraft.

An Auto Takeoff system is a challenging engineering application for any aircraft manufacturer and this work aimed to help giving a step forward in the analysis of the technical viability of it.

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