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Adaptive Control Implementation to include Ground Effect on UAV Simulator

Advisor: Prof. Marco LOVERA
Co-Advisor: Eng. Mattia GIURATO

Thesis by:
Usman ARSHAD Matr. 842207

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To my dear parents and wife, Sana, who have been a continues support and help.

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Thank you all

Abstract

It has been observed that the research on Multirotors UAV has been increased rapidly for few years. Most of the time the focus has been on the autonomy, flight control and manoeuvrability of the rotorcrafts and relatively the near ground phenomena hasn't been studied in details. When the rotorcraft flies at low altitudes, the performance can greatly be influenced during some critical phases of flight, especially during the take-off and landing phase.

Previously, some work has been done at Politecnico di Milano on the characterization of the ground effect and then the first approach for the compensation has been implemented. The phenomena was introduced initially in the simulator using results of different flight experiments conducted before and then a compensation was introduced inside the mixer using the optimised formulation of the Cheeseman and Bennett expression.

The main objective of this thesis is to continue the research on compensation by the inclusion of adaptive augmentation on the altitude control system of multirotor UAVs (the same used in previous thesis). First and foremost step is the development of single axis adaptive scheme. Once the adaptation is performed on 1-DOF altitude dynamics, the scheme is then integrated in the complete simulation model, which is then analysed and compared with the previous model without adaptation.

Sommario

È stato osservato che la ricerca sugli UAV multi-rotore è rapidamente aumentata per alcuni anni. La maggior parte delle volte, l'attenzione sull'autonomia, il controllo del volo e la manovrabilità delle pale rotanti e dei fenomeni di terra relativamente vicini non sono stati studiati in dettaglio. Quando l'aereo si muove a basse altitudini, le prestazioni possono essere significativamente influenzate durante alcune fasi critiche del volo, specialmente durante la fase di decollo e atterraggio.

In precedenza, al Politecnico di Milano è stato svolto un lavoro sull'inclusione dell'effetto suolo nel modello dinamico di aeromobile ad ala rotante progettato nell'università stessa e infine è stato studiato il compenso. I fenomeni sono stati introdotti per primi nel simulatore utilizzando i risultati di diversi esperimenti di volo condotti prima e poi è stata introdotta una compensazione all'interno del mixer usando la formulazione ottimizzata dell'espressione di Cheeseman e Bennett.

L'obiettivo principale di questa tesi è di continuare la ricerca sulla compensazione mediante l'inclusione di Adattamento Avanzato sul sistema di controllo dell'altitudine degli UAV multi-rotore (lo stesso usato nella precedente tesi). Il primo passo è lo sviluppo dello schema adattivo ad asse singolo. Una volta eseguito l'adattamento sulla dinamica di altitudine 1-DOF, lo schema viene quindi integrato nel modello di simulazione completo, che viene quindi analizzato e confrontato con il modello precedente senza adattamento.

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Introduction

This thesis presents the modelling of the single axis altitude dynamics with the inclusion of adaptive control scheme and then how to implement the proposed algorithm on a complete rotorcraft simulator. All this is done to prevent the instabilities in a virtual scenario near the ground surface, since the more the rotorcraft flies near ground, the more instabilities arise and it effects the flight performance. The users have to deal with a lot of issues during take off and landing. The aim of this thesis will be to present an improvement in the flight simulator and future perspective of using adaptive control for the complete rotorcraft simulation.

The thesis is organised as follows:

- The Chapter 1 gathers the most relevant works regarding the adaptive controller and the implementation schemes proposed before. Moreover, the literature survey has also been done on Ground effect and the techniques already been used.
- In the Chapter 2 ,the Model Reference Adaptive Control (MRAC) is being introduced to single-axis dynamic system. Comparative analysis between the systems with and without adaptation is performed, results are obtained and sensitivity analysis is performed with respect to Adaptation rate.
- The Chapter 3 includes the issue of the integrating the adaptation scheme inside the full-scale UAV simulator through a well defined procedure.
- Then the results of the proposed model are examined in Chapter 4 as well as the sensitivity analysis with respect to Adaptation rate.
- At the end, conclusions are made and some directions for further improvements are indicated.

Chapter 1

Background and State of Art

The main goal of this chapter is to recall the already established theories to define or implement ground effect in literature and its influence on the behaviors of helicopters and multirotors based on the references selected.

The chapter is divided into 2 subsections:

- First, we will have an overview of the literature in the multirotor field specifically when it comes to inclusion of ground effect during the simulations.
- Then, an overview of the work done on standard model reference adaptive controller will be given and commented. Here, the selected model for the thesis will be discussed as well.

1.1 Previous related works in the multi-copter field

Drones are extensively being used in many civilian applications. The quadrotors give an excellent research opportunities especially when it is comes to novel control techniques. One of the major applications of quadrotor is the operation in confined environments in which the vehicle is flying near the objects or ground. When the rotorcraft is flying in such environmental conditions, the flight is affected because of the aerodynamic interactions which can be viewed as air flow changes [1]. The drones are equipped with number of sensing and computing devices in order to control and such systems can be operated remotely or with some degrees of autonomy based on the efficiency of controllers. In the initial research phases of drones, they were mostly deployed for military missions but now there are a number of civilian applications on which they have been used, which include the surveillance, photography, inspection, bird eye view for emergency response. The rotorcraft under study is quad-copter which is a four-rotor helicopter. Four propeller blades along with the respective motors are mounted over a symmetric cross like frame. The throttle of each motor controls the movement of quadrotor, which have mechanically simple dynamics and are cheap [2]. In the research development of rotorcraft (UAV), many studies have been conducted on the interaction of vehicle with the surrounding objects or people or proximity ground. Because of these interactions the performance during the flight may change significantly. This is due to the fact the control effort may get reduced as a result of such interactions.

A considerable amount of computational load is required in order to describe such interactions and the research is still open for improvement in order to be used in the real-time control of the quadrotor. Since the flight in indoor scenarios is a challenging task, so mostly the research is conducted on the UAV control when we are considering the handling dynamics in free space where the interaction of aerodynamics with the nearby surfaces can be easily neglected, which makes the problem much simpler. In some works, the aerodynamic interactions are considered as random disturbances which are then compensated by using feedback

Among the studied aerodynamic effects, one of the most important actions is the ground effect which is referred as the upward lift force caused as a result of the reaction from ground underneath the vehicle. This reaction force causes the air to compress beneath the drone. When we talk about physical interactions with the environment and its real time simulation model, especially for UAV case, the airflow simulation is not computationally cheap, it requires more computational time and effort in order to implement the real time control loop. One of the most classical ways to simulate in real time is by using experiments which itself is time consuming. Particularly, the phenomena of ground effect were first studied on the full-sized helicopters [3, 4]. By using the results of real time simulations, mathematical approximations for single rotor were then proposed in [5, 6]. Though extensive research has been carried out in the field of indoor flights of quad-rotor but still a lot of work needs to be done. For the improvement of control scheme, a knowledge gap is found when it comes to the vehicle interactions with nearby objects.

Quadcopter design as a test-bed for various projects has been studied and summarized by [7] and then prominent controller techniques for the drones were reviewed by [8]. We can categorize the control techniques developed for UAVs into two classes:

- Linear controllers
- Nonlinear controllers

Out of which, linear control techniques have always been the first choice for flight control of UAVs since they make the problem simpler and easy to implement.

Linear controllers have been successfully implemented to some extent in the real-world UAV systems except the cases when the interactions with external objects is being under investigation or when the rotorcraft deviates from the operating conditions. The projects summarized or discussed by [7] are as follows:

- In Stanford [9], using hybrid decomposition and reachable set theory the collision avoidance and control in tricky manoeuvres were studied.
- In U.Pennsylvania [10], using fuzzy logic controller the robustness and rejection of disturbance was improved.
- In UTC [11], in the presence of external perturbation, the precise measurement and prediction of attitude and altitude was conducted.
- In EPFL [12], using the robust control, the uncertainties and external disturbances were compensated.
- In Cornell U. [13], for the obstacle avoidance, parallel algorithms were proposed.
- In METU [14], linear quadratic tracking control was simulated.
- In Cranfield U. [15], in the presence of gust, real time trajectory was generated.
- In U. of Maryland [16], in the obstacle laden environments: robust stabilization and command tracking behaviour was studied.

In order to overcome the shortcomings of linear control methods which have been applied on drones, some nonlinear control techniques have also been proposed over the course of time, which are based on nonlinear dynamic models. These nonlinear models include the adaptive control and MPC which have been implemented on the quadrotors, and which are still under research radar. It is observed that these non-linear models perform better than linear controllers when it comes to the rejection of disturbances, uncertainties and tracking precision. The research field is still in development because of the high computational cost for the implementation.

One of the most famous techniques which has been used in industry and in the quadrotors is PID controller, which can easily be implemented by tuning the gains without going in details of the dynamic model. Preciously, a linearized model has already been controlled using PID. However, for controlling rapid manoeuvres, we cannot use linearized system, and to overcome this problem some cascaded PID controllers have also been implemented previously, in which case two loop scheme has been implemented (one for the stabilization of angular rates and the other one for the stabilization of Euler angles). Researchers have done extensive work to achieve fine tuned PID controllers.

As discussed before that the ground has a remarkable effect on the aerodynamics of rotary wing aircraft, it has been studied in literature for quite a few times. One of the most referenced model which has been implemented in many other research works was introduced by Cheeseman and Bennett [5]. For a single rotor, they predicted the ratio of in ground effect (IGE) to the out of ground effect (OGE) thrust, which is a function of rotor height w.r.t. reference and the radius of propeller. The ratio was expressed as:

$$\frac{T_{IGE}}{T_{OGE}} = \frac{1}{1 - \frac{1}{16}\frac{R}{z}^2[\frac{1}{1+(V/v)^2}]} \tag{1.1}$$

Where T_{IGE} and T_{OGE} are the thrust corresponding to in-ground effect and out-of-ground effect respectively, R is the rotor radius, z is the height of rotor above ground, V is the airspeed and v is the rotor induced velocity. After this, the ground effect has been studied mostly based on the experimental exploration and then comparative study with Cheeseman and Bennettt analytical expression.

1.2 Standard Model Reference Adaptive Controller Introduction

As discussed earlier that the problem of control law development for multirotor UAVs has been studied in the literature widely. When we talk about operating in nominal conditions the controllers with fixed gains which tend to give satisfactory results. Moving beyond the nominal conditions and adding nonlinear effects (e.g. external disturbances, uncertainties, time delays etc.), fixed gain controllers can no longer satisfy the system. In such cases, more advanced approaches are used like the Adaptive controller. One of the main reasons of using Adaptive control scheme is the ability to deal with uncertainties and tracking the dynamic system with high performance. Implementation of Adaptive control technique on the small-scaled UAVs has a much shorter history.

In [17], an adaptive augmentation control algorithm has been proposed for multi-rotor UAV, in which a linear robust controller is being combined with the adaptive controller. The architecture is the one which will be followed for this thesis to develop a scheme for altitude controller. The proposed scheme was developed for the direct Model Reference Adaptive Control (MRAC) and indirect L1 Adaptation scheme. In both the schemes, alongside the robust controller, a baseline controller is also present for the stability of closed loop system in nominal conditions. The proposed scheme makes use of the observer model, placed at the region of uncertainties. The adaptive schemes developed were then validated via simulations and experimentation. The results were analysed based on the settling of the signal on the desired set point trajectory. Once the results were obtained, it was observed that the tracking performance was improved but at the cost of reduction in robustness. The experiments were then conducted in order to compare the results of simulation and an improved tracking performance with adaptive law was observed.

MRAC is an adaptive control technique which has many interesting applications especially on the multirotor UAVs, one of which is the use of baseline controller which has already been configured for nominal conditions. Some limited work has been done in this field of interest. In [18], a small quadrotor is being studied and the controller is augmented in such a manner that both the baseline controller and model reference adaptive controller are implemented. In normal operations only baseline controller is activated but in case of failure or uncertainty the adaptive control gets activated and plays a vital role to stabilize the system and to regain the performance as close as the original one. It is observed that with the failure or uncertainty in system, there is a significant loss of thrust which alters the overall performance of the system. This can be minimized by using the adaptive scheme. In [19], a similar scheme is proposed with a standard baseline control with fix gain which includes PI controller and direct MRAC scheme in order to compensate mass uncertainties and to have improved performance compared to LQR. The architecture is then validated with the flight tests conducted inside closed environment.

One of the interesting features which we see in adaptive schemes is lumping all the uncertainties of the system in single term or parameter. Such approach is useful for the baseline controller since no modification is required in baseline and we can add the adaptive part easily. One such scheme was implemented in [20], in which the neural network is augmented with nominal PID. The inversion error is adaptively reduced by designing the control law in which an approximate inversion model is used. The same technique is used in [21], and is tested on quadrotors of different sizes. It is observed that the nominal performance can be restored using the adaptive control law.

In addition to this, in [22], a back-stepping controller is used to exploit the techniques of adaptation in order to control the quad-rotor in the presence of uncertainties. Some more complex designs of adaptive control has also been studied, like in [23], where the mass of the plane is uncertain. The UAV is modelled with model parameter uncertainties instead of neural networks. Another model was proposed in [24], in which the ground effect is compensated using the online lift coefficient estimation, which is then implemented on tele-operated quadcopter. In addition to this, a sliding mode framework is also used as adaptation in order to carry out the simulations for uncertainty and noise in [25]. The same sliding mode framework is then implemented by [26], the difference is that adaptive fuzzy logic is introduced to approximate the input control and disturbance which includes the ground effect as well. Other approaches being implemented on the ground effect using adaptation included the intuitive visual feedback, and developing some empirical relations based on experimentation, but they cannot be generalized to other vehicles.

Chapter 2

Single-axis Adaptive Scheme

Before proceeding with the adaptive control implementation on the complete rotorcraft system, a single axis adaptive scheme is being developed here in this chapter. Once the feasibility of the proposed adaptive model is confirmed on 1D dynamic system, the algorithm will then be implemented on complete UAV case. The chapter is divided into:

- Firstly, the problem statement is defined and thrust is then linearized around hovering condition.
- The proposed mathematical model for the adaptive solution along with the control law is developed.
- Then, the Simulink implementation of the proposed model is carried out.
- The analysis is then performed on the results obtained and possibility of using the same model on complete rotorcraft system is discussed.

2.1 Problem Statement

As mentioned earlier, we are going to develop a single axis Adaptive scheme that can then easily be implemented in an already existing control architecture of UAV simulator. The main aim is to compensate the altitude in order to reduce the ground effect. For that purpose a simple dynamic system is studied here. The plant dynamics is given by:

$$m\ddot{z} = T + d - mg \tag{2.1}$$

$$\dot{v_z} = \frac{1}{m}\left(T + d - mg\right) \tag{2.2}$$

Where m is the mass of quadrotor vehicle, z is the altitude of vehicle with respect to ground, T is the external thrust, d is the disturbance and v_z is the body vertical velocity. We assume that the thrust force is directly proportional to the angular velocity and is given by:

$$T = K_t \Omega^2 \tag{2.3}$$

The constant K_t is uncertain. Since the system is non-linear, the implementation of adaptive control will require more computation, so linearization is performed on the equation 2.3 around the hovering conditions.

$$T = K_t \Omega^2 \approx K_t {\Omega_h}^2 + (2K_t\Omega_h)\Delta\Omega \tag{2.4}$$

From the above equation $K_t{\Omega_h}^2$ is the hovering thrust equivalent to weight (mg) and $\Delta\Omega$ is given by $\Delta\Omega = \Omega - \Omega_h$. So the total thrust becomes:

$$T = mg + 2K_t\Omega_h\Delta\Omega \tag{2.5}$$

Substituting the total thrust in the dynamic system (2.2):

$$\dot{v_z} = \frac{1}{m}\{2K_t\Omega_h\Delta\Omega + d\} \tag{2.6}$$

Now, let the nominal values be denoted by subscript 0 and the uncertainty values be denoted by subscript δ. Then the K_t constant can be rewritten in the following way by using multiplicative perturbation form:

$$K_t = K_{t0}\Lambda_{k_t} \tag{2.7}$$

Where the Λ_{k_t} is given by:

$$\Lambda_{k_t} = 1 + \frac{K_{t\delta}}{K_{t0}} \tag{2.8}$$

For the nominal system, $K_{t\delta} = 0$, a baseline feedback controller has already been developed in the previous projects. The same baseline controller will be used here in this thesis as well. Now, the control input is introduced by simply adding the inputs of the two algorithms:

$$u = u_b + u_a \tag{2.9}$$

Where, u_a is the control action provided by the adaptive controller and u_b is the control action provided by the baseline controller. The control input is linked with the rotor velocity as follows:

$$\Delta\Omega = G(s)u \tag{2.10}$$

The actuator is modeled as a low pass filter given by:

$$G(s) = \frac{1}{\tau s + 1} \tag{2.11}$$

2.2 Introduction of Adaptive Control Scheme

The plant model 2.6 is transformed as follows:

$$\dot{v_z} = \frac{1}{m} K_t \Omega_h \Delta\Omega \tag{2.12}$$

$$\dot{v_z} = \frac{1}{m} K_t \Omega_h G(s)u \tag{2.13}$$

Substituting the input from equation 2.9 in equation 2.13:

$$\dot{v_z} = \frac{1}{m} K_t \Omega_h G(s)(u_b + u_a) \tag{2.14}$$

Representing the equation in terms of multiplicative identity.

$$\dot{v_z} = \frac{1}{m} K_{t0} \Lambda_{k_t} \Omega_h G(s)(u_b + u_a) \tag{2.15}$$

The nominal part is given by:

$$\frac{1}{m} K_{t0} \Omega_h G(s) u_b \tag{2.16}$$

Now adding and subtracting the nominal part in eq 2.15

$$\dot{v_z} = \frac{1}{m} K_{t0} \Lambda_{k_t} \Omega_h G(s)(u_b + u_a) \pm \frac{1}{m} K_{t0} \Omega_h G(s) u_b \tag{2.17}$$

Now introducing the adaptive control gains in the plant model:

$$\dot{v_z} = \frac{1}{m} K_{t0} \Omega_h G(s) u_b + \frac{1}{m} K_{t0} \Lambda_{k_t} \Omega_h (\alpha G(s) u_b + G(s) u_a) \tag{2.18}$$

Where the first part is nominal and the second part of the equation is the uncertain part with:

$$\alpha = \left(1 - \frac{1}{\Lambda_{k_t0}}\right) \tag{2.19}$$

Note that ${\Lambda_{k_t0}}^{-1}$ always exist since:

$$\Lambda_{k_t} = 1 + \frac{K_{t0}}{K_{t\delta}} > 0 \tag{2.20}$$

because K_{t0} and K_δ are positive and positive semi-definite respectively.

2.3 Control Law

Based on the equation 2.18, the following control law for u_a can be defined:

$$u_a = -\hat{\alpha} u_b \tag{2.21}$$

Where $\hat{\alpha}$ is the estimate for α, hence:

$$\Delta\alpha = \hat{\alpha} - \alpha \tag{2.22}$$

Implementing the above change in equation 2.18:

$$\dot{v_z} = \frac{1}{m} K_{t0} \Omega_h G(s) u_b - \frac{1}{m} K_{t0} \Lambda_{k_t} \Omega_h (\Delta\alpha G(s) u_b) \tag{2.23}$$

2.4 Observer Reference Model

Now the reference model in shape of observer is defined for the nominal part:

$$\dot{\hat{v}}_z = \frac{1}{m} 2 K_{t0} \Omega_h G(s) u_b + Le \tag{2.24}$$

Where the error signal is defined as:

$$e = \hat{v}_z - v_z \tag{2.25}$$

And L is the Hurwitz constant, being introduced to assign the error in the dynamics which is given by:

$$\dot{e} = Le + \frac{1}{m} 2K_{t0}\Lambda_{k_t}\Omega_h(\Delta\alpha G(s)u_b) \tag{2.26}$$

2.5 Adaptive Laws

The following adaptive law can be deduced based on the control law and error dynamics.

$$\dot{\hat{\alpha}} = Proj(\hat{\alpha}, -\Gamma u_b e^T PB) \tag{2.27}$$

Where the $Proj(',')$ is the projection operator as found in [19], the intial condition of which is: $\hat{\alpha}(0) = 0$. In the above law, P is symmetric which is obtained by solving the following Lyapunov equation:

$$A^T{}_e P + PA_e = -Q \tag{2.28}$$

Q is always greater than zero, and was chosen to be equal to identity.The constant K is chosen in the form of $L = -K_L I_1$, in which the K_L is positive scalar.

2.6 Simulink Implementation

The above developed or proposed model is then implemented in Simulink. The baseline controller implemented is a simple PID controller which generates nominal thrust. And with that and adaptive controller is added.

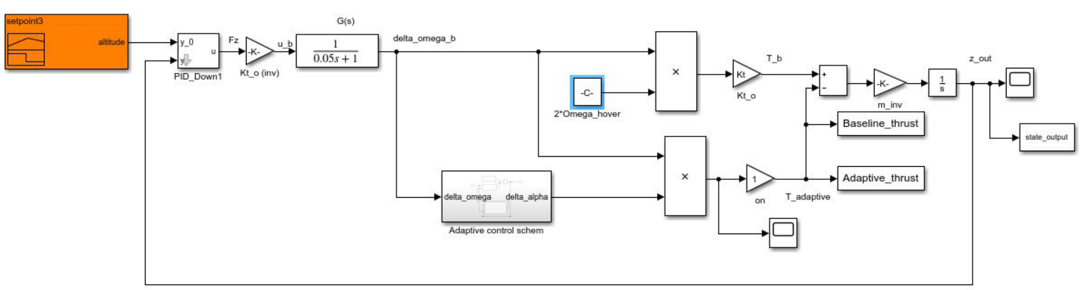


Figure 2.1: Simulink representation of single axis adaptive scheme

As mentioned in the Figure 2.1, the baseline thrust is obtained by implementing PID controller, which is being tuned to achieve satisfactory performance in terms of tracking the signal with reference to the setpoints. The tuning parameters used during the simulation are tabulated in the Table 2.1 and the setpoints defined is a mission profile which includes takeoff, hovering and then landing as shown in the Figure 2.2:

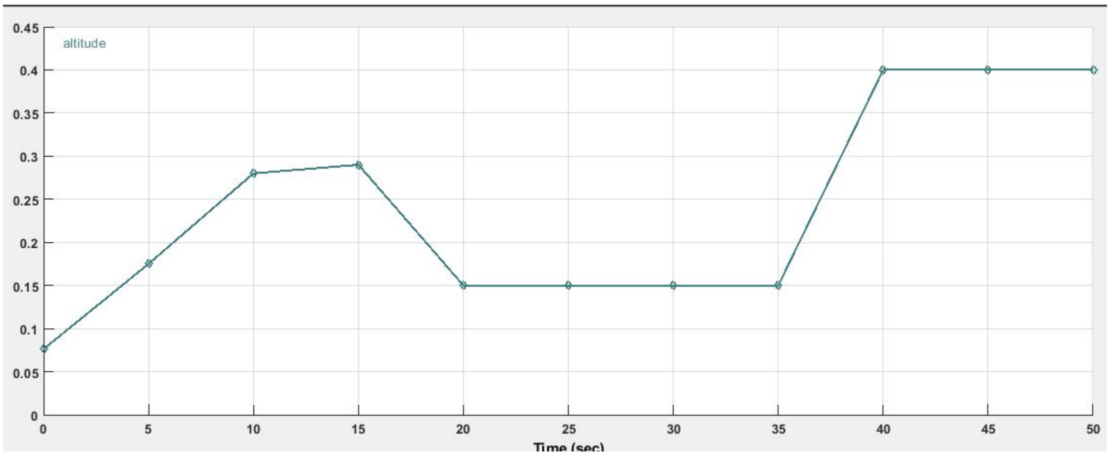


Figure 2.2: The desired flight path

Table 2.1: Baseline controller gains

Gain	Value
K_P	4.1
K_I	1.9
K_D	0.08

The adaptation is performed using projection operator which has the inputs coming from the error signal obtained from the error dynamics (shown in Figure 2.3), the baseline control signal coming from the baseline controller, parameters obtained from Lyapunov equation (2.28) and the adaptation rate which is finely tuned in order to achieve the best desired results.
The error dynamics is pretty straightforward and easy to understand which then is applied to the projection operator(Figure 2.4 in order to achieve the reference adaptation coefficient for the adaptive thrust.

2.7 Study of results

Now that the Simulink model has been developed, the first analysis can be performed in order to check if the proposed model is feasible to be implemented on

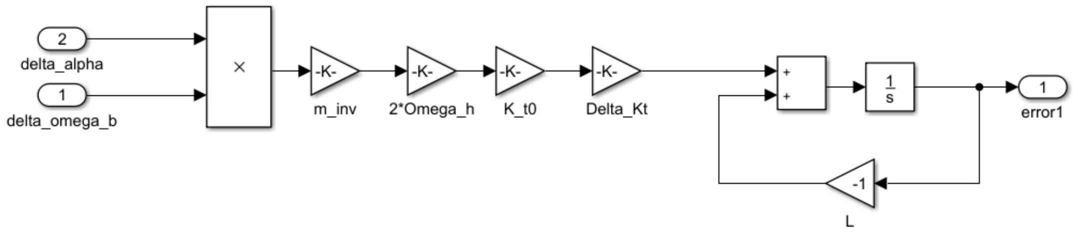


Figure 2.3: Error dynamics for single axis adaptive scheme

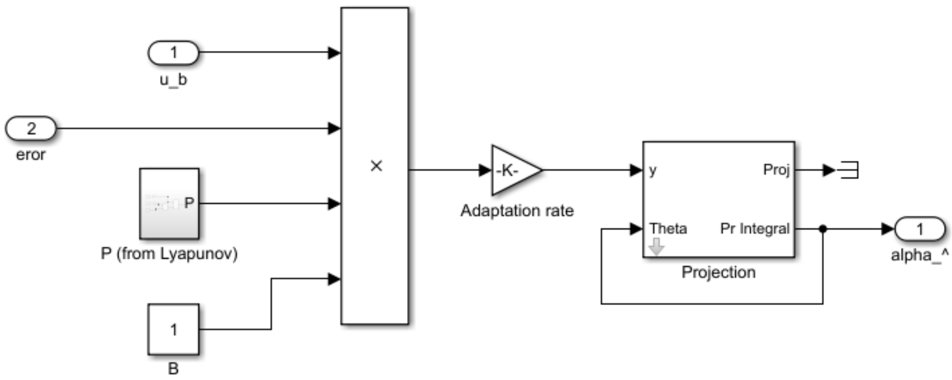
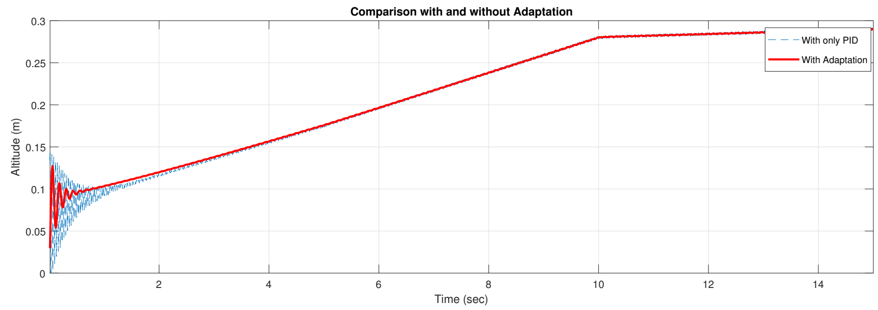


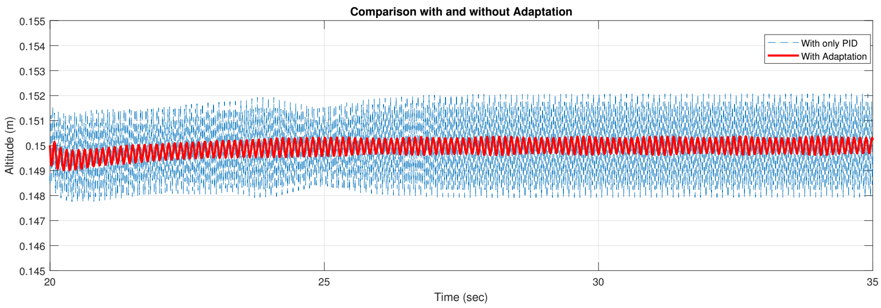
Figure 2.4: Adaptation law for single axis scheme

the complete rotorcraft dynamics or not. The analysis includes the time history plots of altitude, the altitude error with respect to the setpoints, the growth of adaptation coefficient, and at the end, sensitivity analysis is performed on altitude and altitude error by changing the values of adaptation rate, as it is assumed that the adaptation rate has significant effect on the system response.

A comparative study is performed in order to see how system responds before and after adaptation. When the adaptation is turned off, the system behaves under nominal control (only baseline thrust is produced). The altitude response has been reported in Figure 2.5. As we can see, the outcome of the simulation after the adaptation gives comparatively better result compared to the one in which we don't have adaptation activated. In order to have better understanding, a small portion of time span (20 sec-35 sec) is then observed, during which body keeps on oscillating with PID controller, however, with the implementation of adaptation rule, the oscillations are minimized as shows in Figure 2.5b. This has been achieved as a result of series of simulation performed with different adaptation rates.



(a) Complete simulation



(b) Zoomed analysis

Figure 2.5: Time history of Altitude for single axis scheme

It can be observed that the addition of Adaptation controller improves the response of the system to a great extent which makes it more reliable control scheme. Moving further the altitude error is plotted in Figure 2.6 with respect to time. As expected the error signal tends to go to zero more quickly when we have adaptive control activated as compared to the case without adaptation.

Next, the variation of adaptive gain has been plotted with respect to time in Figure 2.7. As you can see that initially a higher value of gain is required which then reduces as the system goes towards settling to the desired configuration. Once the system is settled, the adaptive gains remains almost constant.

All the analysis was performed by taking the value of adaptation rate of the order -4. The value is achieved after a series of simulations performed with different set of adaptation rates. The sensitivity analysis proves that the less the order of the adaptation rate, the more quickly the system gets settled as shown in the Figure 2.8 for the variation of altitude and Figure 2.9 for the variation in altitude

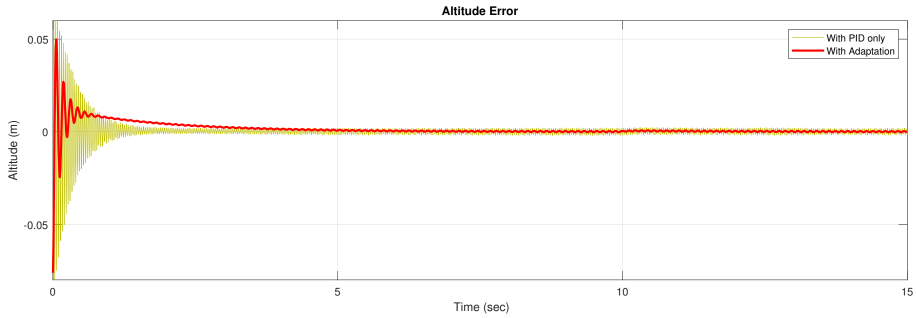


Figure 2.6: Altitude error time history for single axis scheme

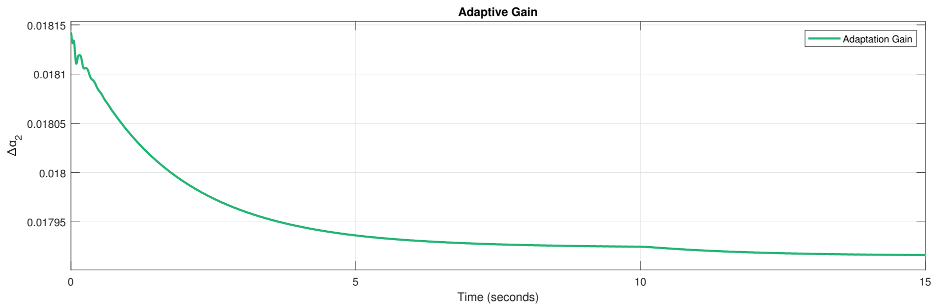


Figure 2.7: Adaptive gain time history for single axis scheme

error.

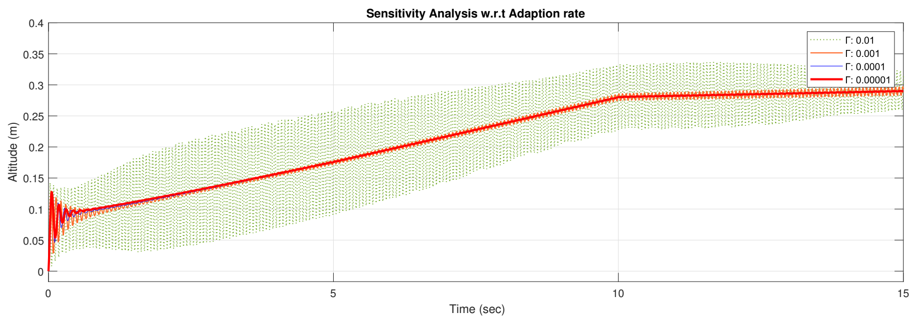


Figure 2.8: Sensitivity analysis on altitude for single axis scheme

As seen from the results, it is quite clear that adaptive control model is an efficient method which can be used with the baseline controller in order to achieve better results especially during the take-off or landing phases. From the results it can be observed that the body undergoes an initial oscillations which then are compensated, first by using only baseline controller and then by the addition of adaptive controller alongside baseline. In the baseline case, the altitude slowly

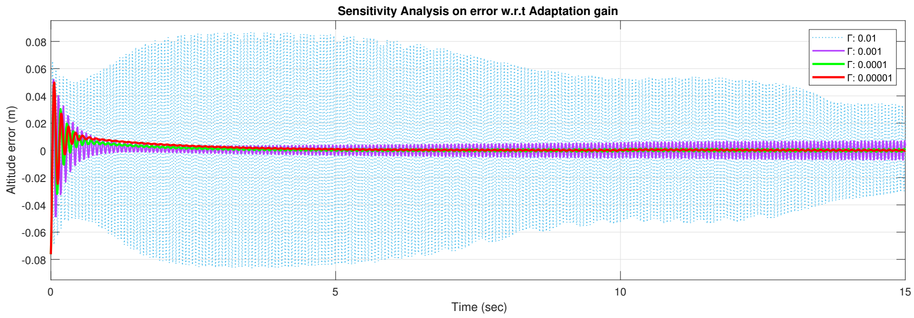


Figure 2.9: Sensitivity analysis on altitude error for single axis scheme

goes to the desired position after series of oscillatory motions, however, with the adaptive controller, the oscillations gets reduced and the body reaches the desired set-points quickly and with less oscillations. The next step is to implement the same algorithm on the complete rotorcraft dynamics, which has already been used in previous projects. The next chapters will include the implementation and then the simulation of adaptive scheme on such model.

Chapter 3

Complete model Adaptive Scheme

In the previous chapter the MRAC scheme was implemented on a 1D system. The results of which proved that the system responds positively with the addition of adaptation. Now the same algorithm is taken and is implemented on the complete rotorcraft dynamic model. This chapter includes:

- Brief introduction of Flyart project and the simulink model already developed before.
- Detailed mathematical model of the MRAC is developed.
- Once the model is developed, it is then integrated in the simulation model of rotor-craft.

3.1 Previous work done on Flyart project

Over the past few years, some important works have already been on the flyart project. Here is a brief history of the research work already done along with the limitations and important points which were observed before and which needed to be improved to have the problems tackled. The quadrotor which has been under experimental observations is shown in Figure 3.1. Though there have been some modifications in the design of quadrotor over the past few years, but for the sake of ease, for this thesis the simulation model developed by [27] is used. The main aerodynamic and physical features of the UAV is listed in Table 3.1 and Table 3.2 below.

Figure 3.1: Quadrotor previously used

Table 3.1: Physical Characteristics of the drone used in simulation

Variable	Value
Arm length b	$0.275[mm]$
Weight	$1.51[kg]$
Inertia I_{xx}, I_{yy}	$0.035[kgm^2$
Battery	LiPo $400[mAh]3S$

Table 3.2: Aerodynamic Characteristics of the propeller used in simulation

Variable	Value
Radius	$0.1524[m]$
Average chord length c	$0.02[m]$
First flap frequency	$9[Hz]$
Solidity σ	$0.083[/]$

Though some detailed control study has been conducted on the attitude dynamics of the vehicle and is then compared with the experimental results and there are still some room for improvements in the attitude control model as well, however, the model under consideration at this moment is the altitude controller which consists of a simple PID controller. Kalman filter has been used in order to estimate the altitude.

With reference to the inclusion of ground effect in model, some experiments were conducted initially in two phases: first the effect of height was studied on a single rotor and then the same effect was studied on the entire quad-rotor. Comparison of the performance was performed at different heights keeping some of the parameters constant. Both the cases were plotted along with the numerical result of Cheeseman and Bennett expressed and it was observed that the there was a mismatch between the two cases and also with respect to the Cheeseman and Bennett expression as well, since the expression was was generated based on the assumption of inviscid flow. The complete quadrotor case showed more deviation from Cheeseman and Bennett expression because of the possible airflow interactions due to the proximity.

This pointed out possibility of doing further research on the phenomena of ground effect. The limitations were encountered during the initial simulation and experimental phase and it was needed to be resolved. For this, improvements were added to the simulator in [27]. A simple and easy solution was proposed and implemented on the simulation which relied on the force balance in the initial phases of simulation. A reaction force was applied in order to stop the drone from falling, since it was observed that the the drone falls down for few seconds at the time of launch. So, this ground compensation was implemented in Simulink model first. Furthermore, the Cheeseman and Bennett equation was optimised by introducing a correction factor ρ, which was determined such that the error between experimental results and the theoretical numerical model is minimum. Once, the correction factor was obtained, this was further used to optimise allowing a better fitting of the experimental data with the numerical model.

Once the ground effect was implemented using numerical approximation that relied on global thrust of drone, it was then further modified by adding the experimental curve obtained through real experiments, which allowed more specific and precise model for the drone under investigation. In addition to this, ground effect phenomena was added in each motor as well, this further improved the results. It is observed that different rotors are not at the same altitude especially when the drone is maneuvering or taking off or landing, therefore the following modification was introduced to match the real flight data. In order to obtain the propeller thrust and moments, the vector of square of speed Ω is multiplied by a matrix K which includes the information about the control thrust and torque. Initially the

K matrix was given by:

$$\begin{bmatrix} -K_t & -K_t & -K_t & -K_t \\ \frac{\sqrt{2}}{2}K_t b & -\frac{\sqrt{2}}{2}K_t b & -\frac{\sqrt{2}}{2}K_t b & \frac{\sqrt{2}}{2}K_t b \\ \frac{\sqrt{2}}{2}K_t b & \frac{\sqrt{2}}{2}K_t b & -\frac{\sqrt{2}}{2}K_t b & -\frac{\sqrt{2}}{2}K_t b \\ -K_q & K_q & -K_q & K_q \end{bmatrix} \tag{3.1}$$

Where: b is the drone arm length, K_t and K_q are the parameter functions for thrust and torque coefficients respectively. Thrust variation was included in the system in order to add the ground effect by using look-up table where the optimized Cheeseman and Bennett expression was implemented, as shown in Figure 3.2. In the simulator, ground effect was represented using 'if case' which guarantees the robustness in the system but it only takes into account the following cases:

- 1st case is at very low or very high altitude, where K_t is kept constant, since the Cheeseman and Bennett expression cannot work at the height most closest to ground.
- 2nd case is the region in between low and high altitude, where the lookup table is implemented (Cheeseman Bennett is applicable)

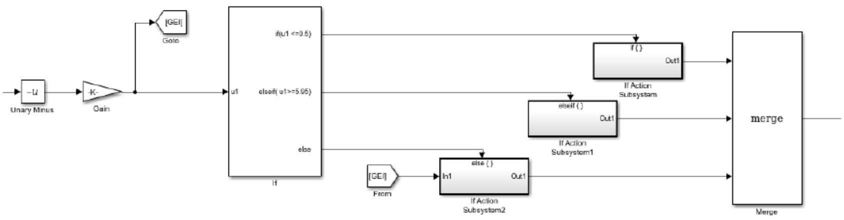


Figure 3.2: Ground effect implementation inside the old simulator

Once the above improvement was introduced in the system, it was then simulated and the results showed that there was further room for improvement. As a result of which the ground effect was then introduced on each motor as follows:

$$\begin{bmatrix} -K_{t_1} & -K_{t_2} & -K_{t_3} & -K_{t_4} \\ \frac{\sqrt{2}}{2}K_{t_1} b & -\frac{\sqrt{2}}{2}K_{t_2} b & -\frac{\sqrt{2}}{2}K_{t_3} b & \frac{\sqrt{2}}{2}K_{t_4} b \\ \frac{\sqrt{2}}{2}K_{t_1} b & \frac{\sqrt{2}}{2}K_{t_2} b & -\frac{\sqrt{2}}{2}K_{t_3} b & -\frac{\sqrt{2}}{2}K_{t_4} b \\ -K_q & K_q & -K_q & K_q \end{bmatrix} \tag{3.2}$$

Where K_{t_1}, K_{t_2}, K_{t_3} and K_{t_4} are the thrust coefficients for all the motors. This improvement was then introduced in the Simulink model as shown in Figure 3.3, which shows that altitudes of each motor are computed first which are then brought to the four subsystems as input which then computes the four coefficients of the 2.25, and finally the required matrix is constructed.

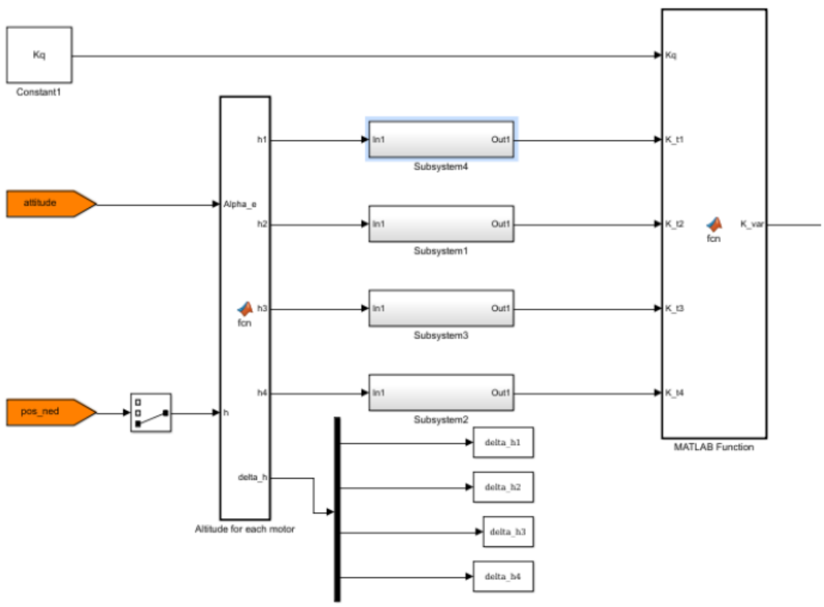


Figure 3.3: Ground effect final improvement inside the old simulator

After simulating the above model,it was observed that the compensation was important and it enhanced the performance as well, however, it still had room for improvements, especially at the time of launch. This is the main concern of this thesis.

3.2 Problem statement for the new framework

As now, we have developed an understanding about the previous work done on the ground effect and it's compensation, now we proceed with further improvement. In the last chapter, a single axis adaptive control scheme was studied and was found effective when it comes to compensation, especially when the normal PID controller wasn't able to achieve the desired results without delays. Here, in this section numerical model will be proposed for the altitude adaptive control by using the old control simulator (including the modifications on Cheeseman Bennett expressions) as baseline controller. Since, now we are dealing with complete rotorcraft model, we assume that each rotor produces a thrust following a static model:

$$T_i = K_{ti}\Omega_i^2 \tag{3.3}$$

Where K_{ti} and Ω_i are the thrust coefficient and velocity of each rotor respectively. This constant K_t is uncertain when we are dealing with flights near ground. We'll follow the same procedure as we did for single axis control. Since the system is non-linear, so linearization is performed on the equation 3.3 around the hovering conditions.

$$T_i = K_{ti}\Omega_{ih}^2 + 2K_{ti}\Omega_{ih}\Delta\Omega_i \tag{3.4}$$

Where, The first part is ($K_{ti}\Omega_{ih}^2$) is assumed to be constant and it must be equal to 1/4 of the gravity force mg and $\Delta\Omega$ is given by $\Delta\Omega = \Omega - \Omega_h$. So the total thrust becomes:

$$T = \sum_{i=1}^{4} K_{ti}\Omega_i^2 \tag{3.5}$$

Substituting (3.4) in total thrust (3.5):

$$T = \sum_{i=1}^{4}(K_{ti}\Omega_{ih}^2 + 2K_{ti}\Omega_{ih}\Delta\Omega_i) \tag{3.6}$$

$$T = \sum_{i=1}^{4} K_{ti}\Omega_{ih}^2 + \sum_{i=1}^{4} 2K_{ti}\Omega_{ih}\Delta\Omega_i \tag{3.7}$$

We can finally assume that the thrust coefficient K_{ti} of the gravity compensation, is constant and equal to K_{t0} for each motor (which implies also the Ω_{ih} of each motor to be equal to Ω_i). So, the thrust becomes:

$$T = 4K_{t0}\Omega_h^2 + \sum_{i=1}^{4} 2K_{ti}\Omega_{ih}\Delta\Omega_i \tag{3.8}$$

Where: $4K_{t0}\Omega_h^2$ is the hovering thrust equivalent to weight (mg). Now, the euler equation for the altitude dynamics is considered:

$$\dot{v_z} = \frac{1}{m}\sum_{i=1}^{4} 2K_{ti}\Omega_h\Delta\Omega_i \tag{3.9}$$

As did before, now the multiplicative perturbation is introduced as follows:

$$K_{ti} = K_{t0}\Lambda_{k_{ti}} \tag{3.10}$$

The nominal values be denoted by subscript 0 and the uncertainty values be denoted by subscript δ in the below equation.

$$\Lambda_{k_{ti}} = 1 + \frac{K_{t0}}{K_{t\delta}} \tag{3.11}$$

For the nominal system, $K_{t\delta} = 0$. Now, the control input is introduced by simply adding the inputs of the baseline control and adaptive control. Each motor has a different control input:

$$u_i = u_{ib} + u_{ia} \tag{3.12}$$

Where, u_{ia} is the control action provided by the adaptive controller and u_{ib} is the control action provided by the baseline controller. The control input is linked with the rotor velocity as follows:

$$\Delta\Omega_i = G_i(s)u_i \tag{3.13}$$

3.3 Introduction of Adaptive Control Scheme

The plant model 3.9 is transformed as follows:

$$\dot{v}_z = \frac{1}{m}\sum_{i=1}^{4} 2K_{ti}\Omega_h\Delta\Omega_i \tag{3.14}$$

And

$$\dot{v}_z = \frac{1}{m}\sum_{i=1}^{4} 2K_{ti}\Omega_h G_i(s)u_i \tag{3.15}$$

Substituting the input from equation 3.12 in equation 3.15:

$$\dot{v}_z = \frac{1}{m}\sum_{i=1}^{4} 2K_{ti}\Omega_h G_i(s)(u_{ib} + u_{ia}) \tag{3.16}$$

Representing the equation in terms of multiplicative identity.

$$\dot{v}_z = \frac{1}{m}\sum_{i=1}^{4} 2K_{t0}\Lambda_{k_{ti}}\Omega_h G_i(s)(u_{ib} + u_{ia}) \tag{3.17}$$

The nominal part is given by:

$$\frac{1}{m}\sum_{i=1}^{4} 2K_{t0}\Omega_h G_i(s)u_{ib} \tag{3.18}$$

Now adding and subtracting the nominal part in eq 3.17

$$\dot{v}_z = \frac{1}{m}\sum_{i=1}^{4} 2K_{t0}\Lambda_{k_{ti}}\Omega_h G_i(s)(u_{ib} + u_{ia}) \pm \frac{1}{m}\sum_{i=1}^{4} 2K_{t0}\Omega_h G_i(s)u_{ib} \tag{3.19}$$

Now introducing the adaptive control gains in the plant model:

$$\frac{1}{m}\sum_{i=1}^{4} 2K_{t0}\Omega_h G_i(s)u_{ib} + \frac{1}{m}2K_{t0}\Lambda_{k_{ti}}\Omega_h \sum_{i=1}^{4}(\alpha_i G_i(s)u_{ib} + G_i(s)u_{ia}) \tag{3.20}$$

Where the first part is nominal and the second part of the equation is the uncertain part with:

$$\alpha_i = (1 - \frac{1}{\Lambda_{k_{ti}}}) \tag{3.21}$$

Note that ${\Lambda_{k_{ti}}}^{-1}$ always exist since:

$$\Lambda_{k_{ti}} = 1 + \frac{K_{t0}}{K_{t\delta}} > 0 \tag{3.22}$$

because K_{t0} and $K_{t\delta}$ are positive and positive semi-definite respectively.

3.4 Control Law

Based on the equation 3.19, the following control law for u_{ia} for each rotor can be defined:

$$u_{ia} = -\hat{\alpha}_i u_i b \tag{3.23}$$

Where $\hat{\alpha}_i$ is the estimate for α_i, hence:

$$\Delta\alpha_i = \hat{\alpha}_i - \alpha_i \tag{3.24}$$

Implementing the above change in equation 3.20:

$$\dot{v}_z = \frac{1}{m}\sum_{i=1}^{4} 2K_{t0}\Omega_h G_i(s)u_{ib} - \frac{1}{m}2K_{t0}\Lambda_{k_{ti}}\Omega_h \sum_{i=1}^{4}(\Delta\alpha_i G_i(s)u_{ib}) \tag{3.25}$$

3.5 Observer Reference Model

Now the reference model in shape of observer is defined for the nominal part:

$$\dot{\hat{v}}_z = \frac{1}{m}\sum_{i=1}^{4} 2K_{t0}\Omega_h G_i(s)u_{ib} + Le \tag{3.26}$$

Where the error signal is defined as:

$$e = \hat{v}_z - v_z \tag{3.27}$$

And L is the Hurwitz constant, being introduced to assign the error in the dynamics which is given by:

$$\dot{e} = Le + \frac{1}{m}2K_{t0}\Lambda_{k_{ti}}\Omega_h \sum_{i=1}^{4}(\Delta\alpha_i G_i(s)u_{ib}) \tag{3.28}$$

3.6 Adaptive Laws

The following adaptive laws can be deduced based on the control law and error dynamics.

$$\dot{\hat{\alpha_i}} = Proj(\hat{\alpha_i}, -\Gamma_i u_{ib} e^T PB) \tag{3.29}$$

Where the $Proj(',')$ is the projection operator as found in [19], the intial condition of which is: $\hat{\alpha_i}(0) = 0$. In the above law, P is symmetric which is obtained by solving the following Lyapunov equation:

$$A^T{}_e P + PA_e = -Q \tag{3.30}$$

Where Q is always greater than zero, and was chosen to be equal to identity.The constant K is chosen in the form of $L = -K_L I_1$, in which the K_L is positive scalar.

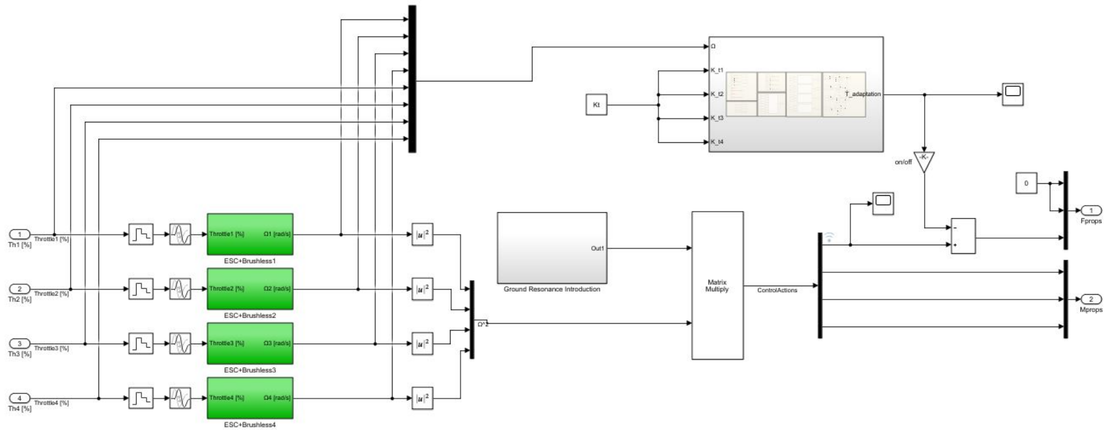


Figure 3.4: New Simulink Model

3.7 Simulink Implementation

The above developed or proposed model is then implemented in Simulink. For the baseline controller, the same model was used which was developed in the previous thesis. The Simulink Model, as shown in Figure 3.4 gets the input from the four actuators of rotorcraft and the nominal K_{t0}. The adaptation is performed based on the above mathematical model to obtain the adaptive control thrust.

The inputs from actuators go to the respective adaptation mechanism, where the projection is performed and while doing so, the adaptation rate is tuned finely in order to obtain the desired results. The projection operator provides bounds on adaptive parameters. It is also to be noted that the equation 3.30 ensures that the adaptive parameter $\hat{\alpha}_i$ is less than some prescribed bound θ_{max}. This adaptation is implemented in Simulink as mentioned in Figure 3.5.

The error dynamics from equation 3.28 is then implemented as shown in Figure 3.6. The error signal is then used as an input for the adaptation law to achieve the reference adaptation coefficient.

Once the simulation model has been developed, next step is to plot the desired results, compare them with the already existing model of controller being previously used, and then finally sensitivity analysis will be performed for the adaptation rate.

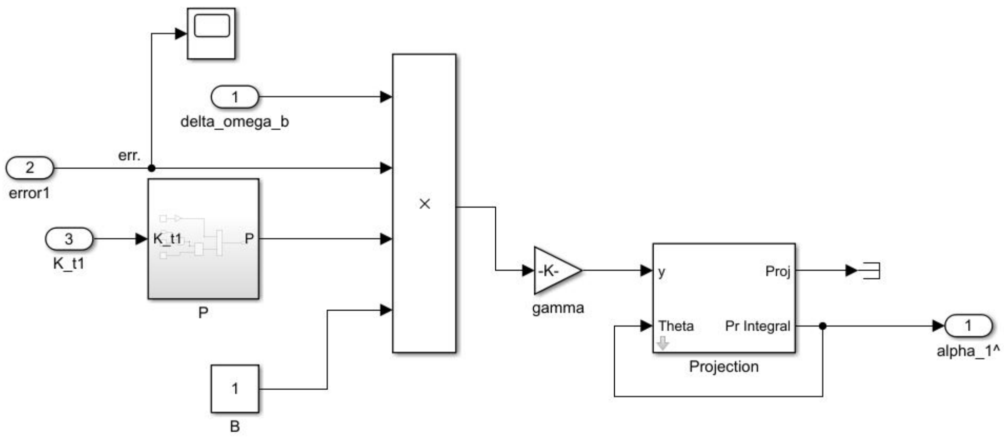


Figure 3.5: Adaptation law implemented on complete UAV model

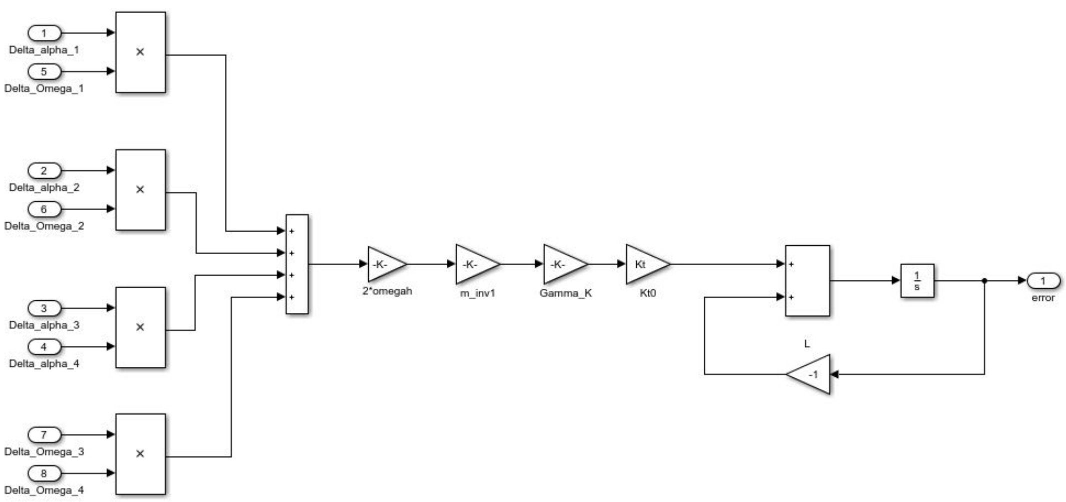


Figure 3.6: Error dynamics implemented on complete UAV model

Chapter 4

Study of Adaptation

The aim of this chapter is to see how the system responds to the proposed model. The analysis will be carried out with the aim to have an understanding of the compensation and its domain or limitations in order to check if the method is worth implementing inside the real drone. In order to achieve these objectives, this chapter is divided into two parts:

- The first part includes the analysis of the time history of altitude, altitude error and adaptation rate.

- The second part includes the study of sensitivity analysis for adaptation rate.

4.1 Results Analysis

For the results, same mission profile is used as used for the single axis adaptation scheme in section 3 as shown in Figure 2.2:

The tuning parameters, which include the gains of PID controller as well as the adaptation rate used during the simulation are tabulated in the Table 4.1.

Table 4.1: Controller gains

Gain	Value
K_P	4.1
K_I	1.9
K_D	0.08
Γ	0.0001

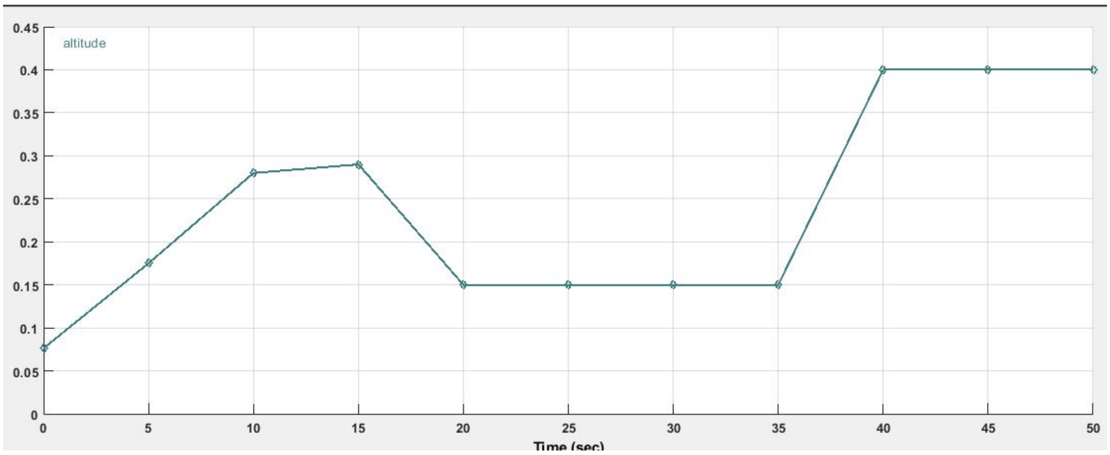


Figure 4.1: The desired flight path

Firstly, the altitude variation with respect to time is plotted in Figure 4.2. Results of the two methods have been plotted together.

- Case 1: Baseline Altitude control, which represents the old simulation model.
- Case 2: Addition of Adaptive control to the same Baseline model

This is done in order to understand if the proposed model is feasible or if we get an improved response or not. As seen in the Figure 4.2, the initial overshoot observed in the baseline model was reduced with the addition of adaptive model.

Moving further, the altitude error is plotted in Figure 4.3 with respect to time. As expected, the altitude error at the start of the simulation is significantly reduced when the adaptation scheme is applied.

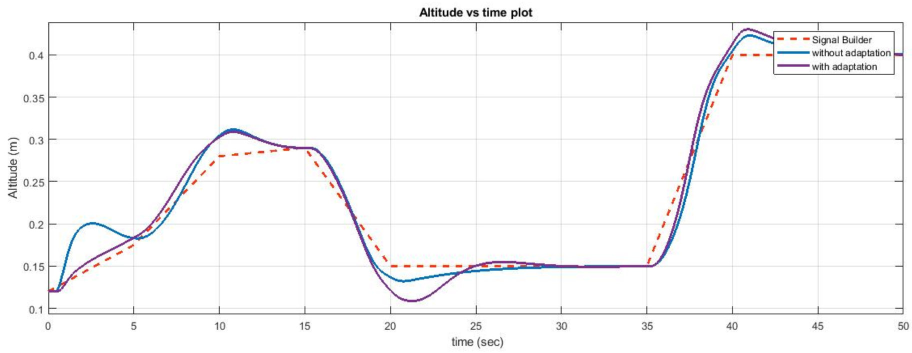


Figure 4.2: Time history of altitude for complete UAV case

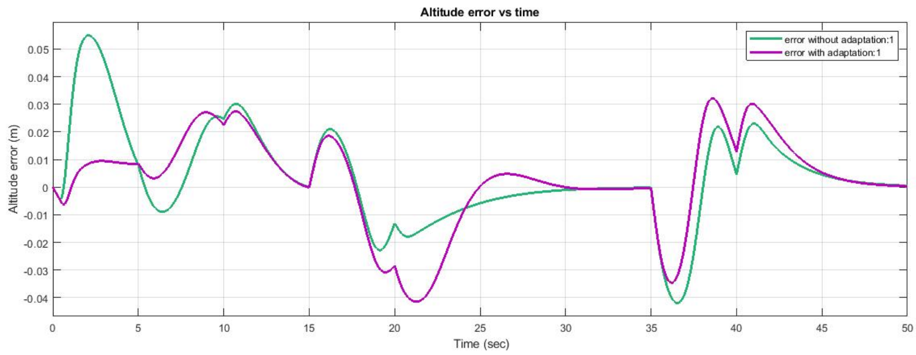


Figure 4.3: Time history of altitude error for complete UAV case

Next, the variation of adaptive gain has been plotted with respect to time in Figure 4.4. As you can see that initially a higher value of gain is required which then reduces as the system goes towards settling to the desired configuration.

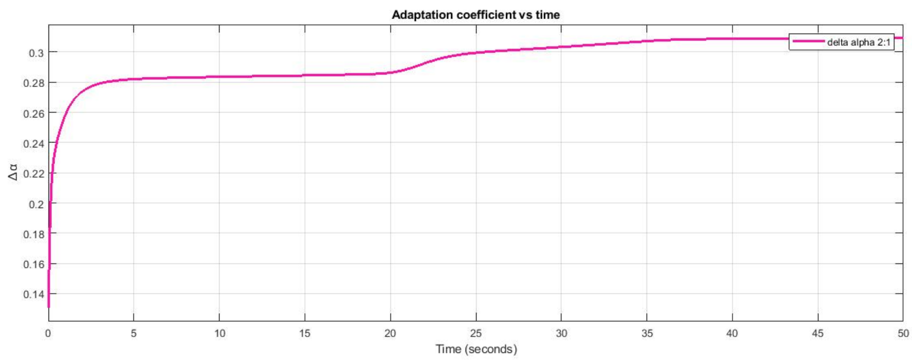


Figure 4.4: Adaptive gain time history for complete UAV case

4.2 Sensitivity Analysis with respect to Adaptation Rate

All the above simulations were performed by using the gains of the controllers tabulated in Table 4.1. Out of which the first three parameters were for baseline controller which were not changed during the simulations. The only parameter which was subjected to change was the adaptation rate.

Sensitivity analysis was performed for the adaptation rate on the altitude of the vehicle, as shown in Figure 4.5. It is observed that the response is sensitive to adaptation rate, however, the sensitivity is more significant when we change the order of adaptation rate. Likewise, the same analysis is performed on the Altitude error in Figure 4.6

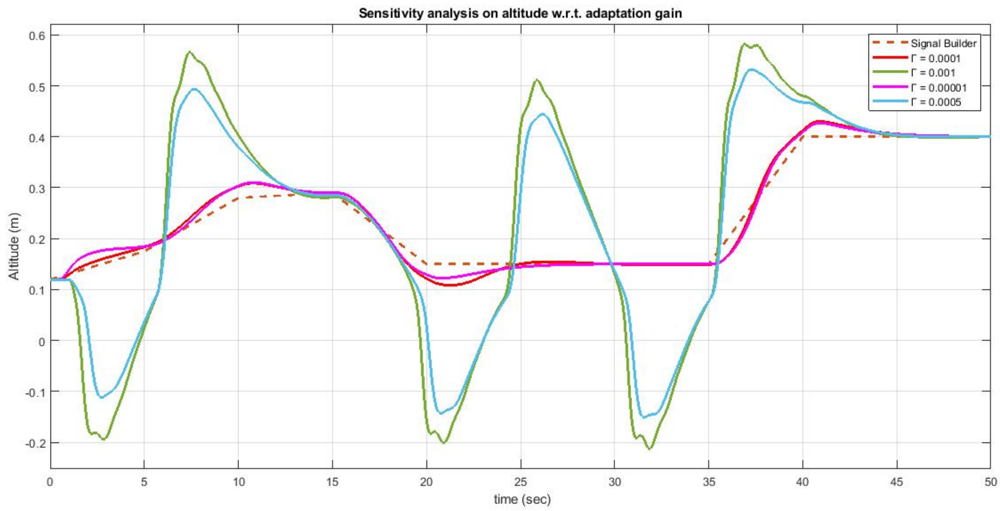


Figure 4.5: Sensitivity analysis on altitude for complete UAV case

As seen from the results, it is observed that the adaptive control is an efficient method especially in the initial phase of simulation. We can effectively implement the same algorithm with the baseline controller in order to achieve better results.The improvement in the results was more significant when single axis system was considered, but when the complete rotor-craft case was studied, the results were satisfactory mostly at the time of launch, which gives a motivation to further improve the adaptive model. At the moment only uncertainty in the K matrix was introduced for the altitude motion. Mass was considered as constant throughout the analysis, however, it is observed that mass uncertainties are also

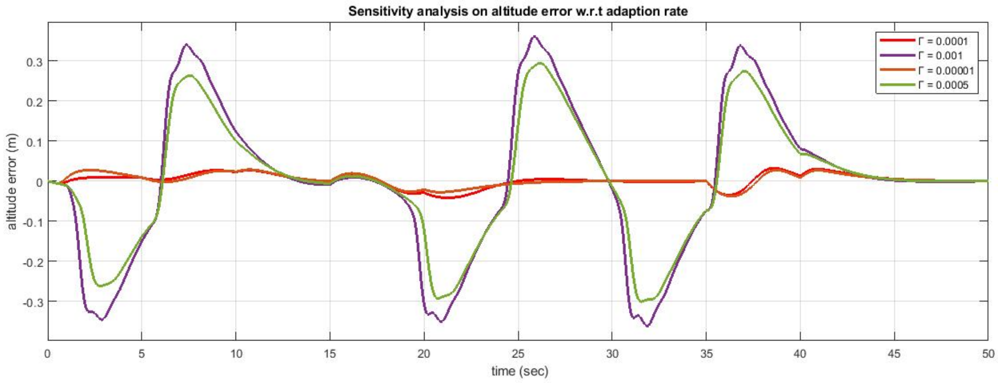


Figure 4.6: Sensitivity analysis on altitude error for complete UAV case

present especially near the ground. So, one such improvement could be considering more uncertainties in the model. This could make the model as close as the real flight. In addition to this, only simulation for the proposed model was conducted, it needs to be proved with the experiments, I believe the method is reliable enough to be applied on real drone, which will further open research opportunities especially to perform an experimental sensitivity analysis of the influence of the adaptation rate.

Conclusions

During this thesis, the numerical formulation of MRAC has been studied in order to compensate the ground effect of multirotor UAV and to compare it with the already developed model.

The first and foremost thing to do is a background study of the topics under consideration. So quick survey of different relevant works have been presented in this thesis. The survey is divided into two portions: One is done on the relevant ground effect techniques being used on UAVs and second one is done on the research work done on the adaptive control model implementation on drones. It was observed that there is no clear lines of thought specifically on the implementation of adaptive controller when it comes to small-sized helicopters or multirotors.

So, before integrating of adaptive model to the full-scale UAV, a mathematical model was developed for a simple one dimensional dynamic system for the pitch motion of helicopter. The problem was then simulated on Simulink and the solutions were obtained depicting a significant improvement of the response of the system in the presence of adaptive controller, provided that a simple PID baseline controller was also present.

Moving further, the same algorithm was integrated on the full scale UAV simulator. In order to achieve this, a similar mathematical model was developed first, as that was developed for one dimensional system. It was found that the system response is sensitive to the adaptation rate, on which sensitivity was performed in order to minimize the error of altitude with respect to the desired trajectory. The tuning was performed based on hit and trial method, and responses are studied on altitude and altitude error.

As a conclusion, with the addition of adaptive model, the system response at the time of launch was improved. It is to be noted that the uncertainty in the K matrix was considered in this thesis study. There is a possibility of uncertainty in the mass matrix as well, since the center of gravity can be effected near the ground, so a detailed analysis with the addition of mass uncertainty will further improve the response.

There are a few things which are still unanswered or which are needed to be improved. Some parameters or rather uncertainties were ignored mainly due to the lack of time. The possible future work recommendations are:ù

- Experimental validation of the new model is necessary in order to prove if the model is feasible in real drone or not. Due to time constraints, no experiments were able to be performed with the modified simulator model.
- Introduction of adaptive scheme on the attitude dynamics in addition of altitude, since it is observed that the attitude response of the UAV is also affected by ground.
- Introduction of mass uncertainty in the dynamic model, which will result in an additional adaptive gain, in order to achieve the response as close as the reality.
- Implementation of the same model on different drone designs and check if the method is feasible for them and in doing so, a more generalized solution can be achieved.

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