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Improvement of Stability in Aircraft Landing System by Using Model Predictive Control

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Abstract: ***The primary focus of this project is to design and develop Model Predictive Control (MPC) in aircraft landing application. MPC is a control methodology that has been applied with significant impact on industrial plants. This thesis describes the models of the aircrafts systems and also finds a method to improve the stability of aircrafts during landing and safety issue in various wind conditions. In addition to that, this thesis also combines this predictive manner into the MPC algorithm for aircraft ability recovery. In this thesis there are some results that are generated by MPC and other controller such as Cerebella Model Articulation Controller (CMAC) and*** **Proportional-Integral-Derivative** ***(PID) to show how MPC can be employed to improve aircraft safety. Also there are many programming using MATLAB for design ideal method to close viewpoint in some different situation and reduce the adverse effect of the wind for performance of the aircrafts.***

Keywords: Model Predictive Control, CMAC, PID

1. Introduction

Model Predictive Control (MPC), has been rigorously developed and investigated over many years, and has gained widespread application into systems with slow, predictable and well modeled dynamics. The main reasons for using MPC is the ability to predict future responses and formulate an optimized control solution that will keep the process within the performance capabilities of the system. Based on its pre-emptive nature, MPC seems well suited for implementation into highly dynamic nonlinear systems such as aircraft. This is mainly due to the computational burdens associated with solving nonlinear system equations and a nonlinear finite horizon control optimization problems in real-time. Furthermore, the accuracy of predictions used within the optimization is heavily dependent on the accuracy of the model, which can affect the reliability of the control process [1].

Predictive control has become more common in mechanical systems with fast dynamics; also aircrafts [2].The early studies [3] used predictive control for flight trajectory following where the aircraft is represented by a linear, discrete time model. In [4] the control problem is solved by predictive control inner loop longitudinal controller and the ability of MPC to handle multivariable processes makes it an ideal method for control in aerospace applications. This is because it is capable of optimizing a range of control inputs to manage multiple outputs in reaching desired references. The proposed system adopted the aircraft model [5], the wind disturbance model [6], MPC, CMAC [7] and PID [7] to do the analysis on how the different controller to assist the safe landing of aircraft in various wind conditions.

2. Aircraft Model

Aircraft modeling begins by elaborating the incremental aircraft variables. They are developed by linearizing the force balance equations (derived from Newton's law) for aircraft motion. Equation (1) (2) (3) shows the differential equations for incremental variables of an airframe. The relations show the variation of longitudinal and vertical speed components u and w in time. Pitch rate q, pitch angle θ, and altitude h are also obtained through this equation, which are due to incremental elevator angle and throttle settling (ft/sec),δ_E and δ_T. Wind gust speed including horizontal and vertical components is u_g and ω_g.

$$\dot{u}=X_u(u-u_g)+X_w(w-w_g)+X_q q-g(\pi/180)\cos\gamma_0\theta+X_E\delta_E+X_T\delta_T \quad (1)$$

$$\dot{w}=Z_u(u-u_g)+Z_w(w-w_g)+(Z_q-[\pi/180]U_0)q+g(\pi/180)\sin\gamma_0\theta+Z_E\delta_E+Z_T\delta_T \quad (2)$$

$$\dot{q}=M_u(u-u_g)+M_w(w-w_g)+M_q q+M_E\delta_E+M_T\delta_T \quad (3)$$

2.1 Wind Disturbance

In this section the environment effect on the aircraft will be discussed. As mentioned before, there may be disturbances such as wind and gust which can change the flight path. In this thesis only the wind is considered. Wind disturbances have two components: constant velocity and turbulence. The magnitude of the constant velocity changes with altitude. Turbulence is two dimensional as it varies with both time and space when the aircraft flies through an airspace region. Equations (4) (5) (6) represents the constant velocity component which has value only in horizontal axis

$$\begin{Bmatrix} -u_{wind_{510}}[1+\dfrac{\ln(h/510)}{\ln(51)}] & \mathrm{h}\geq 10 \\ 0 & \mathrm{h}<10 \end{Bmatrix} \quad (4)$$

$$u_g=u_{gc}+N(0,1)\sqrt{\frac{1}{\Delta t}}\left(\frac{\sigma_u\sqrt{2a_u}}{s+a_u}\right) \quad (5)$$

$$w_g=N(0,1)\sqrt{\frac{1}{\Delta t}}\left(\frac{\sigma_w\sqrt{3a_w}\,(s+b_w)}{(s+a_u)^2}\right) \quad (6)$$

3. Control Models

3.1 MPC model

Figure 1 shows the block diagram of a MPC controller implemented in an aircraft landing system. Altitude, altitude rate, altitude command, and altitude rate command are the inputs of both the aircraft and MPC controller. The MPC controller function is to to stabilize the aircraft in the presence of severe wind disturbance and its performance can be improved through a learning process

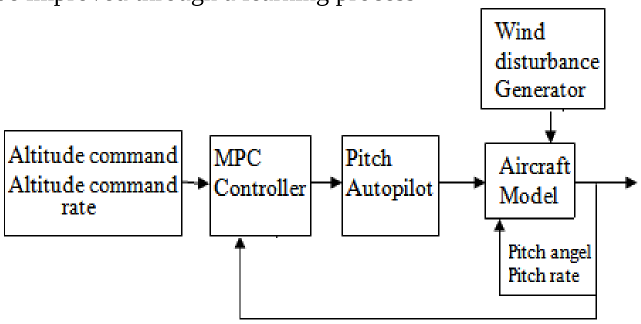

Figure 1: Application of the MPC controllers to the ALS

3.2 CMAC model

CMAC is a kind of associative memory network. Not only it has faster self learning rate than normal neural network by quantities with a few adjustments of memory weights, but also it has good local generalization ability. The function of CMAC is similar to a look-up table, and the output of CMAC is figured from a linear combination of weights which are stored in memory. The concept of CMAC is to store data into overlapped storage hypercube (remembering region) in an associative manner such that the stored data can easily be recalled. Two kinds of operations are included in the CMAC, one is calculating the output result and the other is learning and adjusting the weight.

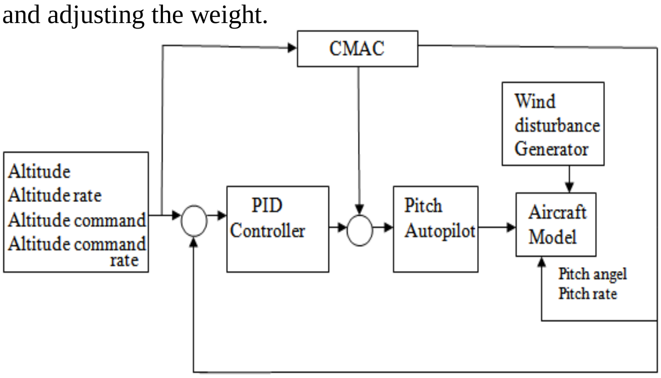

Figure 2: The CMAC control scheme

3.3 PID model

In order to enable aircraft to land more steady when an aircraft arrives to the flare path, a constant pitch angle will be added to the controller. In general, the PID controller is simple and effective but there are some drawbacks such as apparent overshoot and sensitive to external noise and disturbance. When severe turbulence is encountered the PID controller may not be able to guide the aircraft to land safely. [7]

4. Simulation Results

In this section, the overall performance of the proposed MPC based controller has been investigated and compared with two other widely used controllers namely PID controller and CMAC controller. Several simulations of the aircraft landing have been carried out based on different performance relevant parameters. Simulation specific parameters set during various trials were also consistent with those employed in real applications. The aircraft starts the initial states of the ALS as follows: the flight height is 700 ft, the horizontal position before touching the ground is 9240 ft, the flight angle is -3 degrees, the speed of the aircraft is 234.7 ft/sec. Total simulation time for aircraft landing is 200s. In the simulations, successful touchdown landing conditions are defined as follows:

$-3 \le \dot{h}(T)ft/\sec \le 0 \qquad 200 \le \dot{x}(T)ft/\sec \le 270$

$-300 \le x(T)ft \le 1000 \qquad -10 \le \theta(T)\text{degree} \le 5$

. where T is the time at touchdown, $\dot{h}(T)$ is vertical speed of the aircraft at touchdown, $x(T)$ is the horizontal position at touchdown, $\dot{x}(T)$ is the horizontal speed,and $\theta(T)$ is the pitch angle at touchdown.

Figure 3 shows the landing point or horizontal distance variation with wind speed for three different controllers- PID, CMAC and MPC. As illustrated in the figure, both PID and CMAC controllers (green and red lines) fail to maintain necessary and safe horizontal distance for landing point after wind speed approximately 30 ft/s. However, the performance of MPC controller is much better in this regard. As shown in the figure by blue line, the MPC controller can actually ensure safe landing point even at speed 121 ft/s. Therefore, the MPC controller is certainly superior to other two controllers in terms of landing point.

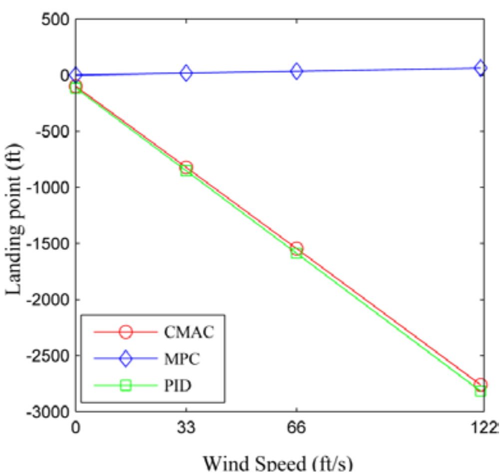

Figure 3: Landing point variation with wind speed for three different controllers- PID, CMAC and MPC

Figure 4 shows the pitch angle variation with wind speed for three different controllers- PID, CMAC and MPC. As shown in the figure, all three controllers have exhibited satisfactory performance for ensuring safe pitch angle for landing of aircraft. In this regard, it is observed that PID controller does not vary pitch angle much with increase in wind speed (green line) but CMAC controller continually reduce pitch angle with increment in wind speed (red line). However, the MPC controller actually increases the pitch angle with increase in wind speed.

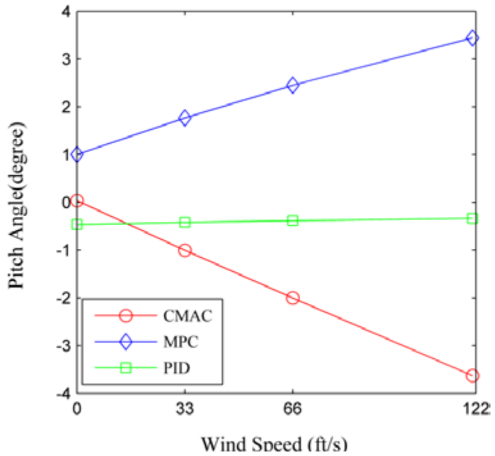

Figure 4: pitch angle variation with wind speed for three different controllers- PID, CMAC and MPC

Figure 5 (a) to 5 (c) illustrate the vertical distance or altitude profile of the aircraft produced by three different controllers (PID,CMAC & MPC) during the execution of a landing simulation. For all three cases, the aircraft has been simulated to descend from a height of 700 ft and total landing simulation time for each controller case was 200s.For all cases, the actual aircraft response (blue line) was also compared with reference condition (red line) as depicted in Figure 5(a) to 5(c). Figue 5(a) shows aircraft's landing trajectory for PID controller which clearly demonstrates efficiency of the PID controller to maintain aircraft altitude in accordance with reference condition. Furthermore, CMAC controller also showed good ability to maintain aircraft altitude in accordance with reference condition except during the initial descending phase of the aircraft as showed in Figure 5(b). Finally, Figure 5(c) illustrates the performance of the proposed MPC based controller which indicates its performance is also satisfactory. Except some instability at the very beginning of descending, the aircraft altitude is well maintained till touch down of the aircraft. Furthermore, Figure 5(d) which compares the deviation of each controller's response from reference conditions also indicates that performance of MPC based controllers is better than other two controllers. It is evident from the figure that MPC based controller reaches reference conditions much faster than other two controllers. For example, MPC controller's deviation approaches zero within 20 or 25s of the beginning of the simulation. However, the other two controllers maintains a deviationtill approximately 100s which means there exists a deviation infact just before the touch down of the aircraft for PID and CMAC controllers.Therefore, the proposed MPC based controller clearly has better capability of reaching stable condition in less time. One of the major advantage of the MPC controller is null steady state error while other two controllers have small error even in steady state.

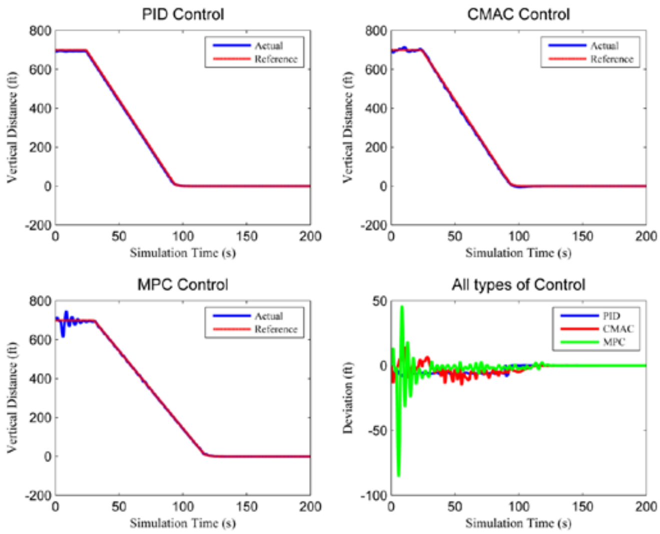

Figure 5: Vertical distance profile of aircraft produced by three controllers (a) PID, (b) CMAC, (c) MPC and (d) comparative deviation plot of three controllers

Figure 6 illustrates the pitch angle profiles of three controllers-PID, CMAC and MPC. Firstly, the blue line in the figure is the PID controller response which effectively demonstrates the controller's inability to control aircraft pitch angle in a stable and robust manner during landing. Specially, the controller's performance is considerablely poor during initial desending (0-5s) and touch down stage (around 80s) of the aircraft. The maximum pitch angle variation for PID controller is also large compared to other two controllers and its value can be as high as around 20 degree as depicted in the figure. Secondly, the red line in the figure is the CMAC controller response which demonstrates better performance than PID controller. Lastly, the green line in the figure indicates the performance of MPC based controller. The response of MPC controller is certainly the best compared to other two controllers considering the fact that the pitch angle has been gradually reduced or adjusted keeping consistency with aircraft vertical distance reduction or decending.Absence of any drastic pitch angle variation except initial stage also ensure safe and smooth landing of the aircraft.

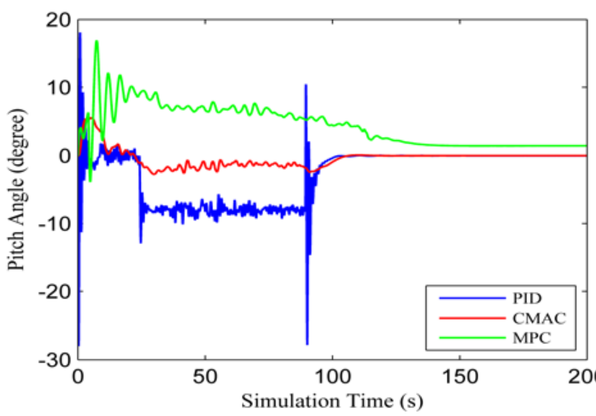

Figure 6: Pitch angle profiles of aircraft produced by three controllers-PID, CMAC and MPC

Figure 7 shows the vertical velocity profiles for three controllers- PID, CMAC and MPC. The green line indicates PID controller's response which demonstrates an approximately constant vertical speed during the landing stage as desirable by the safe and soft landing of aircraft. The red line indicates CMAC controller's performance to maintain vertical velocity of the aircraft. Clearly, CMAC cannot maintain stable vertical velocity during landing. However, its vertical velocity variation is within the range of the vertical velocity requirement for safe landing. Furthermore, the green line indicates the MPC controller's performance for vertical velocity control. It is obvious from the figure that its performance is not as good as PID but the vertical velocity variation is within an acceptable tolerance limit. Also, the vertical velocity is within the range of the vertical velocity requirement for safe landing. The initial high distortion in vertical velocity profile can be attributed as high noise in data which can be ignored as it has minimal effect on the safe landing condition of aircraft.

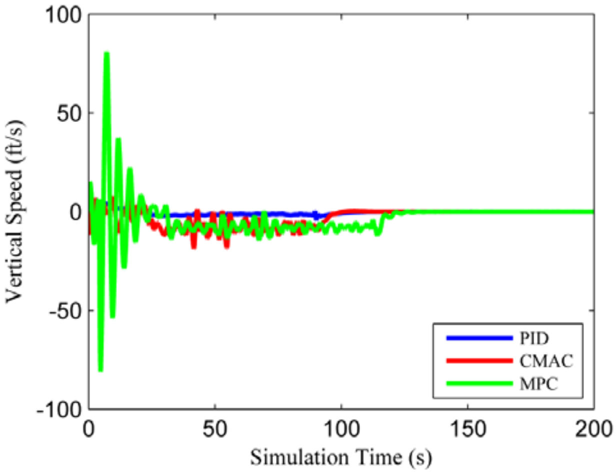

Figure 7: Vertical velocity profiles of aircraft produced by three controllers-PID, CMAC and MPC

Table 1 summarizes the performance test results of three controllers- PID, CMAC and MPC. As shown in the table, the PID, CMAC and MPC controller can successfully guide the aircraft to the landing point through wind speeds of 33, 33 and 121ft/s respectively. The corresponding landing points for three controllers are 821 ft, 851 ft and 63.75 ft respectively. Furthermore, convergence speed of CMAC is the slowest among the three controllers and the best convergence speed has been demonstrated by MPC controller. From the data organized in the table, it is clear that MPC controller is superior to other two controllers in terms of landing point, convergence speed and maximum wind speed.

Table 1: Performance test results

Performance Parameter	*PID*	*CMAC*	*MPC*
Landing point (ft)	821	851	63.75
Horizontal speed (ft/s)	234.7	234.7	234.7
Vertical speed (ft/s)	-0.4	-1.7	-4.1
Pitch Angle (degree)	-.42	-.1	3.4
Convergence speed	slow	slowest	fastest
Maximum wind	33	33	121

5. Conclusion

The model was simulated in MATLAB Simulink and the MPC Toolbox. Robust performance in the presence of relatively strong wind was achieved so it can be concluded that, this model will reduce the influence of uncertainties like wind and gust. Simulation results including aircraft altitude, aircraft velocity and output altitude error has been presented. All simulation results by MPC show the improvement of the aircraft lending stability over the others conventional methods.

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