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Scientific-Research Article

Airplane Ground Collision Avoidance System Design based on Optimal Tracking Control

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The design of a ground collision avoidance system for an airplane based on optimal control theory is presented in this paper. A control system is designed by linear quadratic tracker to track desired Euler angles of airplane. The system independent of 3 dimensional maps, works by using a forward looking camera. In addition, the obstacle is analyzed by digital image processing techniques. An optimal flight control system based on discrete-time linear quadratic tracker is designed, to fly over or pass obstacles like mountains automatically.

Keywords: *Automatic Flight Control System; Ground Collision Avoidance System; Linear Quadratic Tracker; Digital Image Processing; Optimal control system*

Introduction

FROM 1850 designers tried to design an automatic flight control system to make airplanes to avoid collisions into terrain and obstacles like mountains. The goal is to make flight more secure. Many different typed of such systems are designed, some are simple and some are complicated. In [1] is presented some ground and obstacle collision avoidance technique. In[2] is studied all terrain ground collision avoidance and terrain following for automated low level night attack. In [3-6] automatic ground collision avoidance systems are studies using Digital Terrain Databases (DTD). An automatic predictive control for terrain following flight is studied in [7]. Terrain awareness for pilots is analyzed in [8] using ecological approach. Also Image Processing methods are used in Path finding and collision avoidance of UAVs [9,10]. A Traffic alert and Collision Avoidance System(TCAS) is analyzed in [11].
In this paper, we want to design a system to help the pilot to have a more secure flight when there is low visibility, using optimal control theory, and digital image processing technics to analyze the terrain. So,

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it is suggested to use acoustic imaging or ultraviolet cameras, to take photos from the front of the airplane. Then by using digital image processing technics, we detect the edges of the obstacle. Then we analyze these edges to find out if there is a wide way to pass through. So we define three different maneuvers, and the system choose between these three maneuvers, and then the optimal linear quadratic tracker will track the desired inputs we defined earlier. Therefore, the goal is to design a simple and intelligent system. Block diagram of such a system is shown in figure 1.

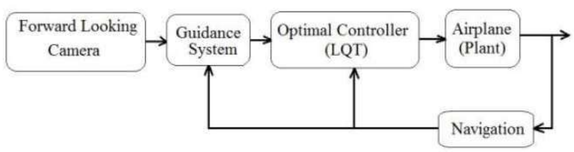

Fig. 1. Block diagram of the closed loop ground collision avoidance system

ANALISYS OF THE IMAGE

First, the cameras will take photos from front of the airplane and then the edges are detected (Figure 2). Then the possibility of passing over or from side of the obstacle is analyzed

Image Edge Detection

We use MATLAB function "edge" to detect the edges (Figure 3). The output of this function is a white-and-black image, and this image is a matrix, containing just zeros and ones. Zeros refer to black and ones refer to white. [12]

Fig. 2. Using acoustic imaging or ultraviolet cameras, to take photos from the front of the airplane and importing it into MATLAB

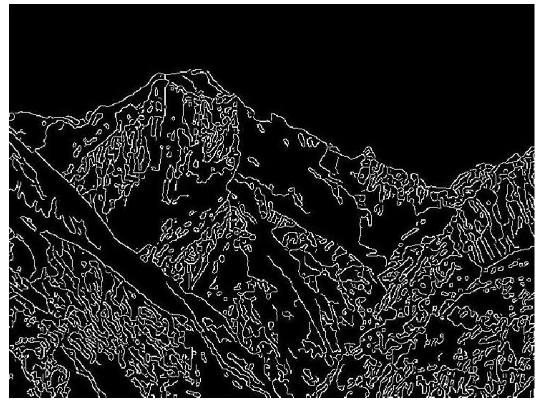

Fig. 3. Edge detection using MATLAB function "edge"

Studying the edges and boundaries

Now we study the edges and boundaries. We want to find a wide-enough way in the image and see if it is possible to fly through it. For this purpose the shortest height of the space, which has dimensions of 50 meters by 50 meters, is examined in the image. Every picture is a matrix, and we check each column of it up to the edges detected earlier. We select the best point of it and we save the position of that point. (Figure 4)

Since every picture is a matrix, we study each column from top to bottom (until it reaches to the edge). It means that we assume a square zero-matrix that scans the picture from top to bottom, and as reaches the edge (edges are "ones"); the position of this point is saved (height and width). This process is repeated for each column and so set of data is prepared. We will use these data to calculate and find the point that we can reach to it in the least time. [13]

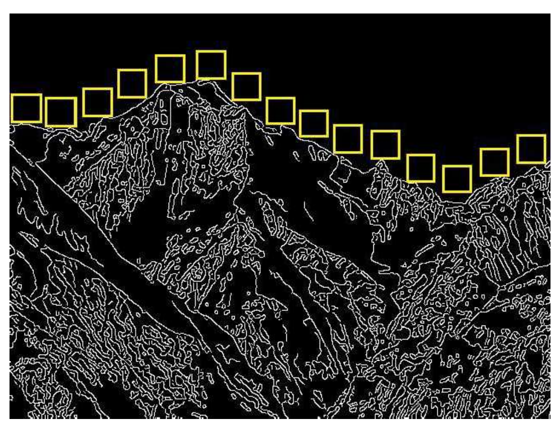

Fig. 4. Schematic of studying the edges of the picture

Generating the desired inputs

First, we define three different maneuvers, and then according to them, we generate desired inputs for the optimal control system to track them.

Maneuver "I": Climb

When the obstacle is not very high, and the airplane is able to climb and fly over it, this maneuver is selected. So the airplane will climb with maximum path angle ($\gamma_{\max}$) and power, until it reaches the top of the obstacle. [14]

$$RC = \dot{h} = V \sin(\gamma) \quad (1)$$

$$\gamma = \arcsin(RC / V) \quad (2)$$

$$\theta = \gamma + \alpha \quad (3)$$

Therefore, the outputs of this guidance system are as (4).
Refer to "(2)," we calculate the path angle. The maximum allowable angle of attack for this airplane is 14 degrees.
So we generate the desired "u", and "θ".

$$\begin{cases} u = 0 \\ \theta = \arcsin(RC / V) \end{cases} \quad (4)$$

In addition, the rate of climb is variable according to the altitude.

Maneuver "II": Climb and Turn

When the obstacle is high, and the airplane is not able to climb and fly over it, this maneuver is selected. Therefore, the airplane will climb with maximum path angle and then will turn according to the maneuver, which is shown in figure 5.
The time to turn "ψ" radian with the turn radios "R" and velocity "V" is calculated by:

$$t = R\psi / V \quad (5)$$

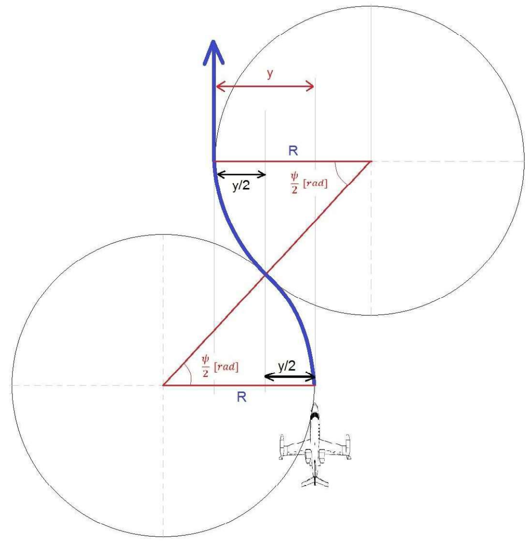

Fig. 5. Defining a path for displacing airplane, the amount of "y" to the left for the maneuver "II"

And for to displace the airplane, the magnitude "y/2" to the left and turn "ψ" radian, we have the following relations:

$$y/2 = R(1 - \cos(\psi/2)) \quad (6)$$

$$R = y/(2(1 - \cos(\psi/2))) \quad (7)$$

So we have found a relation between "y" and "ψ". Therefore, the maneuver time is:

$$t/2 = (y/2 * \psi/2)/(V(1 - \cos(\psi/2))) \quad (8)$$

And the bank angle is:

$$\varphi = \tan^{-1}(t * g/(V * \psi))) \quad (9)$$

Now we check the load factor. If the load factor is less than the allowable load factor, then this maneuver is selected. We calculate the load factor, referred to in (9):

$$\varphi = V^2 /(R * g) \quad (10)$$

So we generate the desired "u", "θ", "φ", and "ψ" as (11).

$$\begin{cases} u = 0 \\ \theta = \arcsin(RC / V) \\ \beta = 0 \\ \phi = \arctan(V^2 / Rg) \\ \psi, from t/2 - (y/2 * \psi/2)/(V(1 - \cos(\psi/2))) = 0 \end{cases} \quad (11)$$

Maneuver “III”: Turn back 180 degrees, and Climb, and then Turn Back 180 degrees again (Figure 6)
When the obstacle is very high, and the airplane is not able to climb and fly over or around it, this maneuver is selected. So the airplane will Turn Back 180 degrees, and Climb, and then Turn Back 180 degrees again, to reaches the top of the obstacle and fly over it. The relations are the same as maneuver 2, and here we generate the desired “u”, “θ”, “φ”, and “ψ”.

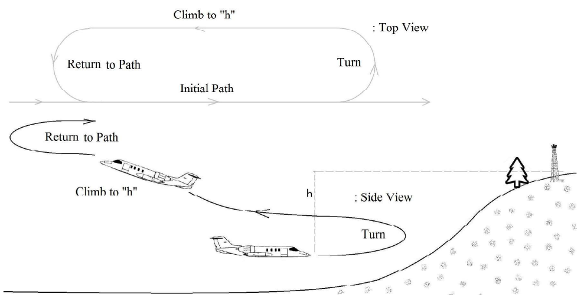

Fig. 6. Defining the desired path for the maneuver “III”

Design of optimal controller

We use discrete-time linear quadratic method to design a closed loop system to tack the desired “u”, “θ”, “φ”, and “ψ” values. Consider the linear state space as bellow: [15]

$$X(k+1) = AX(k) + BU(k) \tag{12}$$

$$Y(k) = CX(k) \tag{13}$$

In addition, the system should be controllable.
To design a controller to track the desired vector “Z”, and minimize the performance index referred to (14),

$$J = (1/2)e'(kf)Fe(kf) + (1/2)\sum_{k=k0}^{kf-1} e'(k)Qe(k) + U'RU \tag{14}$$

And “e” is the error vector and deviation from the desired values, as bellow:

$$e(k) = Y(k) - Z(k) \tag{15}$$

The matrices “F” and “Q”, must be any semi-positive definite matrices, and matrix “R” must be any positive definite matrix. In this paper, we choose diagonal matrices.
Now we should solve the two differential equations, referred to (16) and (17): [15]

$$P(k) = A'[P^{-1}(k+1) + E]^{-1} A + V \tag{16}$$

$$A'\{I - [P^{-1}(k+1) + E]^{-1} E\} g(k+1) + WZ(k) \tag{17}$$

And for simplifications we have:

$$E = BR^{-1}B' \tag{18}$$

$$V = C'QC \tag{19}$$

$$W = C'Q \tag{20}$$

The final values are referred to (21) and (22):

$$P(kf) = C'FC \tag{21}$$

$$g(kf) = C'FZ(kf) \tag{22}$$

So we have the optimal controller as (23): [15]

$$U^*(k) = -L(k)X^*(k) + Lg(k)g(k+1) \tag{23}$$

And for simplifications, we define the feedback gain and feedforward gain as (22) and (23):

$$L(k) = [R + B'P(k+1)B]^{-1} B'P(k+1)A \tag{24}$$

$$Lg(k) = [R + B'P(k+1)B]^{-1} B' \tag{25}$$

And the optimal states are as bellow: [15]

$$X^*(k+1) = [A - BL(k)]X(k) + BLg(k)g(k+1) \tag{26}$$

Simulation

Now we simulate these three maneuvers in MATLAB. Here we choose the linear state space model of longitudinal and lateral-directional motion a light airplane, and the weighting matrices of longitudinal and lateral-directional, are as bellow: [16]

$$A_{Lo} = \begin{bmatrix} -0.0121, 0.096, -6.45, -9.81 \\ 0.116, -1.2773, 100, 0 \\ 0.005, -0.0781, -1.2794, 0 \\ 0, 0, 1, 0 \end{bmatrix} \tag{27}$$

$$B_{Lo} = \begin{bmatrix} 0.0065, 4.6739 \\ 13.1653, 0 \\ -9.069, 0 \\ 0, 0 \end{bmatrix} \tag{28}$$

$$A_{LD} = \begin{bmatrix} -0.5436, 0, -1, -0.0981 \\ -8.3098, -2.3478, 0.3106, 0 \\ 8.8414, -0.0884, -0.0884, 0 \\ 0, 1, 0, 0 \end{bmatrix} \tag{29}$$

Journal of Aerospace Science and Technology
Vol. 14/ No. 2/ Summer – Fall 2021

$$B_{LD} = \begin{bmatrix} 0,8.9563 \\ 13.0409,1.4557 \\ 0,0 \\ 0,0 \end{bmatrix} \tag{30}$$

$$Q_{Lo} = \begin{bmatrix} 0.1,0,0,0 \\ 0,0,0,0 \\ 0,0,0,0 \\ 0,0,0,1 \end{bmatrix} \tag{31}$$

$$R_{Lo} = \begin{bmatrix} 20,0 \\ 0,0.1 \end{bmatrix} \tag{32}$$

$$F_{Lo} = \begin{bmatrix} 0.1,0,0,0 \\ 0,1,0,0 \\ 0,0,1,0 \\ 0,0,0,1 \end{bmatrix} \tag{33}$$

$$Q_{LD} = \begin{bmatrix} 0,0,0,0 \\ 0,0,0,0 \\ 0,0,5,0 \\ 0,0,0,0.3 \end{bmatrix} \tag{34}$$

$$R_{LD} = \begin{bmatrix} 2,0 \\ 0,2 \end{bmatrix} \tag{35}$$

$$F_{LD} = \begin{bmatrix} 0.01,0,0,0 \\ 0,1,0,0 \\ 0,0,0.1,0 \\ 0,0,0,1 \end{bmatrix} \tag{36}$$

The maximum allowable angle of attack is 14 degrees, and the allowable load factor of this airplane is $-3g < a_z < +6g$. However, we assume minimum load factor for human comfort.

Maneuver "I": Climb

In this maneuver, the airplane should reach the height of 408 (m). This maneuver would take 28 seconds. The outputs, optimal controls, angle of attack, and load factor curves are as shown in figures 7 to 11.

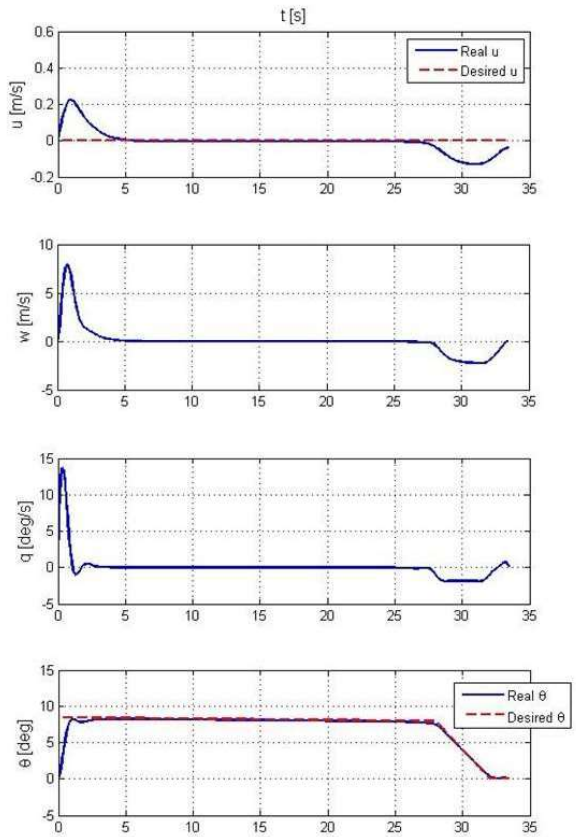

Fig. 7. Longitudinal response of the airplane and optimal states for the maneuver "I"

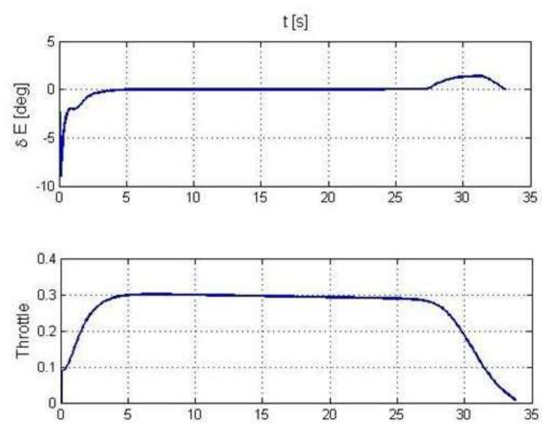

Fig. 8. Longitudinal optimal controls for the maneuver "I"

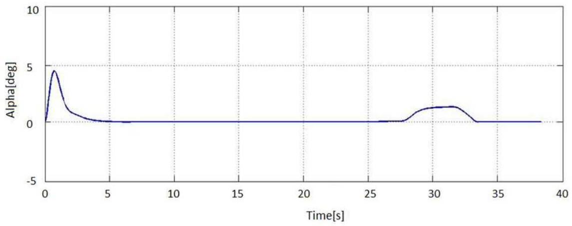

Fig. 9. Angle of attack versus time for the maneuver "I"

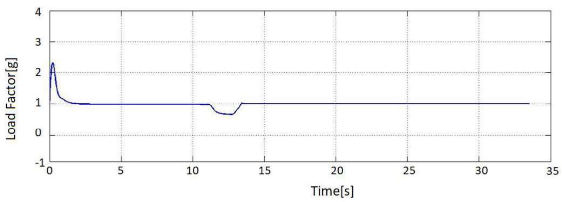

Fig. 10. Load factor versus time for the maneuver "I"

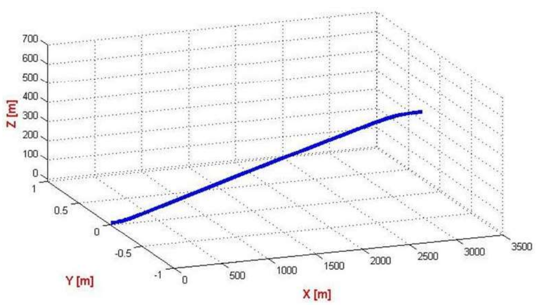

Fig. 11. Flying path for the maneuver "I"

Maneuver "II": Climb and Turn

For this maneuver, the airplane should reach the height of 54 (m), and displace 250 (m) to the left. this maneuver would take 18 seconds. The outputs, optimal controls, angle of attack, and load factor curves are as shown in figures 12 to 18.

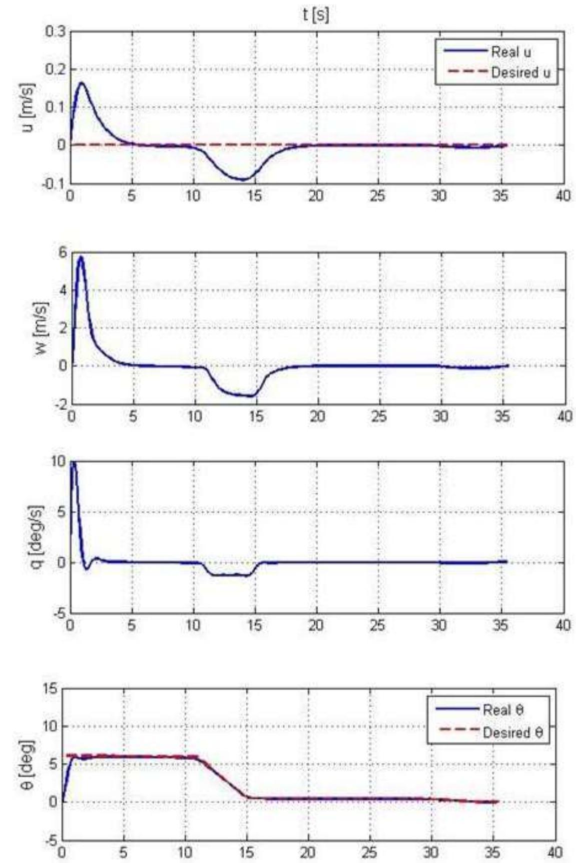

Fig. 12. Longitudinal response of the airplane and optimal states for the maneuver "II"

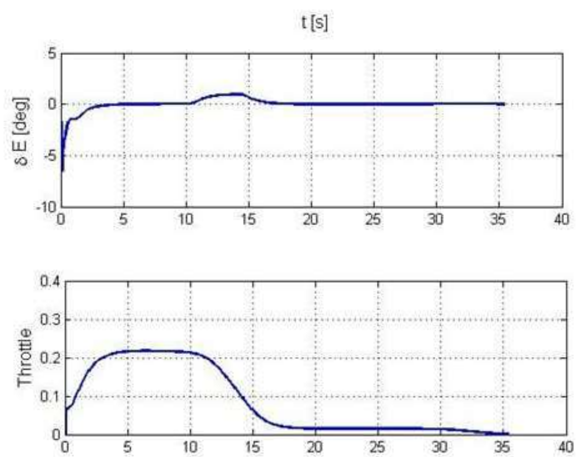

Fig. 13. Longitudinal optimal controls for the maneuver "II"

Journal of Aerospace Science and Technology
Vol. 14/ No. 2/ Summer – Fall 2021

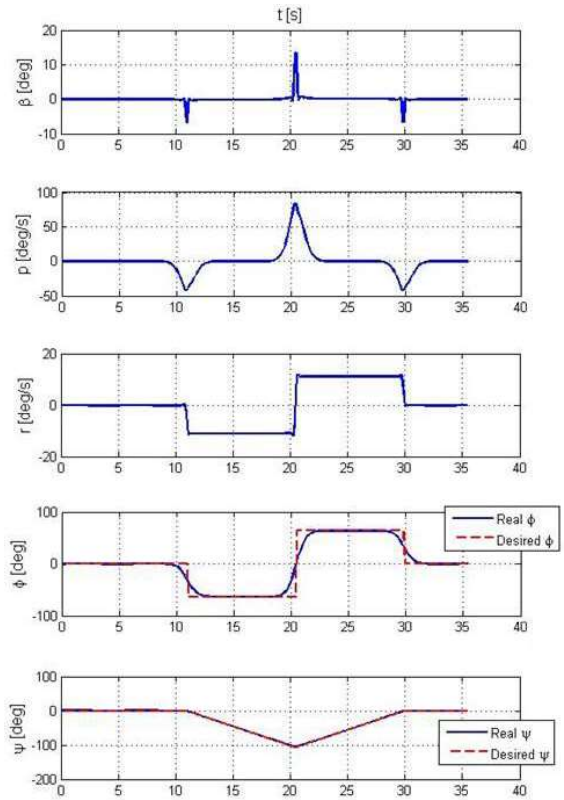

Fig. 14. Lateral-Directional response of the airplane and optimal states for the maneuver “II”

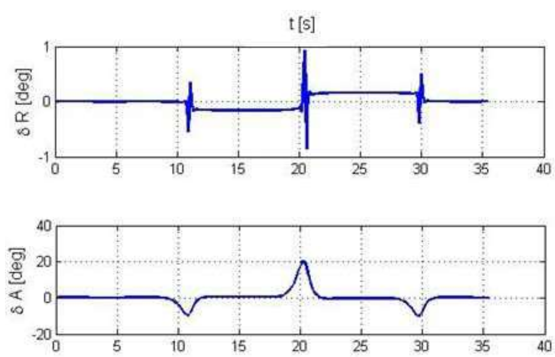

Fig. 15. Lateral-Directional optimal controls for the maneuver “II”

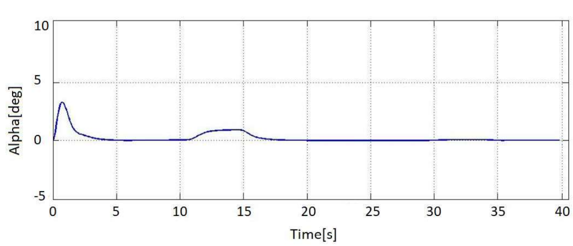

Fig. 16. Angle of attack versus time for the maneuver “II”

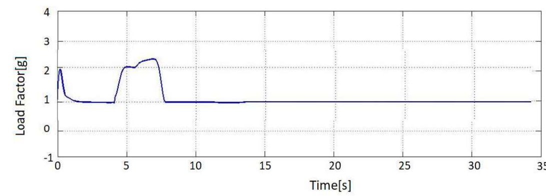

Fig. 17. Load factor versus time for the maneuver “II”

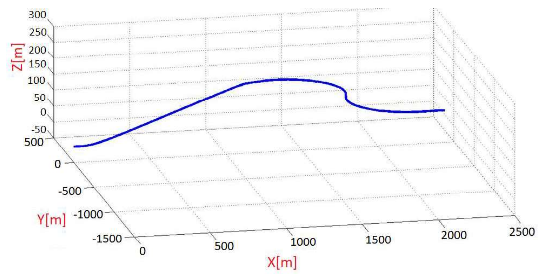

Fig. 18. Flying path for the maneuver “II”

Maneuver “III”: Turn Back 180 degrees, and Climb, and then Turn Back 180 degrees again

For this maneuver, the airplane should reach the height of 450 (m). This maneuver would take 52 seconds. The outputs, optimal controls, angle of attack, and load factor curves are as shown in figures 19 to 26.

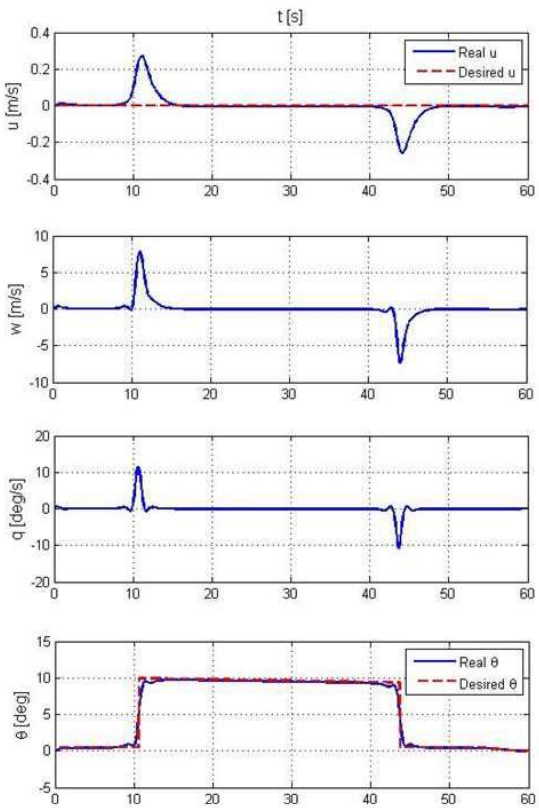

Fig. 19. Longitudinal response of the airplane and optimal states for the maneuver "III"

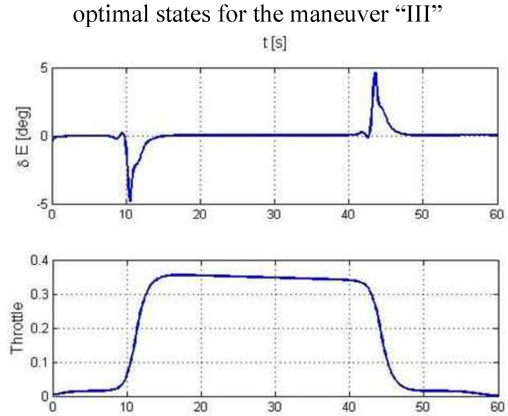

Fig. 20. Longitudinal optimal controls for the maneuver "III"

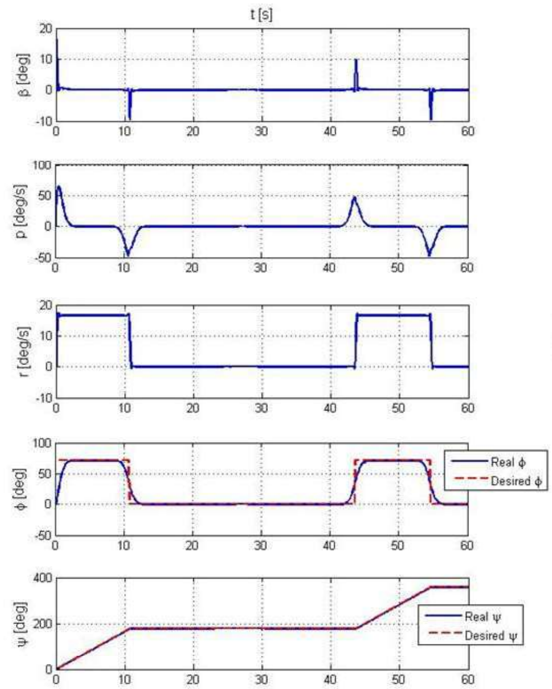

Fig. 21. Lateral-Directional response of the airplane and optimal states for the maneuver "III"

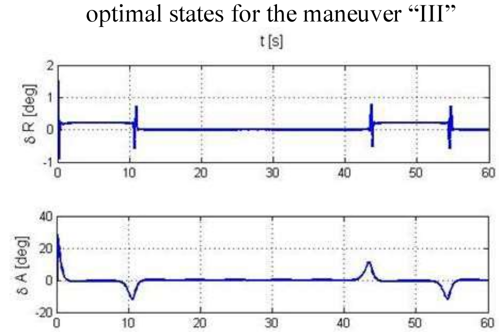

Fig. 22. Lateral-Directional optimal controls for the maneuver "III"

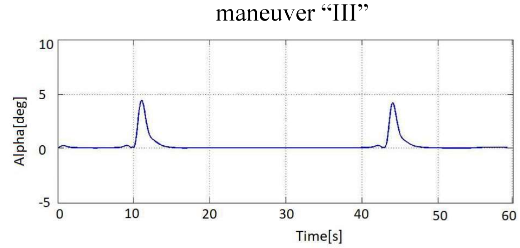

Fig. 23. Angle of attack versus time for the maneuver "III"

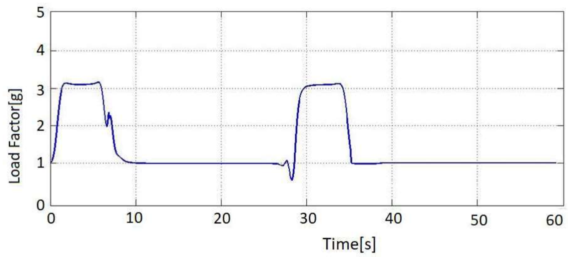

Fig. 24. Load factor versus time for the maneuver "III"

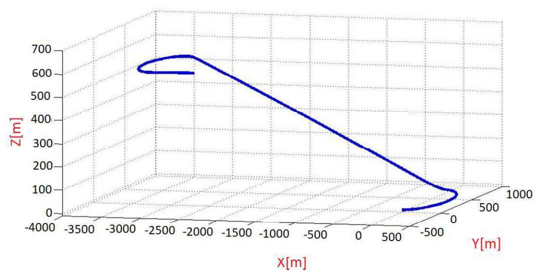

Fig. 25. Flying path for the maneuver "III"

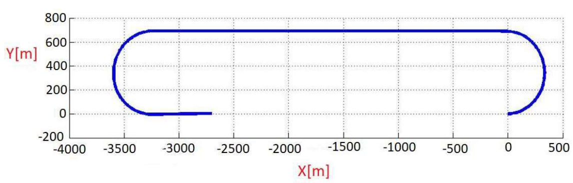

Fig.26. Flying path for the maneuver "III" (top view)

Conclusion

An optimal flight control system based on discrete-time linear quadratic tracker is designed, to fly over or pass obstacles like mountains automatically. So by generating desired state variables in guidance system, and choosing one of the maneuvers that are predefined, the airplane would no more crash into terrain. In addition, the optimal controls, the angle of attack, and load factor, are within the allowable ranges, and are acceptable. The angular velocities and Controls became zero at the end of the maneuvers.

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