Rudder Loss Recovery Autopilot System for a Small Fixed-Wing Aircraft

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Abstract

This paper presents an integrated way of development of an aircraft dynamic modeling including stability and control derivatives and ensuing autopilot design. Stability derivatives are calculated via an automated procedure using a spreadsheet method that is consistent with the MATLAB/Simulink block of the subject aircraft. Bifilar pendulum experiment is used to obtain the actual moment of inertias of the aircraft. The loop shaping control approach is implemented for the stabilizer mode of the subject autopilot system to decouple different command channels of the MIMO system. The system is built in MATLAB/Simulink environment.

1. Introduction

Many accidents in avionics have been caused by loss of flight control of the aircraft [1], [2]. Such loss of control may be caused by mechanical failures, human factors or environmental conditions [3]. Among these failures and accidents, especially the rudder malfunction is a prime suspect. When an aircraft experiences a damage or loss of a control surface, the ensuing motion is called as an "unusual attitude" for the aircraft in which case the flight becomes "uncoordinated" [4]. This is because of the fact that remaining control surfaces should act to balance the abnormal forces and moments [4]. When the servo motors are locked or damaged in the aircrafts control surfaces, automatic diagnosis is crucial for recovery cases. When any emergency occurs, even if the remaining control ability is enough to flight, the necessary amount of work load would be much for a pilot. Therefore, in such case, the need of an automatic pilot system to take control of the situation is obvious. Under these conditions, the requirement to survive for these unusual attitudes is the focus of this autopilot design.

UAVs play active roles in various fields [5]. To widen its appeal, it is necessary to improve the robustness of its navigation and control system [5]. UAVs can be controlled manually or autonomous to prevent any risk of human life [6], [7], [8]. Due to their numerous advantages, control of UAVs and dynamically modeling them are important and essential issue. In addition, a UAV can maintain the flight beyond the limits of a human pilot [9].

In this paper, rudder malfunction for emergency scenario is chosen. Due to the fact that aircraft gravitates towards rudder malfunction direction, recovery system should change the aircraft's direction to the opposite side. Thus, aircraft can obtain stable flight. Controlling the aircraft by using the remaining of control surfaces is the main goal. Because the aircraft surfaces have couplings [10] and when any control surface is induced other surfaces may affect too. For instance, there is a coupling between rudder and aileron surfaces and we aimed a stable flight by using this coupling in the emergency scenario.

Design of a multi input multi output system is the approach which has loop shaping controller [11] method for stable flight. Advantage of loop shaping controller is forming a system that is more stable and less effected by environment conditions. In the theory of control, loop shaping is controlling three control surfaces (throttle, aileron, and elevator) due to rudder jam. Controller is tested in simulation platform after it is obtained in MATLAB/SIMULINK.

This paper is organized as follows: the derivation of the mathematical approach of the controller and autopilot system is described in Section 2. Section 3 represents the simulation results based on the model derived. Section 4 contains conclusions and future work.

2. System Model and Controller Design

A well-known approach to MIMO feedback controller design is loop shaping approach [12]. A standard and simple control system topology is shown in Fig. 1 where r is the reference input, K is the controller, u is the control input to the system, G is the system to be controlled, d is the output disturbance, y is the output, n is the output noise. In the loop shaping methodology S is sensitivity function, and the closed loop transfer function is T. The maximum and minimum singular values of a matrix are denoted $\bar{\sigma}(\cdot)$ and $\underline{\sigma}(\cdot)$ respectively.

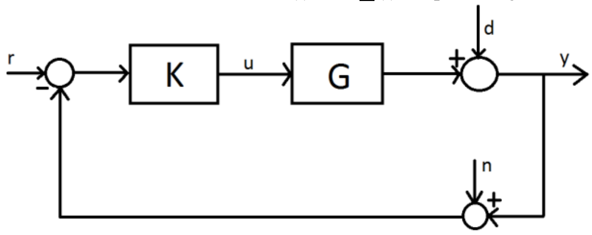

Fig. 1. Control System Topology

$$S = (I + GK)^{-1}. \quad (1)$$

$$T = GK(I + GK)^{-1} \quad (2)$$

In loop shaping design, closed loop objectives in terms of requirements on the open-loop singular values of the compensated system are specified [12]. For good performance it is required to be $\overline{\sigma}((I-GK)^{-1})$ and $\overline{\sigma}((I-GK)^{-1}G)$ small and for good robust stability properties $\overline{\sigma}(K(I-GK)^{-1})$ and $\overline{\sigma}(GK(I-GK)^{-1})$ to be small is required. Equations given in the reference [12] show that the desired closed-loop behavior can be achieved by manipulation of the open loop gains $\overline{\sigma}(GK)$, $\underline{\sigma}(GK)$.

In H_∞ synthesis, closed loop objectives in terms of requirements on the singular values of weighted closed-loop transfer functions are specified and a stabilizing controller is obtained which optimally satisfies these requirements [12]. A difficulty with the H_∞ design approach is that the appropriate selection of closed-loop objectives and weights are not straightforward. These closed-loop objectives and weights need to be developed for each unique example.

Initial step for this approach is computation of a stable-minimum-phase loop-shaping, square-down pre-filter W which should achieve the desired loop shape.

$$G_s = GW \tag{3}$$

$$\sigma(G_d) \approx \sigma(G_s) \quad \forall w \tag{4}$$

$$G = M^{-1}N \tag{5}$$

$$(I-GK)^{-1}, K(I-GK)^{-1}, (I-GK)^{-1}GK, (I-KG)^{-1} \in RH_\infty \tag{6}$$

$$\det(I-GK)(\infty) \neq 0 \tag{7}$$

$$\inf_{K} \left\| \begin{bmatrix} K(I-GK)^{-1}M^{-1} \\ (I-GK)^{-1}M^{-1} \end{bmatrix} \right\|_\infty \leq \varepsilon^{-1} \tag{8}$$

$$\inf_{K} \left\| [F_L(P,K)] \right\|_\infty \leq \varepsilon^{-1} \tag{9}$$

$$K_{final} = WK \tag{10}$$

The objective of the robust controller design is stabilized by a controller K. This controller stabilizes not only the nominal plant but also the whole of the perturbed plant. Robust stabilization to be generated, the internal stability must be achieved for nominal and perturbed plant. For robust stabilization requirement, equations 6 and 7 must be satisfied [13]. K is chosen over all stabilizing controllers and P is standard plant for optimization problem.

For generating the closed-loop system, first the aircraft dynamics is created using MATLAB / Simulink. This system is nonlinear as seen in Figure 2. Nonlinear systems are difficult to control directly [14], [15], [16]. For this reason the plant is linearized around an operating point to obtain G(s), the nominal plant to be used for the loop shaping controller.

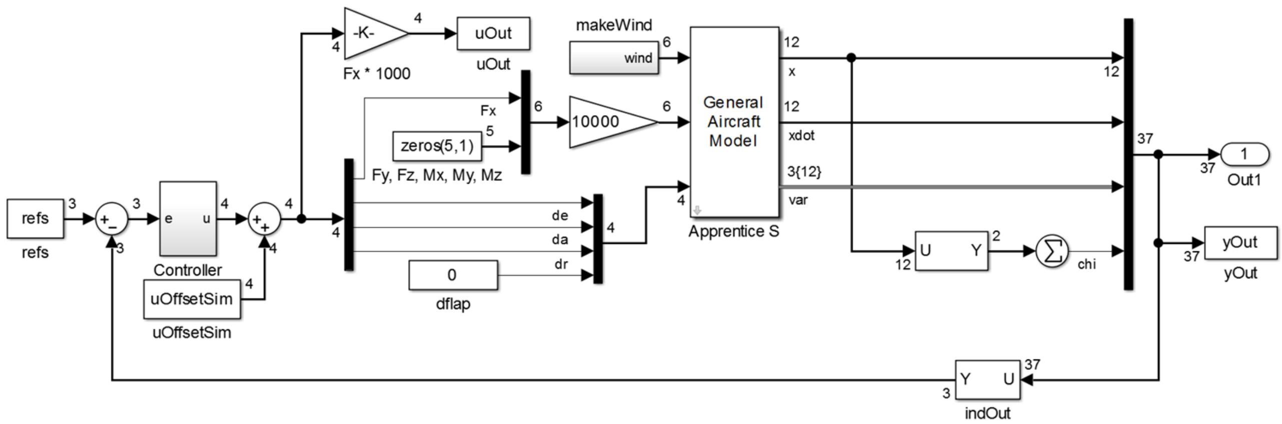

Fig. 2. Non-linear closed-loop system model

In this study, the MIMO system shown in the Figure 2 is simulated in the MATLAB/Simulink environment. If design procedure operates normally then the scenario would has 4 references which are speed, Θ, ψ, ϕ. However, in order to create rudder loss scene, ψ angle will not be appear in the reference block. To be as realistic as possible, wind block has been inserted into the model. Apprentice S flight dynamics and derivatives are embedded into the block as it can be seen in the figure. Simulation results are given in the section III using this Simulink model.

3. Simulation Results

In this paper, rudder malfunction is tested for an emergency scenario. Aircraft gravitates towards rudder malfunction direction. That's why recovery system should change the aircraft's direction to the opposite side to maintain a stable flight.

The system given in the Figure 2 is non-linear. Because of that, trimming is applied to obtain an operation point to linearize the system. Results of this trimmed pre- rudder lock scenario are shown in the Figure 3.

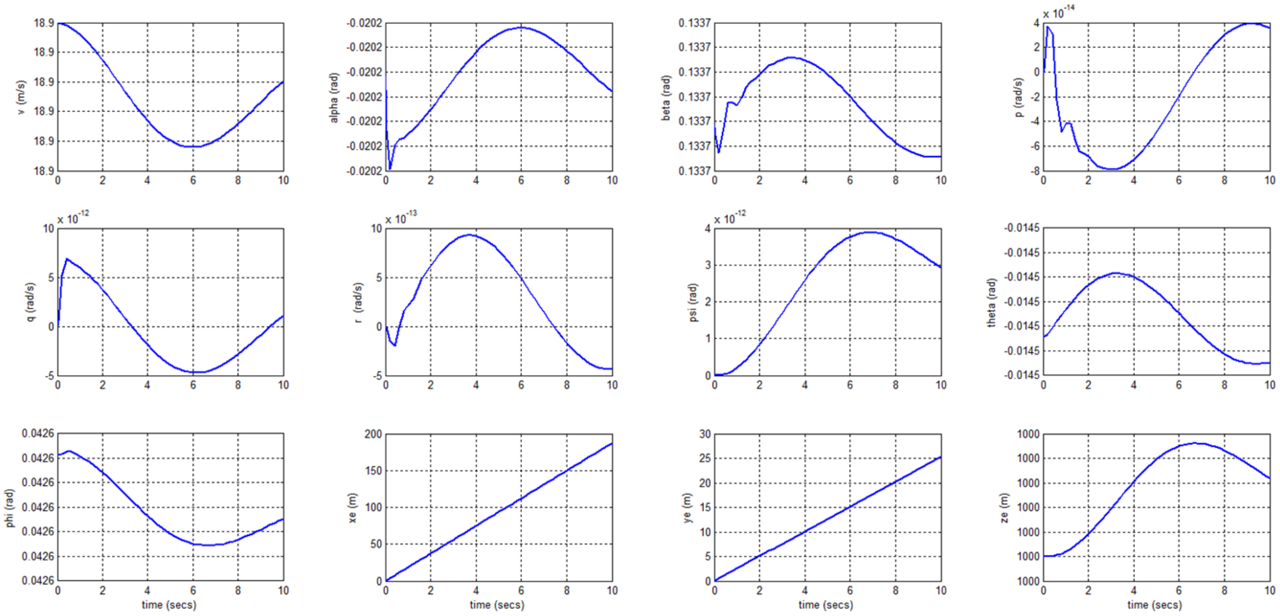

Fig. 3. Arrangement of printing area on an A4 size page for the first and subsequent pages of the manuscript

Operating points are determined for 18.9 m/s speed value and 0 degree for elevator, aileron, and 10 degrees for rudder control surfaces. For the given initial conditions, as it can be seen in the figure 4, the Fx (N) graph (left upper) is fixed at almost 2, $\delta_{elevators}$ graph (right upper) shows the elevators are fixed at 0 degrees, $\delta_{ailerons}$ graph (left lower) shows that the ailerons are fixed at 0 degrees, and δ_{rudder}graph (right lower) shows that the rudder is fixed at 10 degrees.

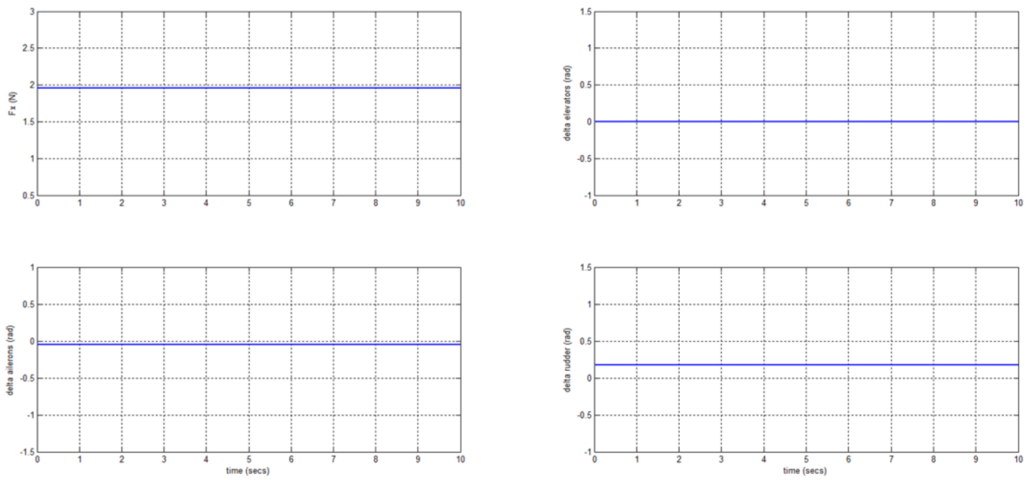

Fig. 4. Simulation results for speed, elevators, ailerons, and rudder initial conditions.

Cross couplings are mentioned earlier. Due to couplings' effect they are needed to be eliminated. Loop shaping controller is used to damp these effects. The result of step responses of the designed loop shaping controller under rudder loss is shown in the figure 5. It can be seen in this figure cross couplings are eliminated and remaining control surfaces are functioning as desired.

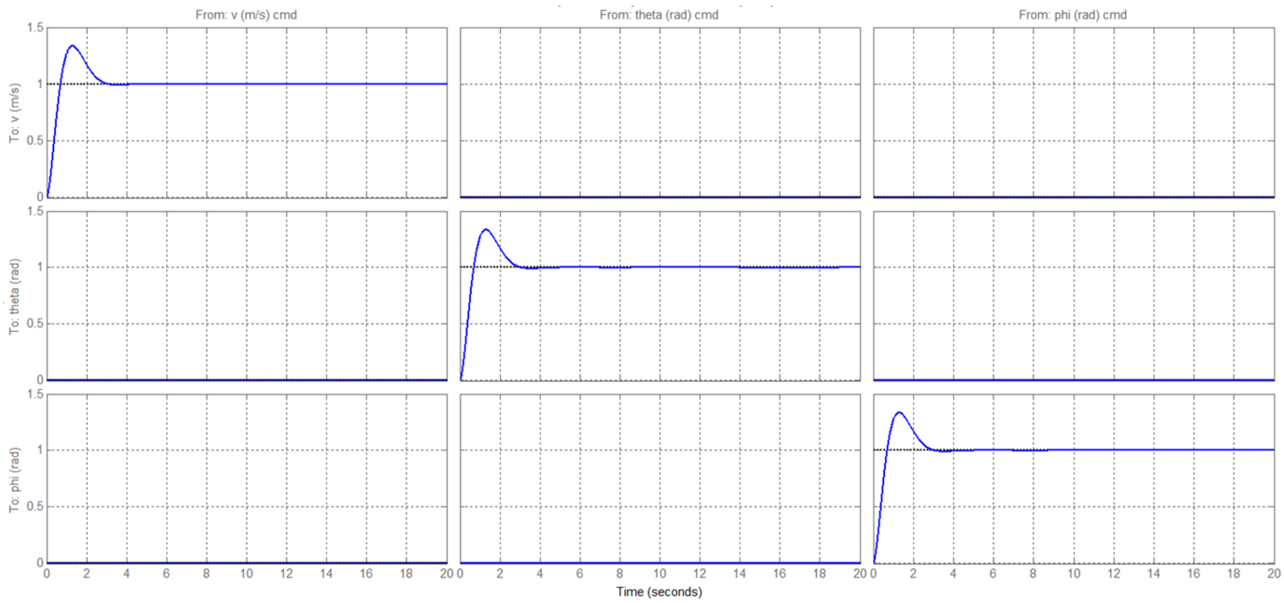

Fig. 5. Step responses of the designed loop shaping controller under rudder lock scenario.

For a given plant in this paper, sensitivity, complementary sensitivity, desired shape and achieved shaped diagrams are given in Figure 6. This diagram indicates the desired loop shape can be used as a controller. Because it is in the lines between target loop shape and target loop shape boundaries.

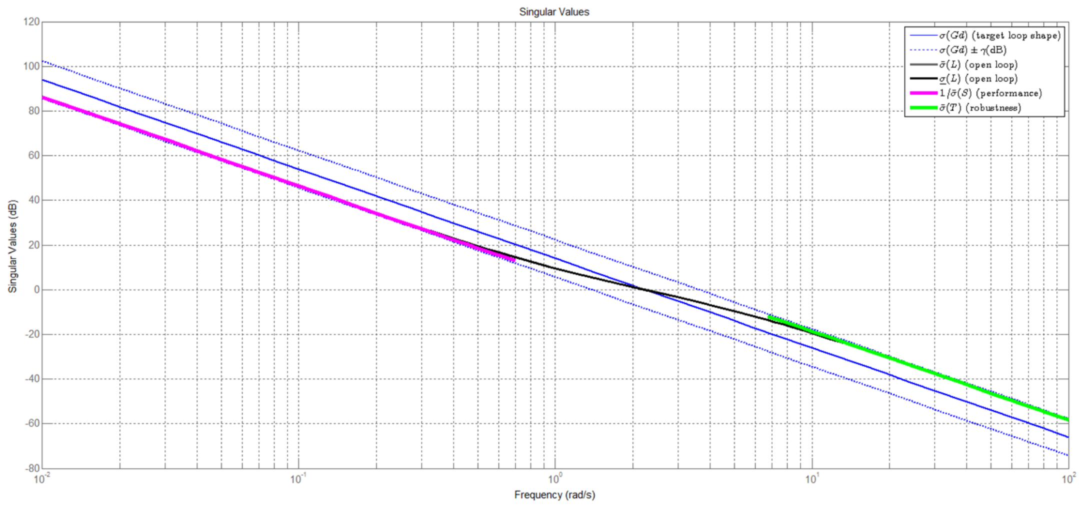

Fig. 6. Sensitivity, complementary sensitivity, desired loop shape, and achieved shaped diagrams.

In figure 7 it can be seen that the first 10 seconds the aircraft is in normal condition. At 10th second, under rudder lock scenario the designed controller is activated. The locked rudder caused some drag force and this is the reason the speed reference decreased to 15 m/s which can be seen from the first graph. Using the cross correlation between the rudder and aileron control surfaces, the unwanted effects of locked rudder corrected by aileron. As seen in phi angle (ϕ) when the scenario began the controller change the reference of roll angle in favor of correcting the locked rudder surface. The theta angle (Θ) and speed has the same relation as roll and yaw. The changes in pitch angle are for tracking the speed reference. The last three graphs show that the position of aircraft related to earth surface. It can clearly be seen that the aircraft is hovering without an altitude loss.

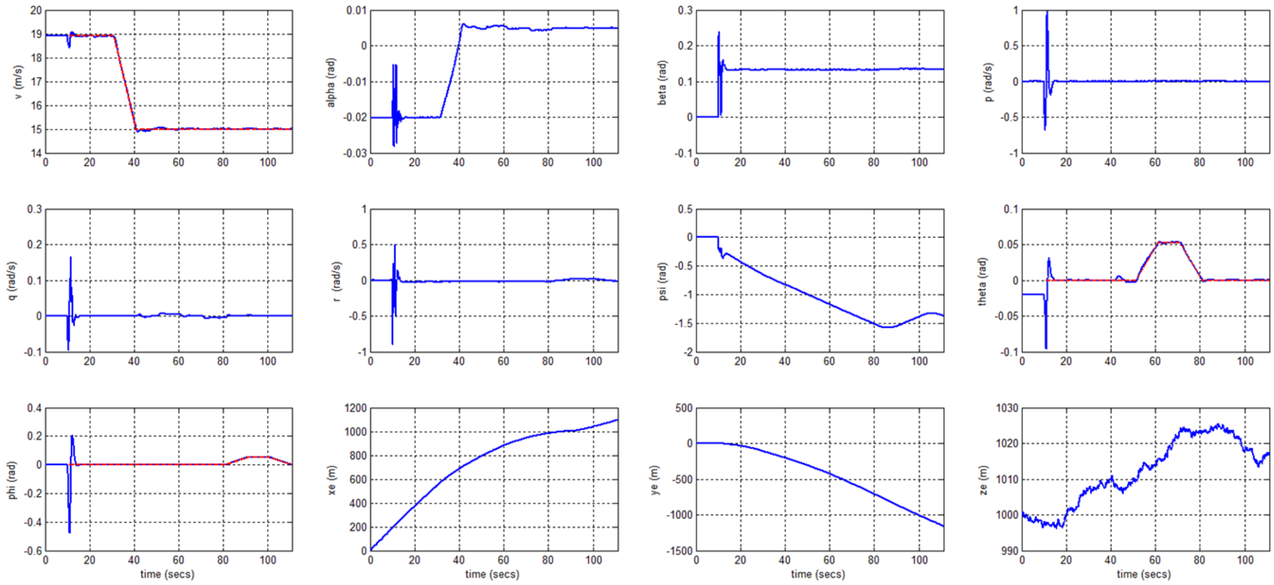

Fig. 7. Simulation results of the rudder loss case outputs (solid blue) under speed, theta, phi commands (dashed red).

In order to prevent excessive control outputs, the control surfaces commands must be checked whether if they are in the bounds that the real aircrafts control surfaces movement capability shown in figure 8. These graphs clearly show that these control inputs are suitable for real flight tests.

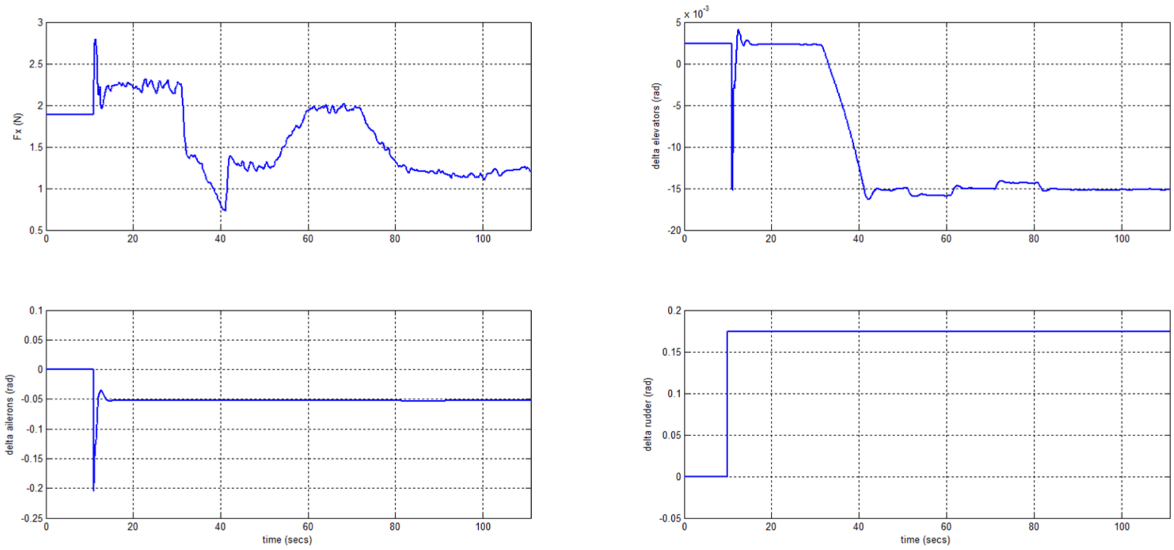

Fig. 8. Simulation results for rudder loss case inputs under speed, theta, phi commands.

In figure 9 the aircrafts position has given by three individual graphs. The three dimensional graph shows the actual position of the aircraft. It is obvious that the designed controller is successful on rudder lock at 10 degree scenario.

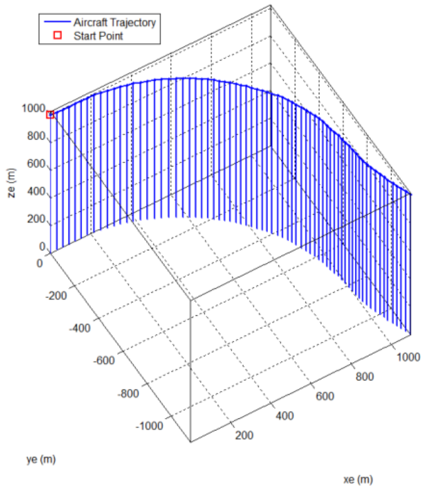

Fig. 9. Three dimensional figure for the position of the aircraft according to the earth surface.

4. Conclusion and Future Work

In recent years, many aviation accidents have been caused by the sudden or gradual loss of control of an aircraft. Such losses of control surfaces may be occurred by mechanical failures, human factors or environmental conditions. In this study, rudder jam is the surface loss scenario. A MATLAB/Simulink based nonlinear aircraft model is used to develop autopilot system for the disabled aircraft. The flight control laws are first validated steady state flight conditions and rudder jam is applied to demonstrate the automatic recovery. A successful MIMO system is built using loop shaping control method to recover from rudder loss scenarios. The given approach explained in this paper shows that loop shaping method can be used for such scenarios and can be expanded for other control surface losses.

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