Hypersonic Flight Control with Inverse Dynamics Approach using FlightGear

A.W. Pahlevi, E. Susanto*, and M.R. Rosa

School of Electrical Engineering, Telkom University, Bandung, 40287, Indonesia

erwinelektro@telkomuniversity.ac.id

Abstract

Hypersonic flight is one of the technological developments for aircraft with speeds above Mach 5, the speed at which air separation begins to become significant. This paper presents a control of hypersonic flight with inverse dynamics systems. Hypersonic Flight Control (HFC) is approached as a non-linear system and controlled by inverse dynamics. The design of the proposed inverse dynamics equation aims to cancel all non-linear terms so that the closed loop system is linear, so that we can simulate the system performance. The control strategy aims to change the aircraft's altitude and speed quickly and accurately. The simulation result deployed by MATLAB shows the effectiveness of the proposed control scheme. We include FlightGear simulation to visualize the aircraft's 3D motion. MATLAB and Simulink can be used for inverse dynamics control of hypersonic aircraft, while FlightGear can be used to visualize aircraft motion, making it easier to observe and verify control effectiveness. In the simulation, we use an altitude of 1000 with the PD controller gains $K_p = diag(10, 10, 10, 10, 10, 20)$ and $K_d = diag(10, 10, 10, 10, 10, 1)$ that gives less oscillation for the proposed scenario. We focused our research on the control of the aircraft using the Vector Field approach so that it solves the standard local minima problem in the path following method. The urgency of this research is crucial because it can revolutionize aircraft navigation and serve as a reference for the development of unmanned aircraft, shaping the future of world aviation.

1. Introduction

A hypersonic aircraft is an aircraft at a speed exceeding the speed of sound. The speed of a hypersonic aircraft can exceed 6000 km/h and the Mach (M) number is greater than five, $M > 5$ [1]. Hypersonic aircraft can be the key to modern aircraft in the future especially for the military and humanity purposes.

The hypersonic should consider the air temperature which has diatomic molecules [1]. When the speed of is low, then of the molecular bonds and the magnitude of the force generated by the air in the plane is changed. On the other hand, when the hypersonic speed is high, the molecules break apart yielding an electrical plasma charging around the plane. Due to expansion, shock vibrations then pressure and air density vary much more.

The control of hypersonic motion and flight has attracted many attentions for years due to the attractive and difficult flight conditions associated with its high Mach number [2]. Thus, many researchers have attempted to find out the advanced controllers for HFV (Hypersonic Flight Vehicles) for achieving the stable reference trajectory tracking purpose.

Moreover, the robust control method was also reported to keep the control stability and withstand parametric uncertainties [3]. A MIMO system with unstable and uncertain parameters of was investigated by designing an adaptive sliding controller. The result showed that the proposed controller was robust to parameter uncertainties [4]. The alternative method ready to withstand external interference from HFV and system uncertainty was the active fault rejection control approach [5].

In this study, the inverse dynamics is used to control the hypersonic aircraft. This research contributes to the study of the inverse dynamics and vector field method for a hypersonic aircraft that eliminates the local minima problem, which usually occurs in the potential field method. Here, we use Simulink Matlab, which is connected to FlightGear, to demonstrate the system design and control scheme for a hypersonic aircraft. Visualization in 3D using FlightGear was used to verify the movement of the controlled aircraft with an inverse dynamics approach [6].

2. Model and Control

The standard approach for describing the dynamic equation of mechanical and multibody systems is via

the Euler-Lagrange (EL) equation [7, 8]. This technique's structural properties have facilitated the development of practical controller design procedures such as Liapunov-based methods, passive-based controls, and backstepping stabilization schemes [9, 10]. Furthermore, this method reports the motion equation of the n-link robot in the form of [11].

Most literatures dealing with setting the starting point of EL systems concentrate on the global asymptotic stabilization of the closed-loop equilibrium state, outlining basic concepts such as potential energy generation and attenuation injection. However, there are still some weaknesses that prevent the use of this methodology in practical application. For example, global stabilization of a unique equilibrium point often requires control inputs beyond the actuator's physical saturation constraints. This led to the development of saturation controllers applicable to EL systems with limited growth rates of the potential energy function for large position values [12].

The general form of the equation of a mechanical system to EL can be written as Eq. 1.

$$D(q)\ddot{q} + C(q,\dot{q})\dot{q} + g(q) = \tau \tag{1}$$

2.1. Inverse Control

This control scheme is a typical control method for upon to complete the system. Also, applying a proportional derivative (PD) control can linearize the closed-loop system. Within known parameters, nonlinearity cancellation can be achieved via controller [13]. Thus, (1) can be rewritten for the system as follows

This control scheme is a typical control method for Euler – Lagrange systems which is called upon to complete the system. The inverse dynamics based control's aim is to revoke all system's non linearity. Also, by using a simple proportional derivative (PD) control, this strategy can make the closed loop system linear. Within known parameters, non-linearity cancellation can be achieved via controller [13]. Thus, (1) can be rewritten for the system as follows

$$D_i(q_i)a_i + C(q_i,\dot{q}_i)\dot{q}_i + g_i(q_i) = \tau_i \tag{2}$$

where a_i is defined as $a_i = \ddot{q}^d - K_d\dot{e}_i - K_p e_i$, with $e_i = q_i - q^d$ and K_p, K_d are the proportional derivative gains of the PD multivariable control.

Notice that $q^d, \dot{q}^d, \ddot{q}^d$ are the path, velocity, and acceleration that will be used in this study. Now, by substituting all equations above, we will obtain

$$D_i(q_i)\ddot{q}_i - \ddot{q}^d + K_d\dot{e}_i + K_p e_i = 0 \tag{3}$$

$$\ddot{e}_i + K_d\dot{e}_i + K_p e_i = 0 \tag{4}$$

$$\begin{bmatrix} \dot{e}_i \\ \ddot{e}_i \end{bmatrix} = \begin{bmatrix} 0 & I \\ -K_p & -K_d \end{bmatrix} \begin{bmatrix} e_i \\ \dot{e}_i \end{bmatrix} \tag{5}$$

Hence, the second-order error equation can be formed as

$$\begin{bmatrix} \dot{q}_i \\ \ddot{q}_i \end{bmatrix} = \begin{bmatrix} 0 & I \\ -K_p & -K_d \end{bmatrix} \begin{bmatrix} q_i \\ \dot{q}_i \end{bmatrix} + \begin{bmatrix} 0 \\ I \end{bmatrix} (\ddot{q}^d + K_d\dot{q}^d + K_p q^d) \tag{6}$$

Since it is more complex to derive the formula, then the inertia matrix obtained from the Euler - Lagrange equation is needed. Here is the inertia matrix on Euler – Lagrange

$$\begin{bmatrix} m & 0 & 0 & 0 & 0 & 0 \\ 0 & m & 0 & 0 & 0 & 0 \\ 0 & 0 & m & 0 & 0 & 0 \\ 0 & 0 & 0 & I_x & 0 & -I_{xz} \\ 0 & 0 & 0 & 0 & I_y & 0 \\ 0 & 0 & 0 & -I_{xz} & 0 & I_z \end{bmatrix} \begin{bmatrix} \dot{u} \\ \dot{v} \\ \dot{w} \\ \dot{p} \\ \dot{q} \\ \dot{r} \end{bmatrix} +$$

$$\begin{bmatrix} 0 & -m\bar{r} & m\bar{q} & 0 & 0 & 0 \\ -m\bar{r} & 0 & -m\bar{p} & 0 & 0 & 0 \\ -m\bar{q} & -m\bar{p} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -I_z\bar{r}-I_{xz}\bar{p} & -I_y\bar{q} \\ 0 & 0 & 0 & -I_z\bar{r}+I_{xz}\bar{p} & 0 & I_x\bar{p}-I_{xz}\bar{r} \\ 0 & 0 & 0 & I_y\bar{q} & -I_x\bar{p}+I_{xz}\bar{r} & 0 \end{bmatrix} \begin{bmatrix} \dot{u} \\ \dot{v} \\ \dot{w} \\ \dot{p} \\ \dot{q} \\ \dot{r} \end{bmatrix}$$

$$+ \begin{bmatrix} sin\theta mg \\ -sin\phi cos\theta mg \\ -cos\phi cos\theta mg \\ 0 \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} \tau_1 \\ \tau_2 \\ \tau_3 \\ \tau_4 \\ \tau_5 \\ \tau_6 \end{bmatrix} \tag{7}$$

Where I is the inertial tensor and τ_2, τ_4, τ_6 are the moment acting on the x, y, z coordinates. Then as the Euler angle $\bar{u}, \bar{v}, \bar{w}$ functions as velocity and $\dot{u}, \dot{v}, \dot{w}$ functions as the angular velocity of the UAV (Unmanned Aerial Vehicle) along the x, y, z angle in the aircraft body frame [13].

2.2. FlightGear

FlightGear is one of the open flight simulator Application for research and academic as well as industrial engineering tools [14, 15]. Historically, in the early 1960s, the hypersonic flight has been developed in many projects benchmark data as for hypersonic boundary layer transitions [16].

The control system is displayed by Fig. 1 and explained as follows:

- The input signal is a setpoint q containing x, y, z, $\phi, \theta, \psi, \dot{x}, \dot{y}, \dot{z}, \dot{\phi}, \dot{\theta}, \dot{\psi}, \ddot{x}, \ddot{y}, \ddot{z}, \ddot{\phi}, \ddot{\theta}, \ddot{\psi}$ thus has 18 setpoints used for calculations given by the user as a target value to be reached by the state. The x, y, ψ setpoints are obtained from the Reference Path: Orbital Path and Straight Line.
- To activate the controller, the system needs the error signal; the difference between the setpoint and the actual parameter.
- The control process; inverse dynamic process with EL dynamics is deployed in Matlab.
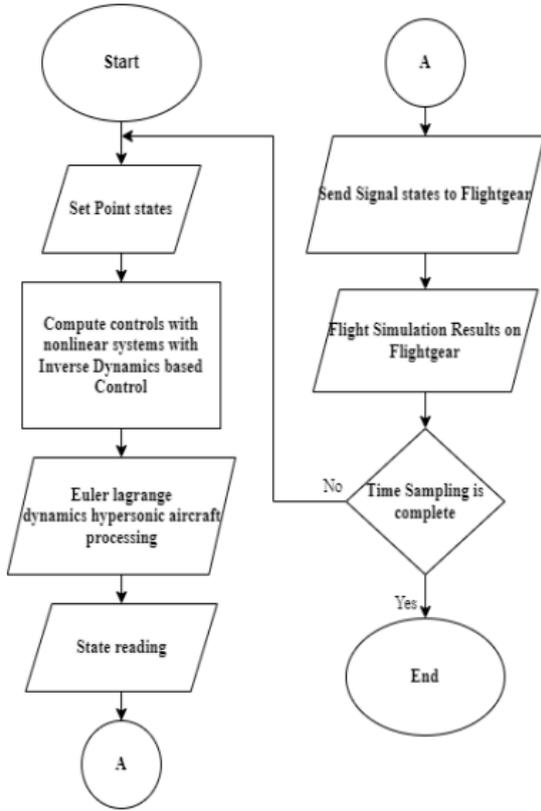- Flightgear simulator presents the 3D's visualization of aircraft motion.

Fig. 1. Flowchart of the control algorithm

Fig. 2. Inverse Control

3. Result and Discussion

The calculation result is in the form of an Euler – Lagrange dynamics control signal which is then forwarded to Simulink. FlightGear processes a control signal from Simulink to control the aircraft's path and visualize it. Simulation stops is time sampling on Simulink is complete or manually stopped; otherwise, it loops. The specifications used in the inverse dynamics design for hypersonic aircraft are: $m = 1$ kg. $g = 9.80665 \ m/s^2$. The design of this inverse dynamics equation aims to cancel all nonlinear terms so that the closed loop system is linear. From Eq. 1-6, it can be seen that the control input τ is derived as the by choosing K_p and K_d as in Eq. 8-9. Then the values of I used as the inertia tensor are obtained $I_x = 0.02$, $I_y = 0.02$, $I_z = 0.05$, $I_{xz} = 0.01$.

Substituting Eq.1 and Eq.2 lead to a linear error equation in Eq.3. When the gains matrix K_p and K_d are selected as matrices with diagonally positive elements, then the closed-loop dynamics system is linear and stable. The Simulink model in Fig. 2 is developed based on the EL Eq.1. In order to linearize the aircraft data input from 6 DoF, an inverse dynamic based control is needed so that the system is linear referred to Eq.2, see Fig. 3 for Simulink block of $D(q)\ddot{q}$. References that functions as setpoint q, $\dot{q}$, $\ddot{q}$ of aircraft data are obtained from four 6 DoF angle outputs, namely position x, y, z, h and the time derivative (velocity) of them and followed by Euler angles as ϕ, θ, ψ and the time derivative (angular velocity) of them. $D(q)$ itself is ob-
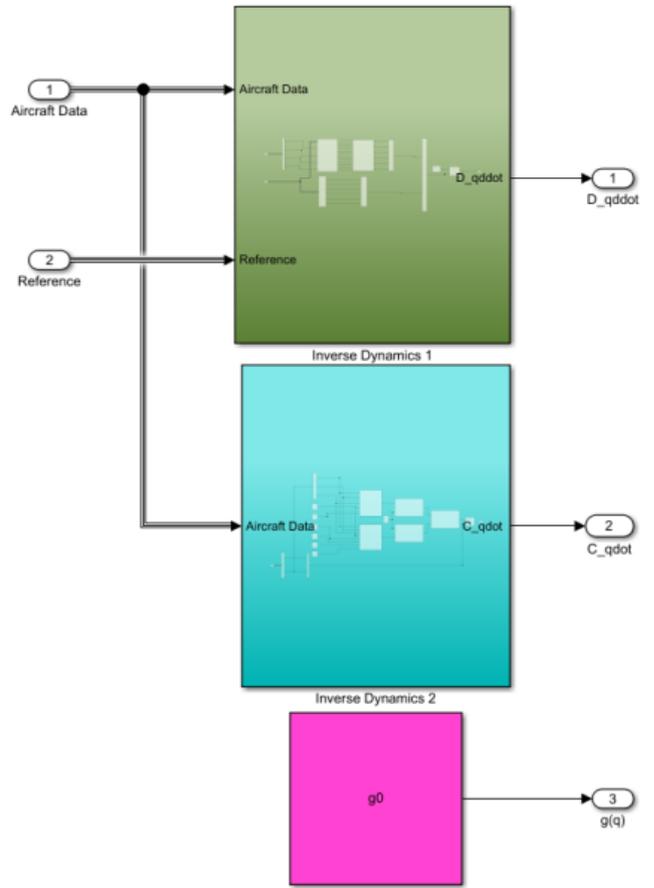
tained from the inertial matrix and q is the substitution result of a_i with K_p and K_d are chosen.

$$
K_p = \begin{bmatrix} 10 & 0 & 0 & 0 & 0 & 0 \\ 0 & 10 & 0 & 0 & 0 & 0 \\ 0 & 0 & 10 & 0 & 0 & 0 \\ 0 & 0 & 0 & 10 & 0 & 0 \\ 0 & 0 & 0 & 0 & 10 & 0 \\ 0 & 0 & 0 & 0 & 0 & 20 \end{bmatrix} \tag{8}
$$

$$
K_d = \begin{bmatrix} 10 & 0 & 0 & 0 & 0 & 0 \\ 0 & 10 & 0 & 0 & 0 & 0 \\ 0 & 0 & 10 & 0 & 0 & 0 \\ 0 & 0 & 0 & 10 & 0 & 0 \\ 0 & 0 & 0 & 0 & 10 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \tag{9}
$$

Fig.4 shows that the plane's trajectory with the plane's yaw movement is proportional even though there are still a few waves during the transition between straight and orbit.

The PD controller restores lost dynamics from Eq.2, while Eq.1 creates a dynamics model with the PD controller. $C(q, \dot{q})$ is obtained from the inertial matrix created with Simulink in Fig.5 Then q is obtained from velocity and angular which is the time derivative of the setpoint $\dot{q}$ and is multiplied by $C(q, \dot{q})$. Parameter $g(q)$
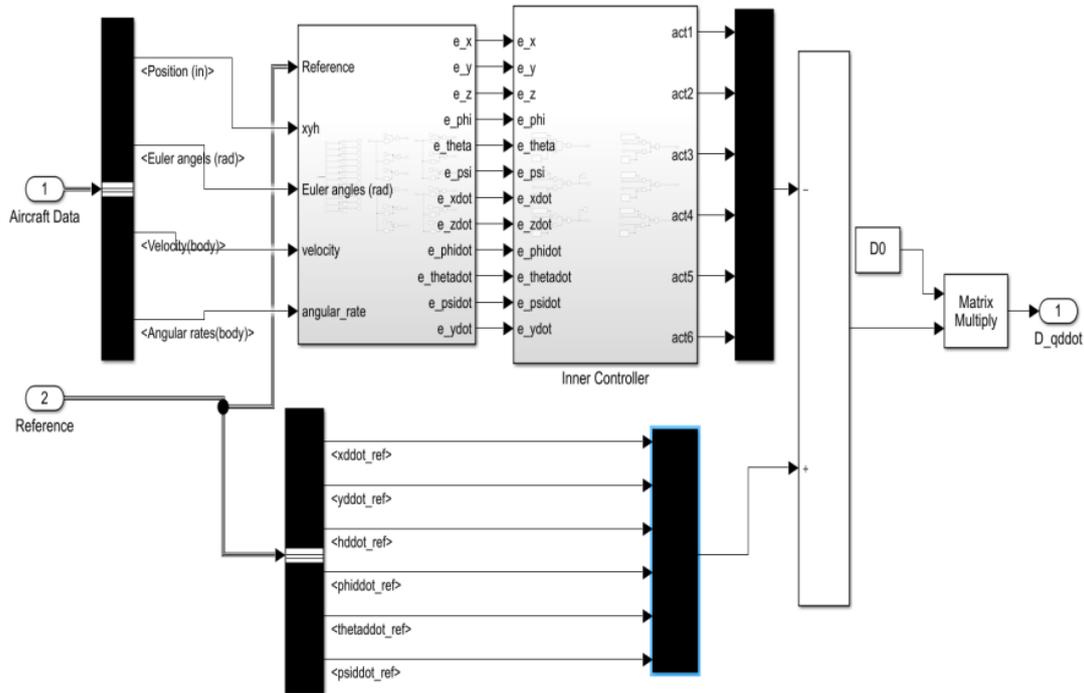
Fig. 3. Simulink block for $D(q)\ddot{q}$

is written in a row matrix

$$\begin{bmatrix} 0 & 0 & -mg & 0 & 0 & 0 \end{bmatrix} \quad (10)$$

Next is the connection from the Simulink inverse control block to the aerospace using 6 DoF Euler angles so it produces necessary outputs, including position, speed, angular velocity, acceleration, angular acceleration, Euler angle, and angular rates as shown in Fig. 6. These outputs are looped to the aircraft data until the system's runtime is complete.
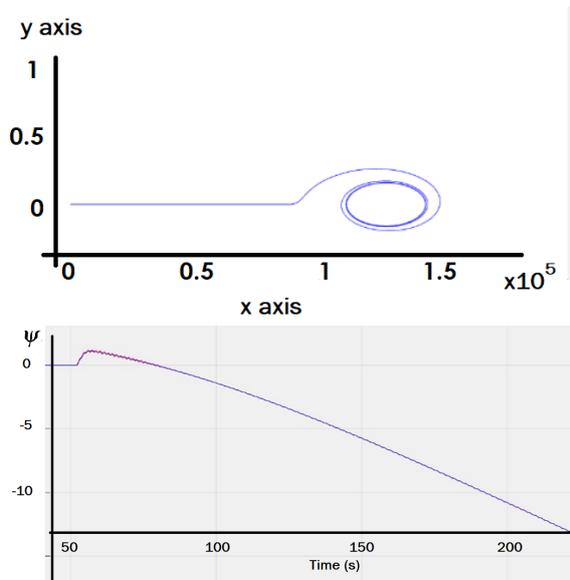

Fig. 4. Aircraft motion in $x - y$ coordinate (upper) and time trajecory of ψ in $x - y$ references (lower)

These results are obtained by combining the XY reference of the straight line and orbital path, then proceed with the visualization of the FlightGear simulation. Furthermore, the final result is obtained by combining the yaw reference for the movement of the aircraft during orbit. Fig.7 shows a visualization of a hypersonic aircraft simulation on FlightGear. One can see the difference in the plane's trajectory during straight and orbit as shown in the pictures.

4. Conclusion

This study utilizes Simulink MATLAB to apply inverse kinematic control of hypersonic asircrafts and visualizes it using FlightGear.The simulation results show that the vi-sualization of aircraft motion at the altitude of 1000. In addition, for better visualization in (FlightGear), Extremely low or high altitudes should be avoided. However, with adequate PD controller tuning for the z-axis, other altitudes can also be used. Here, it is also shown that the inertia tensor used in the simulation can be replaced by any inertial tensor of the different aircraft type so that it gives more flexibility in control system design. By trial and error method, we chose the gain of the PD controller $K_p = diag(10, 10, 10, 10, 10, 20)$ and $K_d = diag(10, 10, 10, 10, 10, 1)$ that gives less oscillation for the proposed scenario.
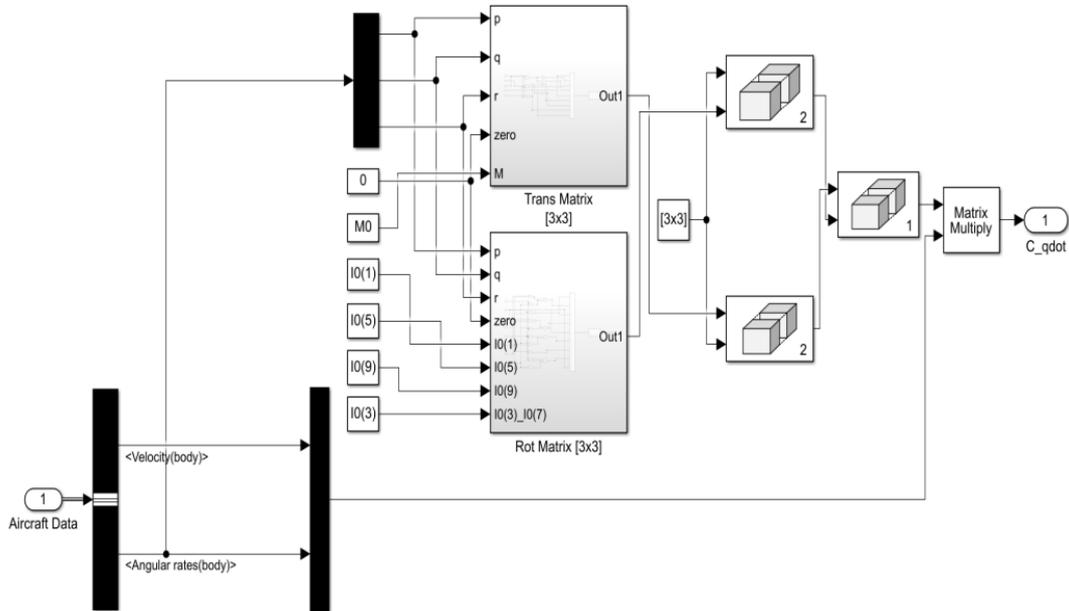
Fig. 5. Simulink block for $C(q,\dot{q})$
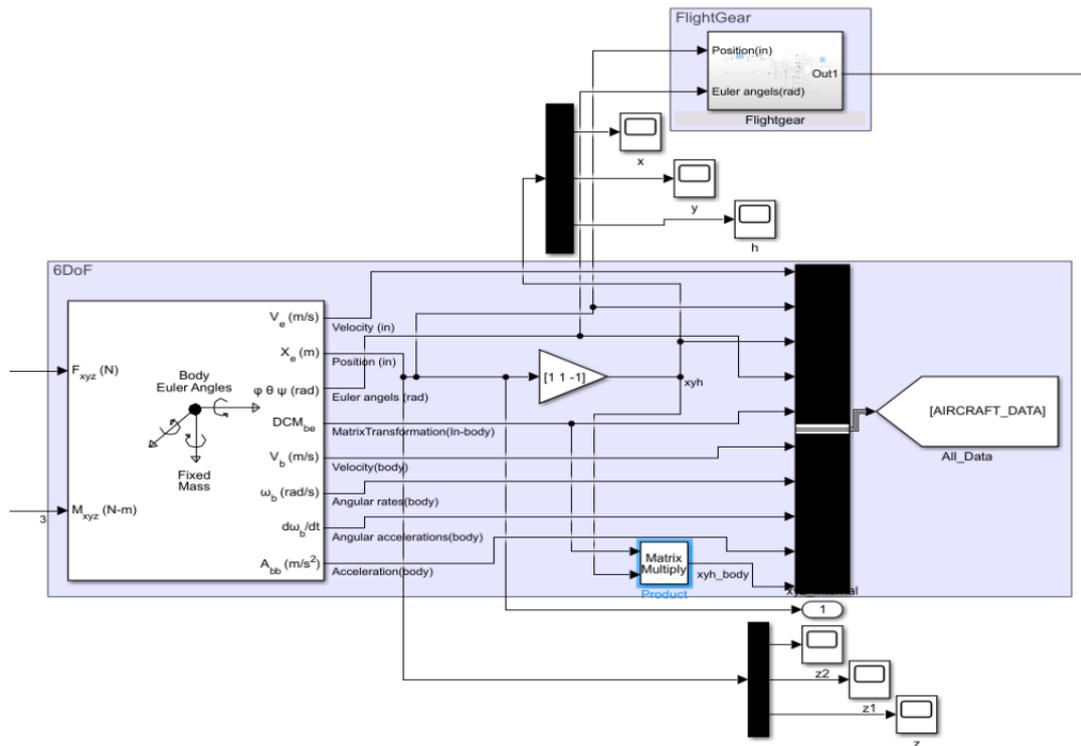
Fig. 6. Simulink block for 6 DoF Euler Angles

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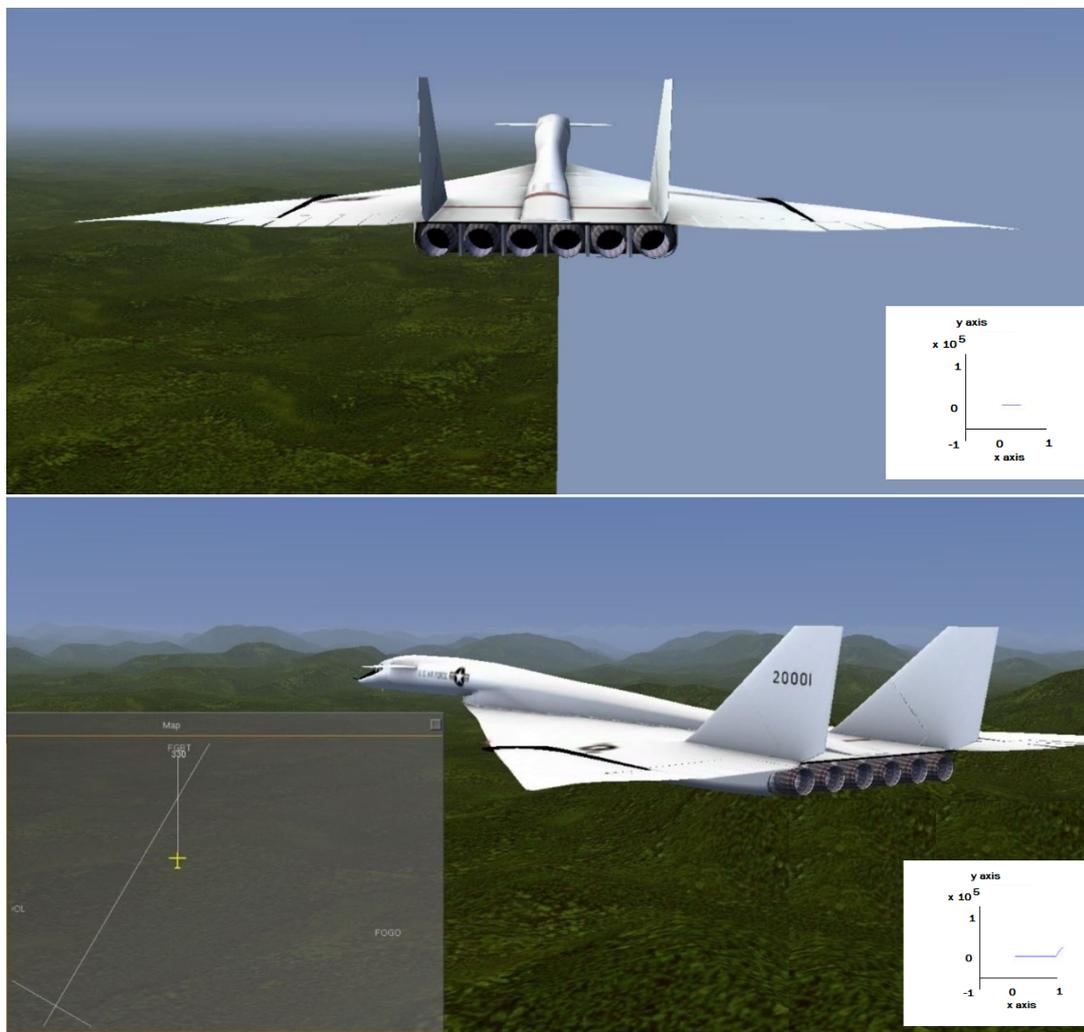[4] H. Xu, P. Ioannou, and M. Mirmirani, "Adaptive

Fig. 7. FlightGear Simulation of aircraft for straight (upper) and orbital (lower) path

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Author Information

Adib Wirayudha Pahlevi was born in Bekasi, in November 11th 1999. He received the bachelor's degree in electrical engineering from Telkom University, Indonesia in 2022. He is interested in Control System and a member of Control System Lab. His research topic for Bachelor's thesis is Hypersonic Flight Control with Inverse Dynamics Systems

Erwin Susanto graduated from Doctoral Program in Intelligent Control Lab., Graduate School of Science and Technology, Kumamoto University, Japan, 2012. His research interest in Control Systems theory and application. Currently, he serves as an editor of national journals and a reviewer for some international journals and conferences.

Muhammad Ridho Rosa received the B.Sc. in physics engineering from Bandung Institute of Technology, Indonesia in 2014 and the M.Sc. in embedded systems with specialization in systems and control from Delft University of Technology, Netherlands in 2018. He is currently lecturer at school of electrical engineering, Telkom University, Indonesia. His research interests are adaptive control with application in networked control and robotics.

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