

Advancing Missile Guidance, Navigation, And Control: A Kalman Filter-Enhanced Architecture For Target Precision

Ramona Devi

Abstract—

This paper presents a novel approach for the control of the flight path angle (γ) by employing a guidance law, with the aim of precisely guiding a missile to its predetermined target while effectively avoiding obstacles. The proposed Guidance, Navigation, and Control (GNC) architecture leverages knowledge of the missile's initial position, as well as a fixed ground target location. This comprehensive framework offers a promising solution for achieving precise target acquisition in missile systems while ensuring obstacle avoidance.

Keywords—missile, Kalman filter, guidance, control, autopilot

Date of Submission: 15-11-2023

Date of acceptance: 25-11-2023

I. INTRODUCTION

The aim is to control flight path angle γ by using input tail-fin deflection δ_p to hit the targeted location. This paper proposes a design of the Guidance, Navigation, and Control (GNC) architecture to guide a missile to its target while simultaneously avoiding obstacles. The missile's initial position, defined by latitude, longitude, and height, is known, and the target is a fixed ground location. The missile's longitudinal dynamics are depicted in Figure 1, with parameters including missile velocity V_T , angle of attack (α), pitch angle θ , and flight path angle γ .

Figure 2 illustrates the initial positions (L, μ, h) of the missile and the target at $t=0$. The objective is to guide the missile to hit the target while ensuring it avoids predefined obstacles in its path. Section 2 provides an overview of the GNC architecture. In Section 3, you will find the space state model of the system, while Section 4 details the explanation of the LQG control design. Lastly, Section 5 delves into the Simulink implementation of the system.

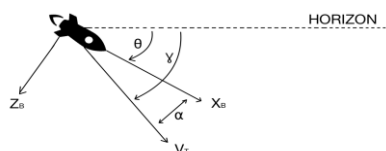


Figure 1: Missile 2D dynamics

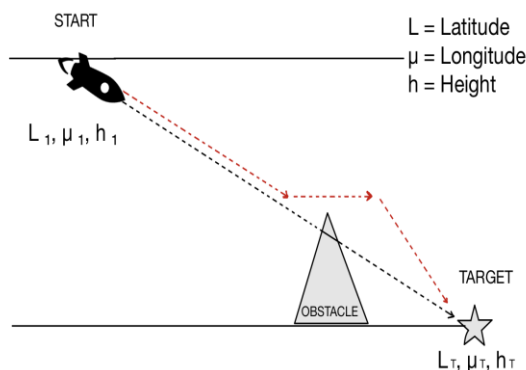


Figure 2: Initial positions of missile and target

II. GNC ARCHITECTURE

The guidance, navigation, and control (GNC) architecture [2-3] for a missile is a crucial system that ensures the missile can accurately and effectively reach its intended target. Figure 3 shows all the important elements of a GNC architecture.

Guidance Law

The guidance component is responsible for determining the missile's desired path and trajectory. It relies on information such as target location, missile position, and environmental conditions. The guidance system computes the necessary corrections to steer the missile towards the target and generate a guidance command. This system may consist of various inputs, including joystick commands for manned aircraft, operator-defined waypoints, or a trajectory generator. In the case of autonomous operations, the system can employ an online path-planning algorithm to construct an environmental map and identify an optimized and viable path.

Control System

Control System: The control system [4-6] is responsible for adjusting the missile's orientation and thrust to follow the guidance commands and maintain the desired trajectory. It uses actuators like fins, canards, and rocket motor gimbal adjustments to control the missile's flight path. PID (Proportional-Integral-Derivative) controllers and other control algorithms are often employed to ensure stable flight. Control allocation distributes the control commands generated by the controller to various actuators and control surfaces of a complex system like an aircraft, missile, or rocket. Its primary objective is to translate the desired overall system behavior, as determined by the controller, into specific actions for individual actuators while respecting physical constraints and limitations. Control allocation algorithms consider factors like actuator availability, redundancy, and saturation limits, optimizing the allocation of control efforts to achieve the desired system response. This ensures that the system operates efficiently and safely, even in challenging conditions, ultimately contributing to the stability, performance, and safety of the controlled system.

Navigation system

The navigation system provides real-time information about the missile's position, velocity, orientation, and attitude. It utilizes sensors like accelerometers, gyros, GPS (Global Positioning System), and inertial measurement units (IMUs) to continuously update the missile's position and orientation relative to the target and to maintain course accuracy. An observer, often referred to as a state estimator [7-10], provides an estimate of the system's internal state variables, such as position, velocity, and attitude, based on available sensor measurements. In situations where sensor measurements may be noisy, incomplete, or delayed, an observer enhances the accuracy and reliability of navigation solutions. It continuously updates the estimated state by incorporating sensor data and system dynamics, allowing the navigation system to maintain accurate situational awareness. Observers are particularly essential in inertial navigation systems and sensor fusion applications, where they help bridge gaps in data and ensure robust and precise navigation, making them vital components for autonomous vehicles, aerospace applications, and robotics.

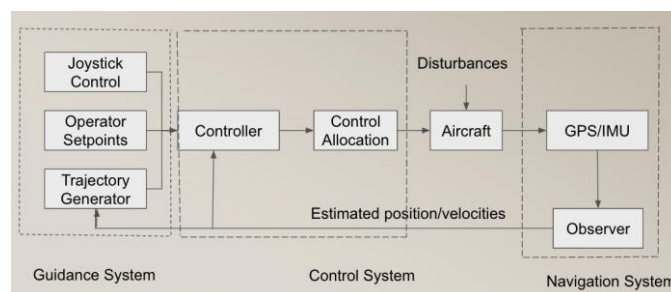


Figure 3: GNC Architecture

III. Missile state space model

A missile's longitudinal dynamics can be described using the short-period approximation of the longitudinal equations of motion [1]. Written in state space notation the basic missile longitudinal plant which shows the short period dynamics is

$$\begin{aligned} \dot{x} &= Ax + Bu \\ Y &= Cx + Du \end{aligned}$$

Where,

$$x = \begin{bmatrix} \alpha \\ q \end{bmatrix} \quad u = \delta_p \quad y = \begin{bmatrix} A_z \\ q_m \end{bmatrix}$$

$$A = \begin{bmatrix} -1.064 & 1 \\ 290.26 & 0 \end{bmatrix} \quad B = \begin{bmatrix} -0.25 \\ -331.40 \end{bmatrix}$$

$$C = \begin{bmatrix} -123.34 & 0 \\ 0 & 1 \end{bmatrix} \quad D = \begin{bmatrix} -13.51 \\ 0 \end{bmatrix}$$

The above dynamics shows an unstable open loop system. An optimal control design is discussed in the next section.

IV. LQG

In this section, the design of a linear quadratic Gaussian control system. The LQG (Linear Quadratic Gaussian) [2] design is a control strategy employed for noisy missile systems to optimize their performance in the presence of uncertainties and disturbances. It combines two critical components: the LQR (Linear Quadratic Regulator) controller, which minimizes a cost function involving the state and control input, and the Kalman filter, which estimates the system's state while considering measurement noise. In the context of a noisy missile system, the LQG design leverages the LQR controller to generate optimal control commands, taking into account both the system's dynamics and noise in the measurements. Simultaneously, the Kalman filter provides an accurate estimate of the missile's true state by filtering out the effects of noise, thus enabling precise control and navigation despite the inherent uncertainties and disturbances in the system.

Consider a noisy system

$$\dot{x} = Ax + Bu + Gw \tag{1}$$

$$y = Cx + v \tag{2}$$

Where x represents a vector of state variables of the system, u is the control vector, y is measured outputs available for feedback. w is the white system noise and v is the white measurement noise.

A linear observer is represented as follows:

$$\frac{d\hat{x}}{dt} = A\hat{x} + Bu + L(y - C\hat{x}) \tag{3}$$

Where L is Kalman gain, Now control law becomes:

$$u = -K\hat{x} \tag{4}$$

Where K is called the feedback gain matrix obtained by solving the Riccati differential equation [11].

V. SIMULINK IMPLEMENTATION

Figure 4 illustrates the system's architectural design, featuring a missile controller that receives flight path angle commands from the guidance block. The disparity between the commanded and measured flight path angle (FPA) undergoes PID control to generate a pitch rate command. The Missile LQG controller encompasses the airframe model and an observer. The controller's output FPA, in conjunction with missile velocity, is employed to compute the missile's updated position, which is then fed back into the guidance law. The guidance block subsequently generates commands for the flight path angle, serving to guide the missile toward its target while ensuring obstacle avoidance. The subsystems of this implementation are discussed in the next sections.

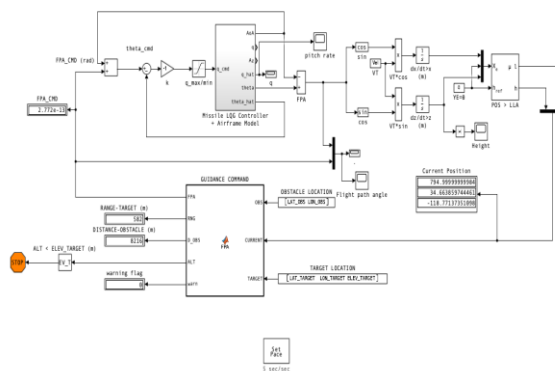


Figure 4: Missile homing loop simulink implementation

Pitch rate feedback loop

The pitch command θ_{cmd} is computed according to the relation $\theta = \gamma + \alpha$, where γ is FPA and α is AOA. This command is then subtracted from the estimated pitch angle, and a proportional controller is employed to follow the estimated pitch. The proportional gain, denoted as k and chosen as $k = -1$, is determined by analyzing the time-domain behavior of the closed-loop system. A saturation block is utilized to ensure that the pitch rate remains within the bounds of $-0.5 < q < 0.5$. This resultant command is subsequently utilized as the pitch rate input for the missile controller.

PN Guidance law

In the subsystem depicted in Figure 5, the state-space system defined in eq. 1-2, is implemented and denoted as the 'Airframe model' within Simulink. The other block represents the implementation of a Kalman filter coupled with a linear quadratic (LQR) controller, which corresponds to a Simulink realization of eq. 3. Here, the discrepancy between the estimated and measured outputs is scaled by the Kalman gain, denoted as L , enabling the estimation of the system's state vector. This estimated state vector is then multiplied by the feedback gain, represented as K , thus constituting the control law described in eq. 4. The determination of the feedback gain is accomplished using the LQR command, while the Kalman gain is calculated through the Kalman command within a MATLAB script. Subsequently, the output pitch rate undergoes integration to yield an estimated pitch angle, which is subsequently fed back into the outer pitch rate feedback loop and further employed in the computation of the flight path angle.

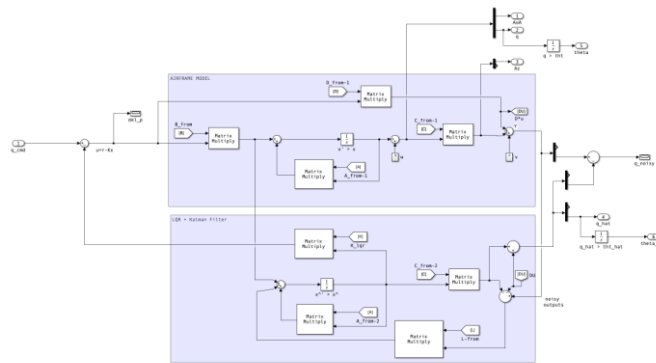


Figure 5: Control law subsystem

Missile position determination

The flight path angle is determined utilizing the same relation $\theta = \gamma + \alpha$, incorporating both the Angle of Attack (α) and the estimated pitch angle generated by the LQG controller. This angle is then employed in the calculation of the missile's position using the following equation:

$$\begin{aligned} \dot{\theta} &= q \\ \dot{x} &= V \cos(\theta) \\ \dot{z} &= V \sin(\theta) \end{aligned}$$

This position is transformed into latitude, longitude, and height coordinates through a MATLAB block called 'Flat Earth to LLA.' This block provides the missile's latitude, longitude, and height values, which are subsequently input into the guidance law block.

Guidance Command

The Guidance law block serves a dual purpose: firstly, it navigates around obstacles, and secondly, it generates a flight path angle command to guide the missile along a desired trajectory. The guidance block takes in the predefined obstacle location and the current missile position as inputs, allowing it to calculate the distances to both the target and the obstacle. If the current distance from the target exceeds a predefined threshold (e.g., 2000 meters), then the command is

$$\gamma_{cmd} = \tan^{-1}\left(\frac{h}{d}\right)$$

where h is the altitude. Otherwise, γ_{cmd} is set to 0. This γ_{cmd} value is then utilized to compute θ_{cmd} . Additionally, the missile's altitude is monitored to halt the simulation when the condition $(h < h_T)$ is met.

Missile position subsystem

This block takes the updated pitch angle from the autopilot block and calculates the real-time position of the missile as shown in eq. 5-6. The resulting current velocity of the missile is fed back into the guidance law block to update the acceleration command in order to track the target.

$$\dot{x} = V\cos(\theta) \quad (5)$$

$$\dot{z} = V\sin(\theta) \quad (6)$$

VI.RESULTS

This section presents the simulation results from simulink implementation. Figure 6 displays the pitch rate throughout the trajectory, and it is evident that it remains within the specified limits. In Figure 7, we observe the missile's flight path angle, which reaches zero as it clears the obstacle, and then gradually decreases as it approaches the target. Figure 8 illustrates the missile's altitude, providing a trajectory view that demonstrates its descent, ultimately reaching zero at the point of impact.

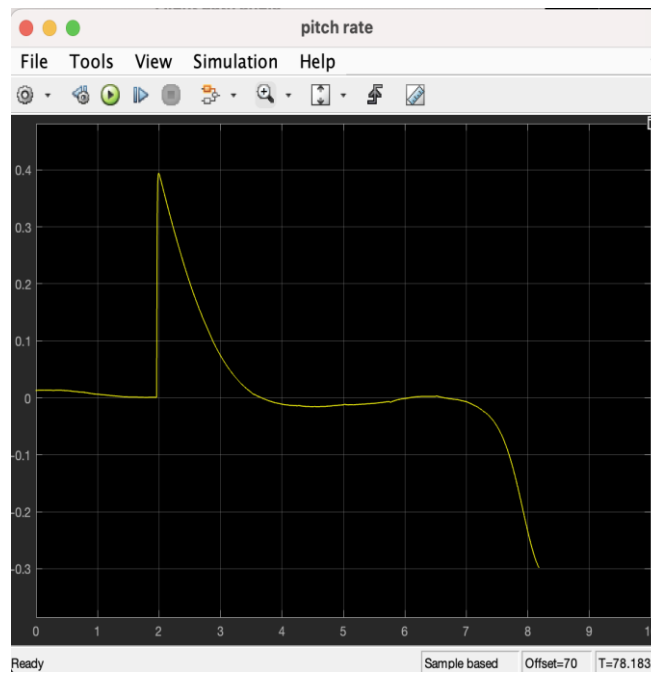


Figure 6: Pitch rate

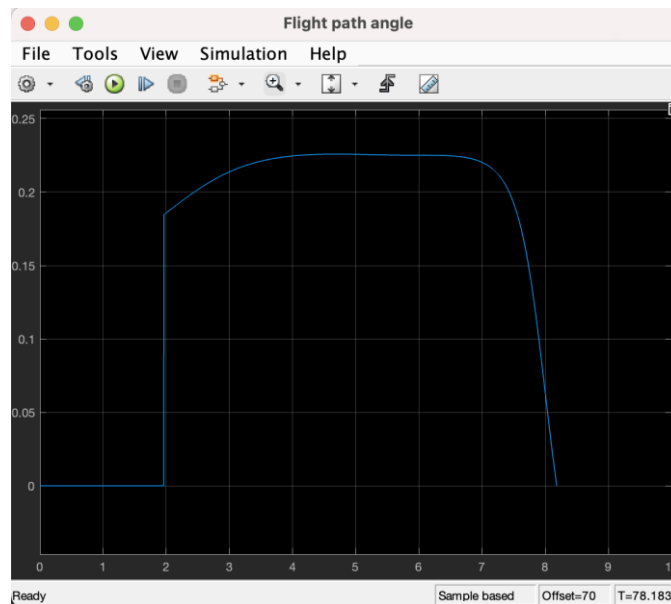


Figure 7: Flight path angle

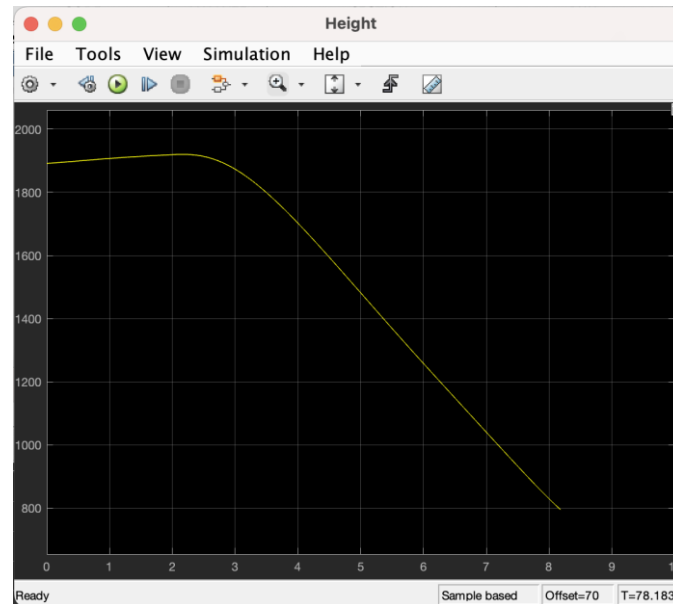


Figure 8: Missile's altitude

VII.CONCLUSION

In summary, the comprehensive analysis presented in this paper has showcased the efficacy and precision of our missile guidance and control system. The data presented in Figures 6, 7, and 8 reveal a well-executed trajectory, with the pitch rate consistently maintained within specified limits, and the flight path angle expertly guiding the missile past obstacles and towards the target. Notably, Figure 8's representation of the missile's altitude further underscores the system's capability, highlighting a controlled descent that culminated in a pinpoint impact at the intended target. These results collectively reinforce the system's robustness, reliability, and its ability to successfully engage and hit a designated target. The findings presented in this paper not only validate the performance of our missile guidance and control system but also lay the foundation for further advancements and applications in the field of missile technology. This work represents a significant step forward in enhancing the precision and effectiveness of missile systems, ultimately contributing to bolstered security and defense capabilities.

REFERENCES

- [1]. Mracek, Curtis, And D. Ridgely. "Missile Longitudinal Autopilots: Connections Between Optimal Control And Classical Topologies." AIAA Guidance, Navigation, And Control Conference And Exhibit. 2005.
- [2]. Palumbo, Neil F. "Guest Editor's Introduction: Homing Missile Guidance And Control." John Hopkins APL Technical Digest 29.1 (2010)
- [3]. Dong, Chen, Et Al. "Distributed Simulation Method For Homing Missiles Guidance, Navigation, And Control." Asiasim 2012: Asia Simulation Conference 2012, Shanghai, China, October 27-30, 2012. Proceedings, Part I. Springer Berlin Heidelberg, 2012
- [4]. Pue, Alan J., Et Al. "Missile Concept Optimization For Ballistic Missile Defense." Johns Hopkins APL Technical Digest 32.5 (2014)
- [5]. Shima, Tal, And Oded Golan. "Implementation Of Guidance Laws In Missiles With Dual Control Systems." AIAA Guidance, Navigation, And Control Conference And Exhibit. 2003.
- [6]. Dancer, Michael, S. Balakrishnan, And Ernest Ohlmeyer. "Discussion And Analysis Of Missile Igc Design." AIAA Guidance, Navigation And Control Conference And Exhibit. 2008.
- [7]. Casasent, David, Charles P. Neuman, And John Lycas. "Optical Kalman Filtering For Missile Guidance." Applied Optics 23.12 (1984): 1960-1966.
- [8]. Clemons, Thomas M., And Kuo-Chu Chang. "Sensor Calibration Using In-Situ Celestial Observations To Estimate Bias In Space-Based Missile Tracking." IEEE Transactions On Aerospace And Electronic Systems 48.2 (2012): 1403-1427.
- [9]. Cloutier, James R., Johnny H. Evers, And Joseph J. Feeley. "Assessment Of Air-To-Air Missile Guidance And Control Technology." IEEE Control Systems Magazine 9.6 (1989): 27-34.
- [10]. Menon, P. K., And S. S. Vaddi. "Target State Estimation For Integrated Flight Control." International Conference On Avionics Systems. 2008
- [11]. Lancaster, Peter, And Leiba Rodman. Algebraic Riccati Equations. Clarendon Press, 1995.