Journal of Solid and Fluid Mechanics (JSFM), 13(6): 1-5, 2024

Shahrood University of Technology

Journal of Solid and Fluid Mechanics (JSFM)

DOI: 10.22044/jsfm.2024.13627.3796

Manufacturing Engineering of Iran

Guidance and control of the Pitch channel of an interceptor missile using neural sliding mode control

Mohammad Mahdi Soori[1], Seyed Hossein Sadati[2]

[1] PhD. student, Department of Mechanical Engineering, K. N. Toosi University of Technology, Tehran
[2] Assoc., Prof., Department of Mechanical Engineering, K. N. Toosi University of Technology, Tehran, Iran
*Corresponding author: sadati@kntu.ac.ir

Received: 09/18/2023 Revised: 11/10/2023 Accepted: 02/17/2024

Abstract

The integrated design method for a missile guidance and control system is such that all the limitations of the subsystems are taken into account during the design in a bid to increase the accuracy and overall performance of the system in the final phase. This will improve efficiency, save time and implementation cost, and as a result, system performance will improve. This article describes the process of designing and simulating the performance of the neural sliding model controller, which was created to guide the missile in a two-dimensional engagement in minimizing the collision time and the miss distance to the target. In the design of the controller, a PID is first considered to evaluate the proposed controller, followed by the design of the neural sliding model controller discussed using neural networks. According to the simulations, it can be shown that the use of this proposed controller and the application of the integrated guidance and control model will reduce the final miss distance and the collision time compared to the PID controller.

Keywords: missile guidance, sliding mode control, neural networks

1. Introduction

Guidance, navigation, and control functions are critical to all forms of air and space vehicles, including missiles. In practice, these functions work together in series to maneuver a vehicle. It is now common, as shown in Figure 1, to develop guidance completely separate from control (autopilot) and the vice versa. Almost all textbooks and technical articles on this topic have dealt with it [1].

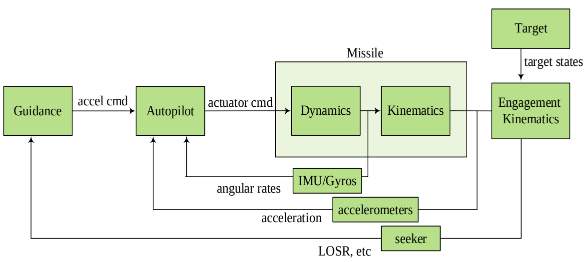

Figure 1. Block diagram of three-loop autopilot

1-2. Integrated guidance and control

Unlike the conventional three-loop autopilot structure, Integrated Guidance and Control (IGC) is an integrated framework in which guidance and control are considered to be integrated together and within, rather than independently of each other. The block diagram of IGC is depicted in Figure 2.

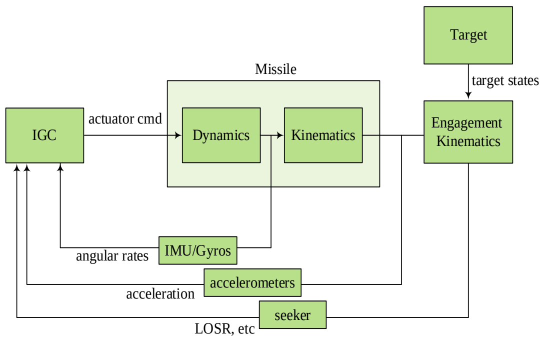

Figure 2. Block diagram of Integrated Guidance and Control (IGC)

The advantage of IGC system is its ability to use interactions between command and control subsystems. IGC intends to increase the performance of the missile by taking advantage of the synergy between the two guidance and control processes. Depending on the structure of the IGC, some provide additional feedback paths in the flight control system, while others require less. Integrating G&C into a single IGC system improves its optimization potential, since optimization of the parameters can be done directly. Cost functions include key performance parameters such as the missile and target relative speed of approach, line-of-sight angle, and impact angle, in addition to the fact that many parameters not readily accessible to the autopilot are now directly available. In the conventional approach, the guidance law has no knowledge of the magnitude of the spin or acceleration applied to the missile; instead, the guidance knows only the relative position and speed of the engagement. As the range-target decreases, small changes in geometry will result in such large acceleration commands that can exceed the performance range of the autopilot limitations. In addition, the autopilot cannot adjust itself based on relative engagement kinematics, as it does not receive this information. As a result, conventional G&C systems rely on making the autopilot time constant as small as possible, hoping to improve stability, or at least keep its margin thereof. The autopilot time constant designs the distance from miss to target in conventional G&C systems [2].

In this article, the design of the neural sliding model mode controller for the integrated guidance and control model is proposed. The design process for this proposed controller starts by devising a proper model of the sliding mode controller, followed by the neural controller design next, and the two are then combined into one to come up with a final integrated controller model. According to the simulations, it can be shown that use of this proposed combined controller along with the application of the integrated guidance and control model can lead to reduced miss distance as well as collision time as compared with those of the PID controller.

2. Mathematical modeling

A missile-target engagement scenario involves a missile trying to intercept a target by changing course. During docking guidance, sensors inside the rocket are used to guide until impact. The initial conditions of this scenario include three main assumptions, (a) middle path guidance is successful, (b) the magnitude of the missile and target speeds are close, (c) at the impact time, the missile/target relative speed will be zero. The geometry of this conflict scenario is shown in Figure 3.
The purpose of this article will be to design a suitable controller in order to accurately track the target. Therefore, the problem of missile-target engagement is first discussed, which includes all the topics required for accurate modeling, including engagement kinematics, missile dynamics, integrated guidance and control model, interception, and guidance strategy.

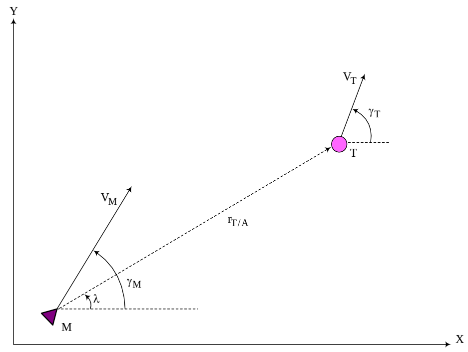

Figure 3. Kinematics of conflict [3]

The equations of the engagement kinematics written in a state space are presented as equation (1) [3].

$$\begin{bmatrix} \dot{r} \\ \dot{v}_r \\ \dot{\lambda} \\ \dot{v}_n \end{bmatrix} = \begin{bmatrix} v_r \\ \dfrac{{v_n}^2}{r} \\ \dfrac{v_n}{r} \\ \dfrac{-v_r v_n}{r} \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ -1 & 0 \\ 0 & 0 \\ 0 & -1 \end{bmatrix} \begin{bmatrix} a_{M_r} \\ a_{M_n} \end{bmatrix} + \begin{bmatrix} 0 \\ a_{T_r} \\ 0 \\ a_{T_n} \end{bmatrix} \qquad (1)$$

The dynamic equations of the missile in state space are given in equation (2) [4].

$$\begin{pmatrix} \dot{\alpha} \\ \dot{q} \\ \dot{\theta} \end{pmatrix} = \begin{bmatrix} \dfrac{\bar{q}S}{mU_0} C_{z\alpha} & 1 & 0 \\ \dfrac{\bar{q}Sl}{I_{yy}} C_{m\alpha} & \dfrac{\bar{q}Sl^2}{I_{yy}2U_0} C_{mq} & 0 \\ 0 & 1 & 0 \end{bmatrix} \begin{pmatrix} \alpha \\ q \\ \theta \end{pmatrix} \qquad (2)$$

In the above equations, $C_{z\alpha}$, $C_{m\alpha}$ and C_{mq} are stability derivatives, and $C_{z\delta}$ and $C_{m\delta}$ are control derivatives.
The complete missile/target model constitutes the engagement kinematics plus the dynamics, along with the integrated controller proposed. It is noted that the mediator between kinematics and dynamics is the lateral acceleration of the missile stated as Eq. (3) [4].

$$a_{M,z} = \frac{\bar{q}A}{m}(C_{z\alpha}\alpha + C_{z\delta}\delta) \qquad (3)$$

As a result, the equations of this system will be in the form of equation (4)[4].

$$\begin{pmatrix} \dot{r} \\ \dot{v_r} \\ \dot{\lambda} \\ \dot{v_n} \\ \dot{\alpha} \\ \dot{q} \\ \dot{\theta} \end{pmatrix} = \begin{pmatrix} v_r \\ \frac{{v_n}^2}{r} + \frac{\bar{q}S}{m} C_{z\alpha}\alpha \sin(\lambda - \theta) \\ \frac{v_n}{r} \\ \frac{-v_n v_r}{r} + \frac{\bar{q}S}{m} C_{z\alpha}\alpha \cos(\lambda - \theta) \\ \frac{\bar{q}S}{mU_0} C_{z\alpha}\alpha + q \\ \frac{\bar{q}Sl}{I_{yy}} C_{m\alpha}\alpha + \frac{\bar{q}Sl^2}{I_{yy}2U_0} C_{mq} q \\ q \end{pmatrix} + \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ \frac{\bar{q}Sl}{m} C_{z\delta} \\ \frac{\bar{q}Sl}{I_{yy}} C_{m\delta} \\ 0 \end{pmatrix} \delta + \begin{pmatrix} 0 \\ a_{Tr} \\ 0 \\ a_{Tn} \\ 0 \\ 0 \\ 0 \end{pmatrix} \quad (4)$$

3. Controller design

Missile-target collision occurs when the r distance between the missile and the target decreases to less than the r-hit value, ($|r| < r_{hit}$) is considered a necessary and effective condition for hitting the target. This condition seems quite logical in practice. Considering that r appears in the denominator in the equations of state, then the condition that it becomes zero is not a desirable value for simulation because in this case the system will become unstable. The way to achieve interception in the integrated state space model is to calculate δ in such a way that criterion in (5) is satisfied [3] [4].

$$\delta : v_n \to 0 \quad (5)$$

Therefore, the control objective in this problem can be defined as requiring the vertical component of the relative velocity vector approach to zero.

3-1. PID controller design

The general form of the PID controller is stated as shown in equation (6):

$$u = K_p e + K_i \int e\, dt + K_d \left(\frac{de}{dt}\right) \quad (6)$$

The Ziegler-Nichols method is used to obtain gains.

3-2. Sliding mode controller design

It is carefully observed in equation (4) that the control input is applied to the state equation related to α. Each sliding mode controller consists of two equivalent and switching parts. The first part takes the output of the system to the sliding level and the second part acts as a means of reducing of fluctuations. These two parts are expressed as equations (7) and (8).

$$\delta_{eq} = \frac{\dot{\alpha}_d - \left(\frac{\bar{q}S}{mU_0} C_{z\alpha}\alpha + q\right)}{\left(\frac{\bar{q}Sl}{m} C_{z\delta}\right)} \quad (7)$$

$$\delta_{sw} = \frac{K_2 \tanh(s_\alpha)}{\left(\frac{\bar{q}Sl}{m} C_{z\delta}\right)} \quad (8)$$

In equation (8), K_2 is a positive constant coefficient. The actual control input is obtained from the sum of two equations (7) and (8). Hence,

$$\delta_{smc} = \delta_{eq} + \delta_{sw} \quad (9)$$

3-3. Classical neural sliding model hybrid controller design

To design the classic neural network controller, the RBFNN neural network is used [5]. The input of the neural network controller can be expressed as Eq. (10):

$$\delta_{nn} = \widehat{W}\bar{\Phi}_R + KS \quad (10)$$

In Eq. (10), $\widehat{W}$ denotes the neural network synaptic weights, $\bar{\Phi}_R$ and K is also a constant obtained from the optimization.
By combining two control inputs from Eqs. (9) and (10), the final control input is obtained as:

$$\delta = \delta_{smc} + \delta_{nn} \quad (11)$$

4. Simulation and results

After completing the design of the controllers used, the performance of the designed controllers is examined in this section.

4-1. PID controller performance simulation

In this section, the performance of the PID controller, whose parameters are set by the Ziegler-Nichols method, is examined.

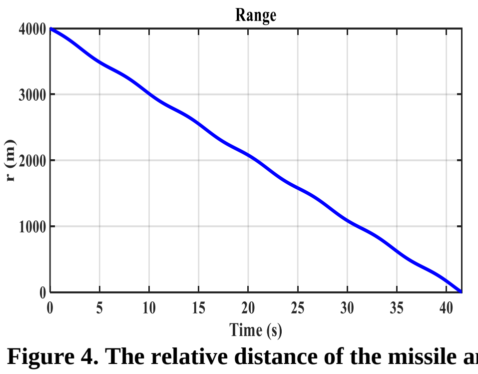

Figure 4. The relative distance of the missile and the target - PID controller

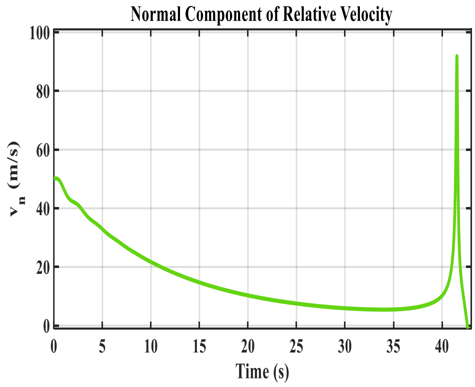

Figure 5. The relative speed of the missile and the target - PID controller

The graphs in Fig. (4) and (5) show that in about 45 seconds, the relative speed of the missile and the target reaches zero. Also, the relative distance between the missile and the target reaches zero in more than 40 seconds. In general, it can be said that the performance of the PID controller is evaluated as unacceptable, since the flight time using this controller is too long, making it unsuitable for air defense scenarios.

4-2. Simulation of classical neural sliding model hybrid controller

In this part, the simulation of the hybrid sliding model controller with classical neural network is discussed.

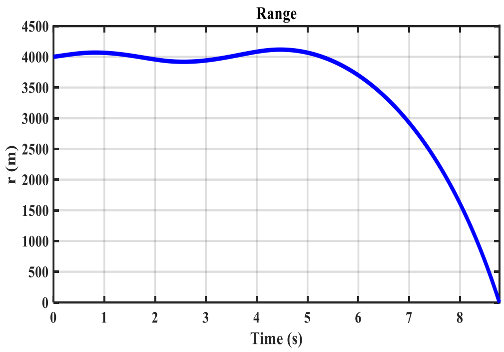

Figure 6. The relative distance between the missile and the target - SMC-NN controller

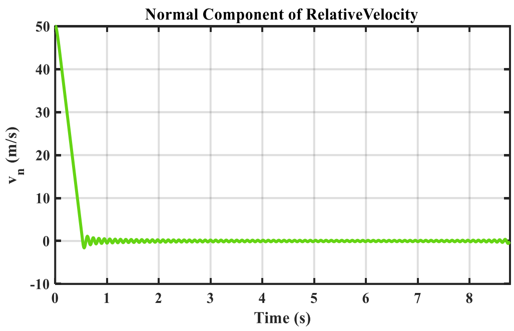

Figure 7. The relative speed of the missile and the target - SMC-NN controller

Fig. (6) and (7) show that the relative missile/target vertical velocity reaches zero in less than 1 second. In addition, the relative missile/target distance reaches zero in about 9 seconds. Next, in Figure 8, a comparison of the missile and target collision time is drawn for the three controllers of this article.

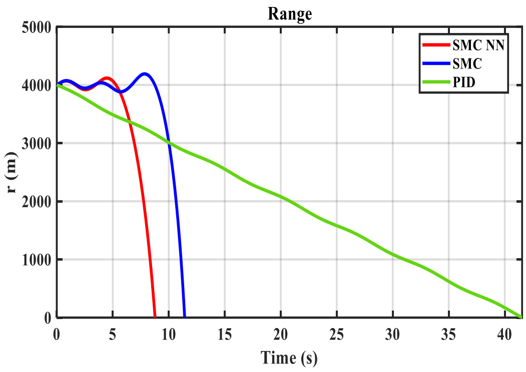

Figure 8. The relative distance between the missile and the target

5. Conclusions

In this paper, the guidance and control of a surface-to-air tracking missile was studied using the proposed neural sliding mode controller for the integrated model of the two-dimensional target/missile engagement. At first, the integrated guidance and control equations of the missile and the target were fully extracted and then the controllers were designed in combinations of the two. First, in order to evaluate the proposed controllers, a PID controller was designed and simulated. The results of this controller were not evaluated favorably due to the long a flight time, rendering the control law inappropriate. Next, the sliding mode controller was designed in combination with a neural network. According to the simulations, it can be said that the time to collision between the missile and the target for both optimal neural controllers is below 10 seconds, making it suitable for air defense purposes, and the control law is also applied within the appropriate range.

6- References

[1] P. Zarchan, Tactical and strategic missile guidance. *American Institute of Aeronautics and Astronautics*, 2012

[2] Neil F Palumbo, Ross A Blauwkamp, and Justin M Lloyd. Basic principles of homing guidance. Johns Hopkins APL Technical Digest (*Applied Physics Laboratory*) , 2010 .

[3] Michael A Cross and Yuri B Shtessel. Single-Loop Integrated Guidance and Control Using High-Order Sliding Mode Control. *In Variable Structure Systems and Sliding-Mode Control*, chapter 14. Springer, 2020.

[4] Michael A Cross and Yuri B Shtessel. Integrated Guidance Navigation and Control Using High-Order Sliding Mode Control for a Missile Interceptor. In 2018 *AIAA Guidance, Navigation, and Control Conference*, page 1121, 2018

[5] Fujin Luan, Jing Na, Yingbo Huang, Guanbin Gao, "Adaptive neural network control for robotic manipulators with guaranteed finite-time convergence," *neurocomputing*, Pages 153-164, Volume 337, 14 April 2019