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RESEARCH ARTICLE

Development of a Stabilizing Adaptive Feedback Control System for Helicopter Gun Turrets

Helikopter Silah Kulesinin Dengelenmesi için Uyarlamalı Geri Beslemeli Kontrol Sistemi Geliştirilmesi

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Abstract
This study introduces a stabilizing controller design for a helicopter gun turret system using an adaptive backstepping control approach. To model the gun turret system, a two-degree-of-freedom manipulator dynamics is employed, which enables precise control over the weapon pointing mechanism. The proposed controller design utilizes an adaptive backstepping control strategy to ensure system stability and robustness against disturbances such as firing and other operational conditions. Additionally, the design includes an advanced feedback mechanism that dynamically adjusts to changes in the helicopter's flight dynamics, further enhancing control accuracy. Simulation results show the efficacy of the controller, achieving stable and precise control of the gun turret system. The study offers a simplified model to enhance the performance of helicopter gun turret systems, with potential applications in military ground and naval vehicles. The proposed controller design is a promising solution to improve the precision and stability of the gun turret system, contributing to safer and more efficient defense systems.

Keywords: Adaptive Backstepping Control, Attack Helicopter, Gun-Turret System, Robot Manipulator, State-Augmented Controller

Özet
Bu çalışmada, uyarlamalı geri adımlama kontrolü kullanarak bir helikopter silah kulesi sistemi için stabil bir kontrolör tasarımı önermektedir. Silah kulesi sisteminin modellenmesinde, silahın nişan alma sisteminin doğru bir şekilde kontrol edilmesini sağlayan iki serbestlik dereceli bir manipülatör dinamiği kullanılmaktadır. Önerilen kontrolör tasarımı, ateşleme ve operasyonel koşullar gibi bozucu faktörlere karşı sistem stabilitesini ve gürbüzlüğünü garanti altına almak için uyarlamalı geri adımlama kontrol stratejisini kullanmaktadır. Benzetim sonuçları, kontrolörün etkinliğini göstermekte ve silah kulesi sisteminin stabil ve hassas kontrolünü sağlamaktadır. Çalışma, helikopter silah kulesi sistemlerinin performansını artırmak için basitleştirilmiş bir model sunmakta ve bu modelin askeri kara ve deniz araçlarında potansiyel uygulamaları bulunmaktadır. Önerilen kontrolör tasarımı, silah kulesi sisteminin hassasiyetini ve stabilitesini artırarak daha güvenli ve verimli savunma sistemlerine katkıda bulunan bir çözümdür.

Anahtar Kelimeler: Uyarlamalı Geri Adımlı Kontrol, Saldırı Helikopteri, Silah Kule Sistemi, Robot Manipülatörü, Durum Artırılmış Kontrolör

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1. INTRODUCTION

In recent years, the evolution of sophisticated weapon systems has become increasingly pivotal in the realm of national security. Central to these advancements is the attack helicopter, which is outfitted with a gun turret system. This system is integral in efficiently neutralizing potential enemy targets and effectively responding to enemy threats during flight, as illustrated in Figure 1. The gun turret endows the helicopter with the capability to target and engage enemies precisely, significantly enhancing the probability of successful missions while concurrently minimizing unintended collateral damage.

However, the effective operation of the gun turret system is often challenged by various disturbances and uncertainties that are inherent in aerial environments. For instance, factors such as mechanical vibrations at the moment of firing, wind gusts, and atmospheric turbulence can substantially impact the stability and accuracy of the gun turret system. These disturbances are often revealed as swaying or wobbling motions of the turret, which can severely restrict the gunner's ability to aim and fire with precision. The impact of these external factors is vividly demonstrated in the FLIR camera images shown in Figure 2, where the motion of the gun barrel can be observed. This scenario underscores the necessity for a meticulously designed stabilizing controller. Such a controller would not only minimize the effects of these disturbances but also substantially enhance the accuracy and overall effectiveness of the gun turret system. By integrating advanced control algorithms and adaptive feedback approaches, this proposed controller design aims to maintain the stability of the gun turret, ensuring more accurate targeting even under the most challenging flight conditions. This control approach is poised to make a significant contribution to the field of military technology, offering enhanced operational capability and effectiveness of smart defense systems.

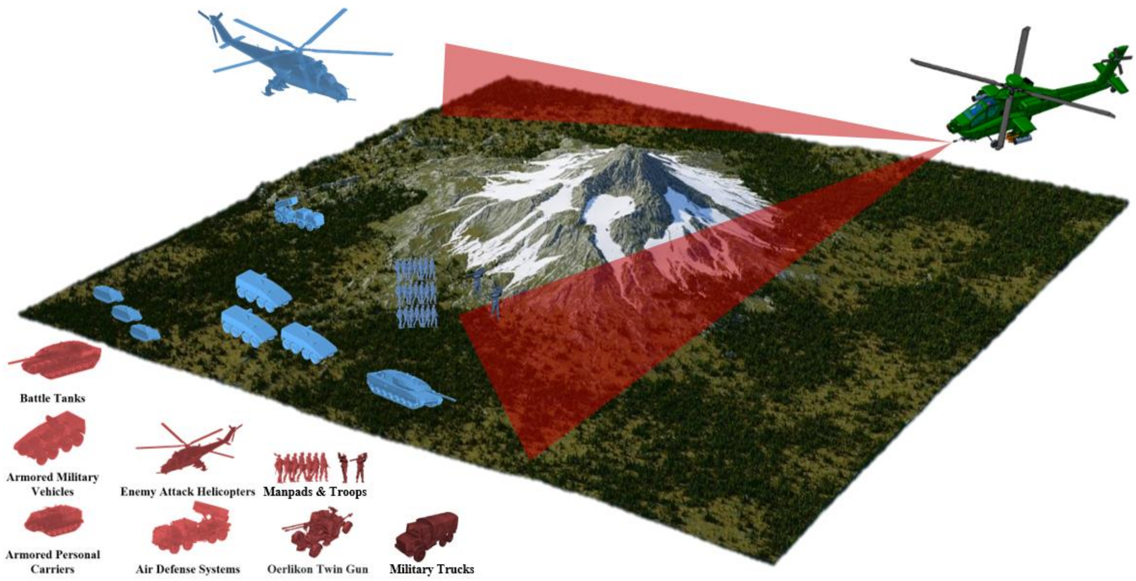

Figure 1. Probable opportunity targets and threats en route.

The helicopter's gun turret, conceptualized as a robotic manipulator arm, seeks to replicate this by precisely controlling the elevation and azimuth angles, a mechanism depicted in Figure 3. However, achieving such control presents significant challenges. It requires the implementation of sophisticated control algorithms capable of dynamically adjusting the gun turret’s position in real-time. These adjustments are essential to counteract disturbances from the helicopter’s movements or environmental factors, as well as to compensate for any changes in the target's position. Despite the inherent challenges, ongoing research in this field is continuously pushing the boundaries of what is possible in control system design. Researchers and engineers are working continuously to refine existing methods and develop innovative new approaches to control smart military systems. The advancements in this area not only promise to modernize smart military defense systems but also have potential applications in other fields that require high precision and stability under dynamic conditions. Therefore, the enhancement of gun turret systems in modern warfare has seen a significant shift towards integrating cutting-edge technologies and sophisticated control strategies in recent years.

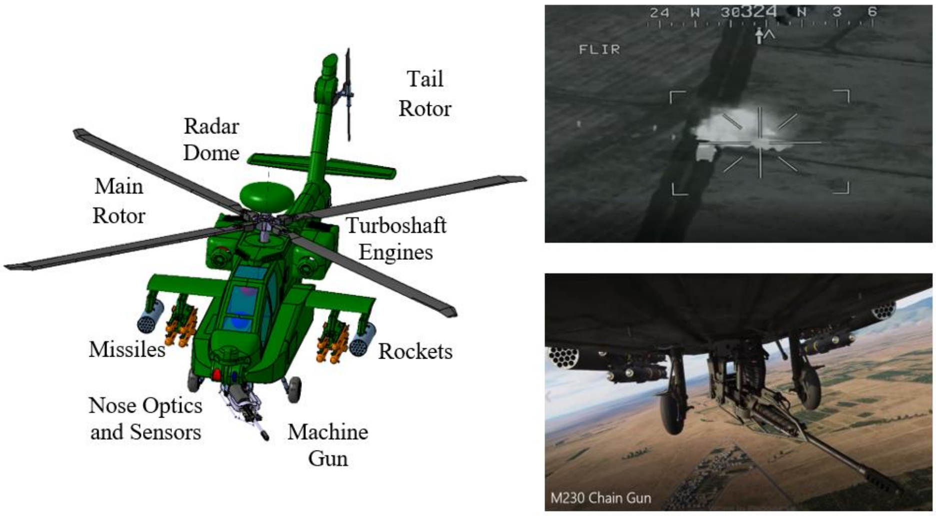

Figure 2. Helicopter’s gun turret system and infrared camera image [1].

On the other hand, the derivation of mathematical models for these gun turret systems is an intricate process that involves considering inter-axis dynamics and the nonlinear coupling between axes of the gun turret system modeled as a robotic manipulator. These models are essential for developing control strategies that can accurately compensate for uncertainties and handle constraints inherent in the system. Furthermore, the effectiveness of these advanced control strategies can be rigorously tested through simulation tests. These simulations provide valuable insights into the performance and reliability of the control approaches under various operational conditions. Moreover, the advancement of automatic targeting systems that rely solely on visual information represents an innovative step in smart weapons technology. Meanwhile, recent advancements in gun turret system control and automation have introduced robotic formulations, optimal and MPC-based controllers, and intelligent algorithms, enhancing performance, accuracy, and safety. These innovations leverage machine learning, deep learning, and fuzzy logic to improve response times and target tracking while addressing environmental constraints and uncertainties [2-8]. Such progress promises significant advancements in military technology, offering sophisticated solutions for automatic weapon pointing and platform systems across various operational scenarios.

In the realm of modeling gun turret systems with robotic formulations, the application of adaptive control algorithms has demonstrated significant potential in enhancing system performance among various control approaches. These sophisticated algorithms are specifically designed to address the challenges posed by the dynamic of gun turret operations. One key aspect of these algorithms is the adaptive control of robotic manipulators. This approach is focused on managing model uncertainties and input disturbances, which are common issues in the real-world operation of gun turrets. By adapting to these uncertainties, the control system maintains high precision and stability in the manipulator's movements, ensuring accurate targeting as aforementioned. Similarly, stability analysis and the design of robust-adaptive sliding mode control represent another critical area of focus. Sliding mode control is known for its robustness against system variations and external disturbances such as vibration and gust. When combined with adaptive strategies, it provides a double layer of safety, ensuring that the system remains stable even under highly unpredictable conditions. Additionally, adaptive backstepping control, particularly when based on combined state augmentation, is explored to handle uncertainties in both dynamics and kinematics, as well as unknown high-frequency gain. This method is especially valuable for dealing with complex, nonlinear aspects of gun turret systems, allowing for precise control even when facing unanticipated changes in system behavior. The primary goal of these studies is to refine adaptive control for robotic systems, enhancing tracking and stabilization through innovations like parameter-adaptive controls, PD feedback with dynamic compensation, and linear adaptive controllers [9-19]. These strategies are not just about maintaining control but also about advancing the control system to new levels of sophistication and effectiveness. By continually refining these adaptive control algorithms, researchers and engineers aim to enhance the operational capabilities of gun turret systems, ensuring they can perform optimally in a wide range of scenarios, from standard operations to high-intensity combat situations. This ongoing development is essential for the advancement of smart military technology, where precision, reliability, and adaptability are key criteria for successful outcomes.

The primary objective of this study is to develop a state-augmented adaptive back-stepping controller for the gun turret system shown in Figure 4, utilizing mathematical expressions akin to those for robotic manipulators. This novel controller design is an integration of adaptive control and feedback linearization techniques, each playing a critical role in enhancing the system's performance and stability. Also, feedback linearization stands at the forefront of this approach. It is employed to transform the inherently nonlinear dynamics of the gun turret system into a linearized framework. This transformation is fundamental as it allows the application of conventional control techniques, which are typically more straightforward and well-understood, to the system. On the other hand, linearization alone is not sufficient to handle all the complexities of the gun turret system. This is where adaptive control comes into play in control system design. It is seamlessly integrated into the control framework to compensate for uncertainties and disturbances that the linearized model does not account for. These uncertainties might include variations in system parameters or external disturbances like wind gusts and mechanical vibrations, which are commonplace in real-world scenarios.

To control complex systems characterized by high-order dynamics, the state-augmented adaptive back-stepping controller is particularly suited. The essence of this approach lies in augmenting the system state with additional variables, which are designed to capture the dynamics of the system that are not directly measured or observed. By incorporating these additional state variables into the controller design, it becomes possible to significantly enhance the overall performance and stability of the gun turret system. The effectiveness of this controller is rigorously tested through comprehensive simulation studies, as illustrated in Figure 6. These simulations are designed to assess the controller's ability to stabilize the gun turret system under a variety of disturbance scenarios, particularly focusing on the challenges in controlling elevation and azimuth angles. The simulations provide a critical evaluation of the controller's performance, showcasing its potential to maintain stability and precision under dynamic and uncertain conditions. Briefly, this research contributes to the field of control systems by offering a sophisticated solution to one of the more challenging problems in modern robotics and defense technology.

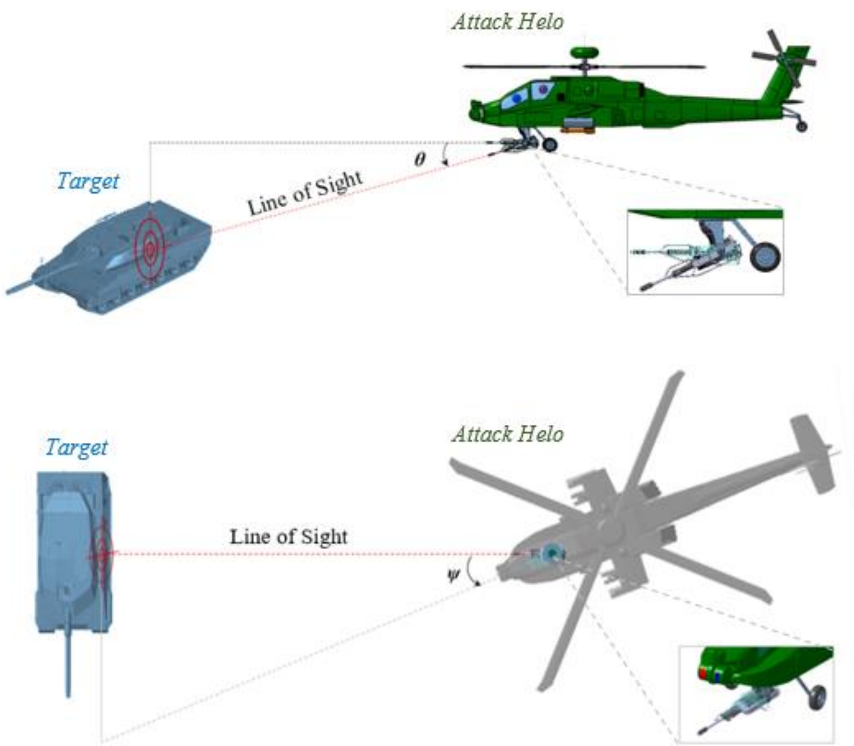

Figure 3. Elevation and azimuth angles of the gun turret system.

2. MATHEMATICAL MODELLING

To thoroughly analyze the dynamics of a helicopter gun turret system and develop an effective control strategy, the fundamental task of deriving dynamic equations is of paramount importance as these equations are essential for accurately predicting system behavior and designing controllers. As shown in Figure 4, one of the critical components of the weapons pointing system is the gun turret, which can be aptly represented using established procedures for modeling robotic systems. This mathematical modeling involves a detailed examination of the gun turret's kinematics and dynamics, akin to those found in robotic manipulator arms, to accurately capture its motion characteristics. The process begins by identifying and defining the turret's degrees of freedom, which typically include rotational movements such as elevation and azimuth angles. These angles play a crucial role in determining the turret's orientation and targeting direction.

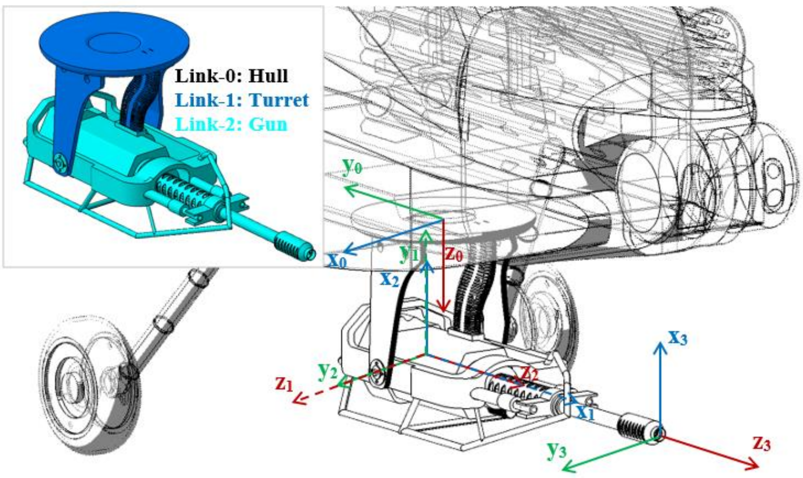

Figure 4. Coordinate frames of the simplified gun turret system.

To effectively represent a gun turret’s movement and pointing path, a three-dimensional vector is essential, which captures the spatial orientation and positioning of the turret's barrel to its target. For a more comprehensive analysis, the gun turret system is modeled as a two-link manipulator, akin to a simplified robotic arm. This simplified model allows for a detailed examination of the turret's mechanics, facilitating the design of a responsive and precise control system. The process of establishing the kinematic and dynamic models for this system closely follows conventional procedures used in robot dynamic analysis. These procedures are fundamental for accurately representing the spherical structure of the gun turret, which is essential for understanding its range of motion and capabilities. The kinematic model addresses the geometrical aspects of the turret's movement, including its position, velocity, and acceleration in three-dimensional space. This model is particularly important for predicting the turret’s behavior and understanding how its different parts move to each other and the helicopter. On the other hand, the dynamic model delves into the forces and torques acting on the gun turret system. It considers aspects such as inertia, friction, and external disturbances, providing a more complete picture of the system's behavior under various conditions.

A key step in this process is assigning a joint coordinate system to the gun turret system by utilizing the Denavit-Hartenberg (D-H) method, which simplifies the analysis and control of its movement. Using this coordinate system in the gun turret, the D-H parameters are presented in Table 1. As known, the D-H table is a standardized way to represent the kinematic chain of a robotic manipulator, providing a systematic method to describe the relative positions and orientations of the links and joints in the manipulator arm [22]. The table leads to the formulation of three one-step homogeneous transformation matrices. These transformation matrices are fundamental in robot kinematics, allowing for the transformation of coordinates from one joint to the next in the manipulator chain. They play a crucial role in calculating the position and orientation of the gun turret in space, enabling precise targeting and efficient control.

Table 1. D-H parameters of the gun turret system.

Link #	$\mathbf{a_i}$	$\mathbf{d_i}$	$\boldsymbol{\alpha_i}$	$\boldsymbol{\theta_i}$
1	*0*	*0.698*	$-\pi/2$	$q_1 = \Omega$
2	*0*	*0*	$\pi/2$	$q_2 = \psi$
Tip	*0*	*1.841*	0	*0*

In the mathematical modeling of the helicopter gun turret system, the angles of rotation are denoted as q_1 and q_2, representing two essential rotational movements of the turret mechanism. The angle q_1 corresponds to the "waist" rotation, which is the rotation between the helicopter's hull and the base of the turret. This rotation allows the turret to rotate horizontally (waist rotation), providing a range of motion in azimuth. On the other hand, q_2 represents the "shoulder" rotation, which occurs between the gun tube and the turret table. This rotation enables the tip of the turret to move vertically, adjusting the elevation angle of the gun tube. Additionally, the length of the gun tube is denoted as d_3. This length is another parameter as it influences the positioning of the gun tube's end-point, affecting the overall geometry of the system.

To understand the spatial positioning and orientation of the gun tube's tip point, which is critical for targeting accuracy, the position vector and orientation matrix are derived from the base frame of the turret system (Link-0: Hull). The base frame serves as a reference point for all movements and rotations of the turret system. The mathematical representation of this relationship is encapsulated in an equation, typically denoted as Equation 1 in the context of helicopter gun turrets. This equation integrates the D-H parameters q_1, q_2, and d_3 and utilizes the principles of robotic kinematics to express the position and orientation of the gun tube's end-point (the origin of frame 3) to the base frame. This kinematic equation is fundamental in the control and operation of the gun turret system. By accurately modeling the relationship between these rotational movements and the position of the gun tube, the equation enables precise aiming and maneuvering of the turret, ensuring effective engagement with targets. This is particularly vital in dynamic environments where both the helicopter and targets may be moving, requiring constant adjustments of the gun turret for accurate targeting.

$$\underset{\sim}{T}_0^3 = \begin{bmatrix} c(q_1)c(q_2) & -s(q_1) & c(q_1)s(q_2) & d_3 c(q_1)s(q_2) \\ c(q_2)s(q_1) & c(q_1) & s(q_1)s(q_2) & d_3 s(q_1)s(q_2) \\ -s(q_2) & 0 & c(q_2) & d_1 + d_3 c(q_2) \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (1)$$

The significance of the transformation matrix, as detailed in Equation 1 in the context of the helicopter gun turret system, cannot be overstated as mentioned above. This matrix plays a pivotal role in understanding and controlling the spatial positioning of the gun turret's tip point, which is crucial for accurate targeting. In the context of robotic kinematics and the modeling of the gun turret system, the transformation matrix provides a comprehensive representation of the relationship between different parts (links) of the turret. Specifically, the position vector of the tip point relative to the base frame of the turret system is embedded in the 4^{th} column of this transformation matrix. This column precisely indicates the tip point's position in three-dimensional space, taking into account the rotations and translations that occur within the turret mechanism. The 4^{th} column effectively captures the x, y, and z coordinates (or the respective equivalent in the specific coordinate system being used) of the tip point, relative to the base frame. Briefly, this transformation is essential for understanding where the gun tube is pointing at any given moment, which is critical for the operation of the turret in real-world scenarios.

Meanwhile, utilizing analytical calculation techniques, joint trajectories can be deduced as described in Equation 2. This equation deals with the motion planning aspect of the gun turret system, which enables the determination of the required rotational angles at the turret's joints (i.e., the 'waist' and 'shoulder' rotations) to achieve a desired position and orientation of the gun tube's tip point. Joint trajectories are vital for the control system of the turret system, as they dictate the precise movements needed to align the gun tube with a target at the moment of firing. By calculating these trajectories, the control system can direct the turret to move in a specific manner, ensuring that the tip point reaches the desired position and orientation to engage targets accurately. The analytical equations expressing joint trajectories can be given as:

$$
\begin{aligned}
&T_0^3(1,4) = p_{0,x}^3 = d_3 c(q_1) s(q_2) \\
&T_0^3(2,4) = p_{0,y}^3 = d_3 s(q_1) s(q_2) \\
&T_0^3(3,4) = p_{0,z}^3 = d_1 + d_3 c(q_2) \\
&q_1 = a\tan\left(\frac{p_{0,y}^3}{p_{0,x}^3}\right),\ q_2 = a\cos\left(\frac{p_{0,z}^3 - d_1}{d_3}\right)
\end{aligned} \tag{2}
$$

The expressions being discussed in Equation 2 are known as analytical inverse kinematics equations, which are fundamental in the field of robotics. These equations are also crucial for the effective control of the gun turret system on a helicopter because of its inverse kinematics. As known, inverse kinematics involves determining the necessary joint trajectories (joint angles) of a robotic manipulator, in this case, the gun turret, to achieve a specific position of the tip point, which is the gun tube's targeting point. By utilizing the position vector of the tip point relative to the base (reference frame), which is obtained from the transformation matrix as mentioned earlier, inverse kinematics calculations enable the determination of the joint trajectories for the gun-turret system.

Table 2. Dynamic parameters of the gun-turret system.

Link-1: Turret

Characteristics		Inertia center	
Volume:	0,032m3	x:	31,266mm
Mass:	43,095kg	y:	-643,235mm
Surface:	1,864m2	z:	214,759mm

Inertia matrix					
Ixx:	2,456kgxm2	Ixy:	0,07kgxm2	Ixz:	0,03kgxm2
Iyx:	0,07kgxm2	Iyy:	3,56kgxm2	Iyz:	-0,237kgxm2
Izx:	0,03kgxm2	Izy:	-0,237kgxm2	Izz:	3,056kgxm2

Link-2: Gun

Characteristics		Inertia center	
Volume:	0,066m3	x:	67,957mm
Mass:	89,971kg	y:	-1251,661mm
Surface:	4,767m2	z:	233,341mm

Inertia matrix					
Ixx:	13,897kgxm2	Ixy:	-0,035kgxm2	Ixz:	-0,103kgxm2
Iyx:	-0,035kgxm2	Iyy:	15,176kgxm2	Iyz:	0,044kgxm2
Izx:	-0,103kgxm2	Izy:	0,044kgxm2	Izz:	2,72kgxm2

The dynamic equations of motion for a 2-degree-of-freedom (2-DOF) robotic manipulator are utilized to model the gun-turret system depicted in Figure 4. The use of a 2-DOF manipulator model is demonstrative of the system's complexity, encompassing the rotational movements at the 'waist' and 'shoulder' of the turret system. To derive these dynamic equations, the Lagrange-Euler dynamical formulation is employed. This formulation is particularly advantageous as it allows for the derivation of dynamic equations that are independent of the reference coordinate frame. This approach is beneficial in providing a more generalized and versatile model of the gun turret's dynamics, applicable under various operating conditions. Meanwhile, in the mathematical modeling process, certain simplifications are made for practicality and computational efficiency. One of the frequent simplifications in mechanical systems involves excluding friction terms from the dynamic equations. While friction can play a role in the real-world operation of the turret, excluding these terms in the model (as in Equation 3) helps to simplify the equations and focus on the primary dynamics of the system. This simplification is a standard practice in the initial modeling stages, providing a clearer understanding of the system's fundamental behavior before introducing more complex factors like friction in later refinements. In this case, the dynamic equation is written as:

$$\underset{\sim}{M}\left(\underline{q}\right)\underline{\ddot{q}}+\underset{\sim}{C}\left(\underline{q},\underline{\dot{q}}\right)\underline{\dot{q}}+\underset{\sim}{G}\left(\underline{q}\right)=\underline{\tau} \quad (3)$$

where $\underline{q} \in R^n = [q_1\ q_2]^T$, $\underline{\dot{q}} \in R^n = [\dot{q}_1\ \ \dot{q}_2]^T$, $\underline{\ddot{q}} \in R^n = [\ddot{q}_1\ \ddot{q}_2]^T$ are the angular position vector, angular velocity vector, and angular acceleration vector of joint variables, respectively. $M\left(\underline{q}\right)$ denotes the manipulator's inertia matrix and is consistently positive definite. $C\left(\underline{q},\underline{\dot{q}}\right)$ is the matrix of the Coriolis and centrifugal forces, $G\left(\underline{q}\right)$ represents the gravity vector, and $\underline{\tau}$ is the torque vector. Each part (link) of the gun-turret system is rotary and the dynamic model is derived for this simplified 2-DOF robotic system. The gun turret's geometrical and dynamical parameters are provided in Table 2.

In the context of the dynamic modeling of the gun turret system, the evaluation of the derived matrices is a critical step in determining the joint torques required for the motion of the turret. This is essential for understanding the required forces to drive the turret's movements and achieve the desired positioning and targeting. Once the dynamic equations, encapsulated in the previously mentioned dynamic equation of motion, are established using the Lagrange-Euler formulation, the next step involves evaluating this equation. Meanwhile, this process typically involves substituting specific values for the system parameters, such as the mass distribution of the turret, length of the gun tube, and moments of inertia, into the derived equations. The outcome of this evaluation is the determination of the joint torques expressed in Equation 4. After evaluating these matrices, the joint torques were determined by employing the following terms:

$$\underset{\sim}{M} = \begin{bmatrix} m_1 & m_2 \\ m_3 & m_4 \end{bmatrix}, \ \underset{\sim}{C} = \begin{bmatrix} c_1 & c_2 \\ c_3 & 0 \end{bmatrix}, \ \underset{\sim}{G} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$$
$$m_1 = I_{yy1} + I_{zz3} c\left(q_2\right)^2 + I_{xx3} s\left(q_2\right)^2 + d_{g3}^2 m_3 - d_{g3}^2 m_3 c\left(q_2\right)^2 - 2 I_{xz3} c\left(q_2\right) s\left(q_2\right) + 1$$
$$m_2 = I_{yz3} c\left(q_2\right) - I_{xy3} s\left(q_2\right)$$
$$m_3 = I_{yz3} c\left(q_2\right) - I_{xy3} s\left(q_2\right)$$
$$m_4 = m_3 d_{g3}^2 + I_{yy3} + 1$$
(4)

3. ADAPTIVE CONTROLLER DESIGN

The development of a state-augmented adaptive backstepping control represents a sophisticated approach to managing the complexities of systems characterized by high-order dynamics. As known, this control strategy hinges on the use of additional state variables, which are specifically chosen to enhance both the performance and stability of the system. The correct selection of these additional variables is a critical aspect of the controller design, requiring an in-depth understanding of the system's dynamics to ensure the overall stability of the system.

Another fundamental component of this control strategy is the design of adaptive laws. These laws play a crucial role in updating the controller parameters in real time, which is essential for maintaining the stability and effectiveness of the control system under varying operating conditions. The design process of these adaptive laws involves a comprehensive analysis of the closed-loop system's stability, ensuring that the controller remains robust and reliable across different scenarios. While the state-augmented adaptive backstepping control strategy offers significant benefits over traditional control methods, in terms of handling complex systems and providing enhanced performance and stability, it does come with its challenges. One notable challenge is the computational intensity of this control approach. Also, the system's performance is sensitive to the selection of adaptation gains, making the tuning of these gains critical.

In the practical design of the controller, the system equations are divided into three distinct subsystems. For each of these subsystems, a virtual control signal is defined. This definition is based on the principles of a Lyapunov function, which is a mathematical tool used to assert and ensure the stability of a dynamic system. The application of the Lyapunov theorem provides a solid foundation for formulating the control signal in a manner that guarantees the stability of the closed-loop system. In light of this, the controller design is further refined by introducing a new Lyapunov function and deriving an adaptation law from it. This step marks an expansion in the adaptive capabilities of the state-augmented backstepping controller. It allows the controller to dynamically adjust to changes in the system's behavior and external disturbances, thereby maintaining optimal performance and stability. This control strategy, as investigated in multiple studies [14-18], represents an advancement in control system design, especially for complex systems with high-order dynamics like robot manipulators or helicopter gun turrets.

In the context of controller design, the error function equation denoted as Equation 5 is integral to the feedback loop of the control system. It is used to continually adjust the control actions, striving to reduce the error to zero, which would indicate that the system is performing exactly as desired.

$$\underline{e} = \underline{q}_d - \underline{q} \tag{5}$$

where $\underline{e} \in R^n$ represents the tracking error and $\underline{q_d} \in R^n$ represents the desired angular position vector. The tracking error and its derivative are defined as two new variables denoted by $\underline{z_1}$, and $\underline{z_2}$in Equation 6, respectively.

$$\underline{z}_1 = \underline{e},\ \dot{\underline{z}}_1 = \underline{z}_2 = \dot{\underline{e}} = \dot{\underline{q}}_d - \dot{\underline{q}},\ \dot{\underline{z}}_2 = \ddot{\underline{e}} = \ddot{\underline{q}}_d - \ddot{\underline{q}} \tag{6}$$

$\underline{\dot{z}_2}$ is expanded based on Equation 3 and Equation 5 as in Equation 7

$$\dot{\underline{z}}_2 = \underset{\sim}{M}^{-1}\left(-\tau + \varphi\theta\right),\ \ \varphi\theta = \underset{\sim}{M}\ddot{\underline{q}}_d + \underset{\sim}{C}\dot{\underline{q}}_d + \underset{\sim}{G} \tag{7}$$

In control systems, particularly when dealing with complex dynamics like those of a helicopter gun turret, the order of the system's equations plays a crucial role in determining the control strategy. For a system with second-order dynamics, the state equations describe how key variables such as position, velocity, or angle change over time, typically involving second derivatives to time. To enhance the performance of such a control system, especially under the presence of uncertainties or nonlinearities, a method often employed is the introduction and augmentation of a new state into the system's equations. This technique is also known as state augmentation, and it's particularly advantageous in dealing with systems that exhibit uncertainties and require robust stabilization.

The new state introduced is typically defined as a weighted integral of the error and state variables such as in Equation 8. This approach allows for incorporating past information about the system's performance (as captured by the error) and its current state into the control process. By integrating these new state equations into the system's dynamics, the control system gains an additional dimension of information, which can be used to fine-tune the control actions. This leads to a more sophisticated control strategy, enabling the system to adapt more effectively to changing conditions and uncertainties.

$$\underline{x}_1 = \eta\int_0^t \underline{e}(t)dt,\ \underline{x}_2 = \underline{e}(t),\ \underline{x}_3 = \dot{\underline{e}}(t) \tag{8}$$

So the new state equations are written as in Equation 9:

$$\underset{-}{\dot{x}}_1 = \eta \underset{-}{x}_2,\ \underset{-}{\dot{x}}_2 = \underset{-}{x}_3,\ \underset{-}{\dot{x}}_3 = \underset{\sim}{M}^{-1}\left(-\tau + \varphi\theta\right) \tag{9}$$

To recursively design the controller for the helicopter gun-turret system, the complex system equations, as outlined in Equation 9, are decomposed into three subsystems. This decomposition simplifies the overall control challenge by enabling focused attention on specific dynamics within each subsystem. For the first subsystem, a Lyapunov function, detailed in Equation 10, is established to ensure its stability. As known, this function is a critical tool in control theory, used to demonstrate that the system's stability is maintained over time. The recursive aspect of the design process involves applying this stability-focused approach to each subsystem in turn, ensuring that each layer of the system is individually stable and effectively controlled.

$$V_1\left(\underset{-}{x}\right) = \frac{1}{2}\frac{\underset{-}{K}_i}{\eta}\underset{-}{x}_1^2 \tag{10}$$

where $\underline{K_i}$ is a positive gain vector. To stabilize the first subsystem, the derivative of the Lyapunov function must be negative definite, as shown in Equation 11.

$$\dot{V}_1\left(\underset{-}{x}\right) = \frac{\underset{-}{K}_i}{\eta}\underset{-}{x}_1\underset{-}{\dot{x}}_1 = \underset{-}{K}_i\underset{-}{x}_1\underset{-}{x}_2 \tag{11}$$

Since $\underline{x_2}$ is considered a virtual control signal for the subsystem, Equation 11 is re-written as $\dot{V}_1\left(\underline{x}\right) = -\underline{K_i}\,\underline{x_1}^2$, which is negative semi-definite. By defining the virtual control, the first subsystem can be stabilized. Then, the Lyapunov function for the second subsystem is considered as presented in Equation 12.

$$V_2\left(\underset{-}{x}\right) = \frac{1}{2}\frac{\underset{-}{K}_i}{\eta}\underset{-}{x}_1^2 + \frac{1}{2}\eta\underset{-}{x}_2^2 \tag{12}$$

Taking the derivative of the Lyapunov function leads to Equation 13:

$$V_2\left(\underset{-}{x}\right) = \frac{\underset{-}{K}_i}{\eta}\underset{-}{x}_1\underset{-}{\dot{x}}_1 + \eta\underset{-}{x}_2\underset{-}{\dot{x}}_2 = \underset{-}{K}_i\underset{-}{x}_1\underset{-}{x}_2 + \eta\underset{-}{x}_2\underset{-}{x}_3 \tag{13}$$

The virtual control signal denoted by $\underline{x_3}$ is defined as in Equation 14:

$$\underset{-}{x}_3 = -\frac{\underset{-}{K}_i}{\eta}\underset{-}{x}_1 - \underset{-}{K}_p\underset{-}{x}_2 \tag{14}$$

where $\underline{K_p}$ is a positive gain vector.

Substituting Equation 14 into Equation 13, the derivative of the Lyapunov function can be obtained as in Equation 15:

$$\dot{V}_2(\underline{x}) = -\eta \underline{K}_p \underline{x}_2^2 \tag{15}$$

The derivative of the Lyapunov function is negative semi-definite, leading to the stabilization of the second subsystem. Finally, the actual control signal, $\underline{\tau}$, is designed based on the entire system equations presented in Equation 9. The Lyapunov function and its derivative are introduced in Equation 16 as:

$$V_3(\underline{x}) = \frac{1}{2}\frac{\underline{K}_i}{\eta}\underline{x}_1^2 + \frac{1}{2}\eta\underline{x}_2^2 + \frac{1}{2}\left(\underline{x}_3 + \underline{K}_p\underline{x}_2 + \frac{\underline{K}_i}{\eta}\underline{x}_1\right)^2$$
$$\dot{V}_3(\underline{x}) = \underline{K}_i\underline{x}_1\underline{x}_2 + \eta\underline{x}_2\underline{x}_3 + \left(\underline{x}_3 + \underline{K}_p\underline{x}_2 + \frac{\underline{K}_i}{\eta}\underline{x}_1\right)\left(\underset{\sim}{M}^{-1}\left(-\underline{\tau} + \varphi\theta\right) + \underline{K}_p\underline{x}_3 + \underline{K}_i\underline{x}_2\right) \tag{16}$$

The control signal vector represented as the torque values of the control surfaces are defined in Equation 17 as:

$$\underline{\tau} = \varphi\theta + \underset{\sim}{M}\left[\underline{K}_p\underline{x}_3 + \underline{K}_i\underline{x}_2 + \eta\underline{x}_2 + \underline{K}_d\left(\underline{x}_3 + \underline{K}_p\underline{x}_2 + \frac{\underline{K}_i}{\eta}\underline{x}_1\right)\right] \tag{17}$$

where $\underline{K}_d$ represents a positive gain vector.

Substituting the control signal in Equation 17 into the derivative of the Lyapunov in Equation 16 will result in Equation 18:

$$\dot{V}_3(\underline{x}) = -\eta\underline{K}_p\underline{x}_2^2 - \underline{K}_d\left(\underline{x}_3 + \underline{K}_p\underline{x}_2 + \frac{\underline{K}_i}{\eta}\underline{x}_1\right)^2 \le 0 \tag{18}$$

The Lyapunov stability of the closed-loop system is effectively guaranteed by carefully designing the adaptive control law, as detailed in Equation 18 [9-11, 20]. Meanwhile, one of the significant challenges in control system design, particularly for dynamic systems like helicopter gun turrets, is that dynamical system parameters are often not precisely known and may vary over time. This variability can significantly impact the effectiveness of the control system. To adeptly overcome this challenge, an adaptive backstepping approach has been proposed in this study. This approach is particularly tailored to handle the uncertainty associated with dynamical system parameters. In this method, instead of relying on fixed parameter values, the parameters of the dynamical system are treated as uncertain and are consequently replaced by their estimates, which is a crucial step in enhancing the controller's ability to adapt to changes and uncertainties in the system.

The state-augmented adaptive backstepping controller is developed by modifying the initial control law expressed in Equation 17. In this modification, the vector of parameters, denoted as "θ", is not used in its direct form. Instead of using this vector, it is replaced by its estimated counterpart, "$\hat{\theta}$". This replacement is a key step to the adaptive nature of the employed control strategy. By employing these parameter estimates, the controller can dynamically adjust to changes and uncertainties in the system parameters [21]. Hence, this adaptability is vital for maintaining the performance and stability of the control system under varying operational conditions. Additionally, to consolidate the theoretical foundation of this adaptive control approach, a new Lyapunov function is stated in Equation 19. Meanwhile, the Lyapunov function in this context serves a dual purpose. First, it provides a mathematical framework to ensure the stability of the adaptive control system. Second, it facilitates the continuous adjustment of the controller in response to the estimated parameters, ensuring that the system remains stable and performs optimally despite the parameter uncertainties.

$$V_4\left(\underline{x},\hat{\theta}\right)=V_3\left(\underline{x}\right)+\frac{1}{2\gamma}\tilde{\theta}^2 \tag{19}$$

where γ is a positive gain. $\tilde{\theta}$ is regarded as an error of estimation $\tilde{\theta}=\theta-\hat{\theta}$. By taking the derivative of the Lyapunov function, the $\dot{V}_4(\underline{x})$ is obtained in Equation 20 as:

$$\dot{V}_4\left(\underline{x}\right)=-\eta\underline{K}_p\underline{x}_2^2-\underline{K}_d\left(\underline{x}_3+\underline{K}_p\underline{x}_2+\frac{\underline{K}_i}{\eta}\underline{x}_1\right)^2+\left[\left(\underline{x}_3+\underline{K}_p\underline{x}_2+\frac{\underline{K}_i}{\eta}\underline{x}_1\right)\underset{\sim}{M}^{-1}\varphi-\frac{1}{\gamma}\dot{\hat{\theta}}\right]\tilde{\theta} \tag{20}$$

The parameter update law is introduced in Equation 21 as:

$$\dot{\hat{\theta}}=\gamma\varphi^T\underset{\sim}{M}^{-1}\left(\underline{x}_3+\underline{K}_p\underline{x}_2+\frac{\underline{K}_i}{\eta}\underline{x}_1\right) \tag{21}$$

Substituting Equation 21 into Equation 20 will result in Equation 22:

$$\dot{V}_4\left(\underline{x}\right)=-\eta\underline{K}_p\underline{x}_2^2-\underline{K}_d\left(\underline{x}_3+\underline{K}_p\underline{x}_2+\frac{\underline{K}_i}{\eta}\underline{x}_1\right)^2\leq 0 \tag{22}$$

In summary, the combination of the adaptive backstepping approach with the state augmentation and the new Lyapunov function forms a robust framework for dealing with uncertainties in the dynamical system parameters of the gun-turret system.

Introducing the adaptive control signal and the parameter update law is a pivotal step in ensuring the stability of the closed-loop system in the helicopter gun-turret controller design. Here, the adaptive control signal is a key component that dynamically adjusts the control inputs based on the current state and estimated parameters of the system. This adaptability is crucial for handling variations and uncertainties in the system's dynamics, which are common in real-world scenarios. On the other hand, the parameter update law complements this by continuously refining the estimates of the system parameters.

The block diagram presented in Figure 5 effectively illustrates the overall structure and workflow of the state-augmented adaptive control method. In this diagram, one can expect to see how the various elements of the control system — including the state augmentation, adaptive control signal, parameter update law, and feedback loop — are integrated to form a cohesive and robust control strategy. Ultimately, this diagram likely outlines the flow of information from the system's sensors to the controller, the processing of this information through the adaptive control algorithm, the generation of control signals, and the feedback mechanism that continuously feeds system performance data back into the controller.

4. SIMULATION RESULTS AND DISCUSSION

The current study emphasizes the application of an adaptive backstepping feedback control law, utilizing an imaginary robot model that represents a helicopter gun-turret system. The primary goal is to rigorously assess the performance of this control system, particularly focusing on its capability for quick convergence in response to initial kinematic deviations and external dynamic disturbances. To accurately assess the control system's performance, a simulation scenario is implemented. In this simulation, the target trajectory for the gun barrel is defined as a semi-circle, as depicted in Figure 6. This trajectory choice is not arbitrary but serves as a structured method to evaluate and analyze the control system's efficiency and responsiveness. A task of the simulation involves intentionally introducing a deviation in the gun barrel's actual pointing path from its desired starting point. Such deviations, common in real-world scenarios where systems might start from an offset position or encounter unexpected changes in their operating environment, are not a result of system error but a deliberate alteration designed to simulate initial kinematic deviation. In simulation, the key aspect being evaluated is the system's ability to quickly and accurately converge the gun barrel's pointing path back to the desired trajectory, despite the initial deviation. This assessment provides valuable insights into the control system’s adaptability, precision, and effectiveness in correcting deviations.

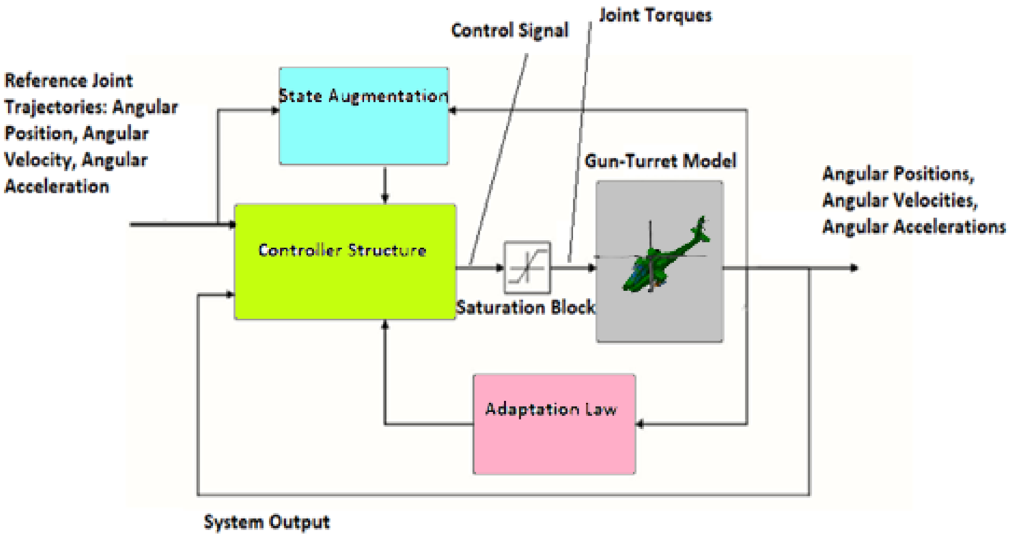

Figure 5. The block diagram of the state-augmented adaptive controller.

The simulation results of the study provide insightful and promising outcomes regarding the performance of the adaptive backstepping feedback control law applied to the helicopter gun-turret system, which demonstrates the effectiveness of the control strategy. A key finding from the simulation is that the gun-turret system, equipped with adaptive backstepping control, is capable of swiftly aligning itself with the desired trajectory. This rapid alignment is a critical factor in operational scenarios, particularly in defense applications where response time can be a decisive factor. Moreover, the system exhibits minimal steady-state error, indicating a high level of precision in maintaining the target path once it is reached. This precision is also essential for ensuring the effectiveness and reliability of the gun turret in accurately tracking and engaging targets. Another significant finding from the simulation is the relationship between the initial kinematic deviation and the system's settling time. The results reveal that decreasing the initial deviation from the desired trajectory leads to a corresponding decrease in the settling time. This relationship highlights the adaptability of the control system to different starting conditions, showcasing its capability to efficiently correct deviations and stabilize the gun turret's path.

Furthermore, the transient response of the gun-turret system, which refers to the system's behavior during the period of adjustment from the initial state to the steady state, was noticeably enhanced by the implementation of the adaptive feedback law. The improvement in transient responses is proof of the effectiveness of the adaptive backstepping approach in handling dynamic changes and disturbances. This simulation result is encouraging as it validates the proposed control strategy, demonstrating its potential to enhance the performance and responsiveness of helicopter gun-turret systems. Hence, the adaptive feedback law, with its ability to swiftly correct deviations and stabilize the system with minimal error, proves to be a robust and reliable approach for controlling complex, high-order dynamic systems in challenging conditions.

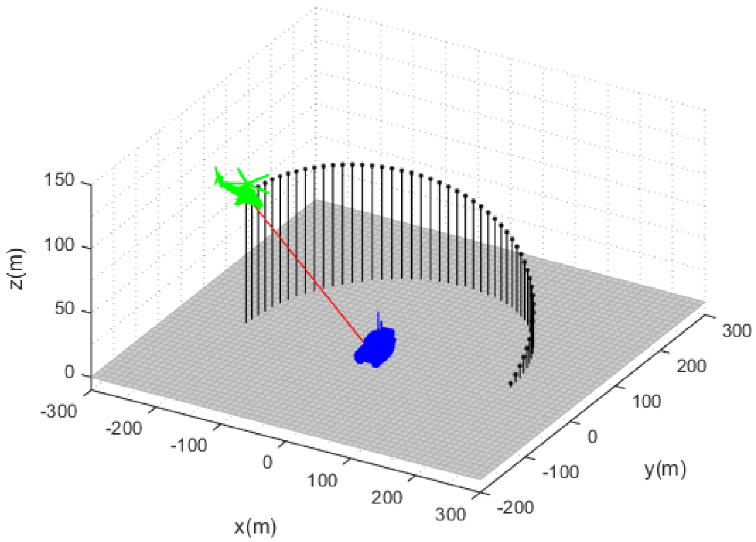

Figure 6. Attack helicopter's flight trajectory against enemy target.

When optimally tuning the controller parameters for the adaptive backstepping feedback control system applied to the helicopter gun-turret system, it's essential to consider specific criteria and constraints. These factors are vital in ensuring that the controller not only meets the desired performance standards but also adheres to practical and operational limitations. Here are some common criteria and constraints that might be taken into account:

- The settling time of the joint trajectories should be limited by 0.5 seconds.
- The disturbances subjected to the azimuth and elevation angles should be attenuated. The disturbances are given as a sinusoidal waveform whose functions are $sin(6\pi t)$ for azimuth angle, and $0.4\ sin(6\pi t)$ elevation angle, respectively. These disturbances are originated from the motion of the gun barrel in the firing sequence, and the spatial acceleration of the helicopter body.
- The limits of the azimuth and elevation angles are $[\pm 45^{\circ}]$, and $[0^{\circ} - 60^{\circ}]$, respecitvely.
- The saturation of the azimuth and elevation control torques are defined as ± 20 kNm.
- The position of the target remains constant.

Under these constraints, the controller parameters are meticulously adjusted as follows:

$$\underline{K}_p = \begin{bmatrix} 1500 \\ 430 \end{bmatrix}, \underline{K}_d = \begin{bmatrix} 1000 \\ 550 \end{bmatrix}, \underline{K}_i = \begin{bmatrix} 500 \\ 250 \end{bmatrix}, \eta = 5, \gamma = 2 \tag{23}$$

The proposed control approach for the helicopter gun-turret system has shown promising results in terms of its responsiveness and accuracy, as evidenced by the performance metrics. With settling times of approximately 0.73 seconds for the azimuth and 0.57 seconds for the elevation angular displacement responses, the system demonstrates a remarkable ability to quickly reach a stable state following a change in command or disturbance. These swift settling times are vital in dynamic combat situations where rapid target acquisition and repositioning are essential for effective operation. Furthermore, the elimination of steady-state errors in both azimuth and elevation responses is a noteworthy achievement of the controller.

Steady-state error is also a critical indicator of the long-term accuracy and stability of a control system. Its absence in this simulation scenario reveals that the system can maintain its target position with high precision over time, which is crucial for applications requiring sustained targeting accuracy.

The root-mean-squared (RMS) errors for azimuth and elevation responses are 0.5577 and 0.5034, respectively. These low values of RMS error underscore the system's high tracking accuracy. RMS error provides a measure of the average magnitude of the error, and its minimal values, in this case, indicate that the system consistently maintains proximity to the desired trajectory, even in the presence of external disturbances or system variations. Additionally, the damping ratios for the azimuth and elevation angular displacement error responses, approximately 0.0459 and 0.1394 respectively, demonstrate the system’s proficient attenuation of disturbances. A damping ratio measures oscillatory systems' ability to mitigate oscillations and return to equilibrium. The relatively low damping ratios here suggest that the system effectively dampens out any oscillatory tendencies, leading to smoother and more stable responses. This is especially beneficial in ensuring the gun turret remains steady and does not overshoot or oscillate around the target. Overall, these performance metrics not only validate the effectiveness of the proposed control approach but also highlight its potential applicability in advanced military systems where rapid, accurate, and stable control is important. The combination of quick settling times, high tracking accuracy, and successful disturbance attenuation establishes this control system as a noteworthy advancement in the field of smart weapon systems.

Figures 7, 8, and 9 present a variety of plots, such as a projection of the actual and desired trajectories in the base reference frame of the helicopter’s gun, an error function of the trajectories over time, and joint torques as the input function over time. Of them, the projection of actual and desired trajectories is crucial for demonstrating the effectiveness of the control system. By displaying the actual trajectory of the gun turret against the desired trajectory within the base reference frame of the helicopter’s gun, Figure 7 visually demonstrates how closely the system follows the intended path. The comparison between these trajectories can reveal the accuracy and precision of the control system.

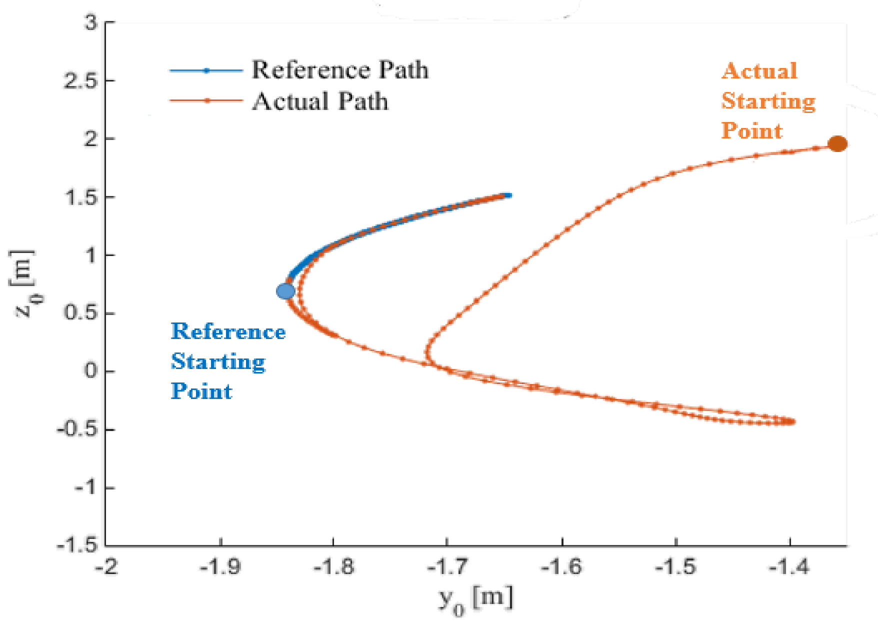

Figure 7. The gun turret's actual and reference trajectories.

The error function of the trajectories over time shown in Figure 8 is essential for understanding the control system's performance over time, which represents the difference between the actual and desired trajectories, as a function of time. It is particularly useful for evaluating how quickly the system corrects any deviations from the desired path and how it handles dynamic changes or disturbances. Also, this temporal view of the error allows for the assessment of the system's responsiveness and stability. Furthermore, joint torques shown as the input function over time in Figure 9 provide insights into the control actions taken by the system. This figure displays the joint torques, which are the inputs to the gun turret, as a function of time. These torques are essential for driving the turret's movements, and their analysis can reveal much about the control strategy's effectiveness. By examining how these torques vary over time, the responsiveness of the system to control commands and its ability to adapt to changes in the desired trajectory or external disturbances can be assessed.

In the simulation of the adaptive backstepping control algorithm, the initial setup involved simulating for one second using a fixed step size of 1e-4 seconds with the ode4 (Runge-Kutta) solver. This setup, with its high-resolution step size, ensured a detailed and accurate representation of the system's dynamics, allowing for a thorough analysis of the control system's response to various inputs and disturbances. To further optimize performance, the study suggests changing the solver configuration to a variable-step approach using the ode23tb (stiff/TR-BDF2) solver, with a maximum step size of 6e-4 seconds. The ode23tb solver is particularly well-suited for stiff systems, which are common in dynamic and complex control environments like those of a helicopter gun turret. A variable-step solver adjusts the step size dynamically based on the system's current state, providing a more efficient simulation. As known, this type of solver increases the step size during less dynamic system states to reduce computational load, and decreases it during more dynamic states to capture the system's behavior accurately. This adaptive step sizing can lead to improved simulation efficiency without compromising the accuracy or reliability of the results.

To rigorously evaluate and ensure the robustness of the control system, especially in the face of parameter uncertainty, a comprehensive simulation was conducted on the helicopter gun-turret system. In the simulation, all parameters of the gun turret system were intentionally varied randomly within a range of $\pm 10\%$ between the real plant and the model. This variation was designed to reflect real-world conditions where system parameters can deviate due to factors like environmental influences, and operational anomalies. The importance of this approach lies in its ability to simulate the control system under conditions that closely resemble actual operational scenarios. In real-world scenarios, it's rare for all system parameters to remain constant or perfectly match their nominal values. Thus, assessing the system's performance under these artificially introduced variations provides a more realistic picture of how the control system would behave in practical situations. The simulation results revealed that the system's convergence remained stable, unaffected by the parameter variations.

Consequently, the adaptive feedback control strategy applied to a helicopter gun-turret system modeled as the imaginary robot model indeed showcases several advantageous features, making it an effective solution for complex control scenarios. The assessment of this strategy reveals key attributes essential for practical and efficient control systems, especially in high-stakes applications like smart defense systems.

Firstly, the approach's decoupled formulation, which effectively eliminates the influence of centrifugal and Coriolis forces, plays a pivotal role in enhancing the control system. By isolating these dynamic terms in Equation 3, the control algorithm can focus directly on the essential aspects of position and orientation control without the added complexity of compensating for these forces. This results in a control system that is not only more efficient in terms of computational resources but also more accurate, as it reduces potential sources of error in the control process.

Secondly, the control system's ability to reject disturbances and exhibit robustness against model parameter uncertainty is another critical feature. Operational conditions are often unpredictable and exposed to various external influences affecting system performance. The control strategy's inherent capacity to handle these disturbances and uncertainties ensures reliable operation under a wide range of conditions.

Thirdly, the high precision in tracking the target trajectory is a standout feature of this control system. In smart defense systems, where targeting accuracy can have significant implications, the ability to precisely follow a designated trajectory is paramount. The high level of accuracy of this control system in trajectory tracking reveals its potential for integration into sophisticated defense technology, where precision is a non-negotiable requirement.

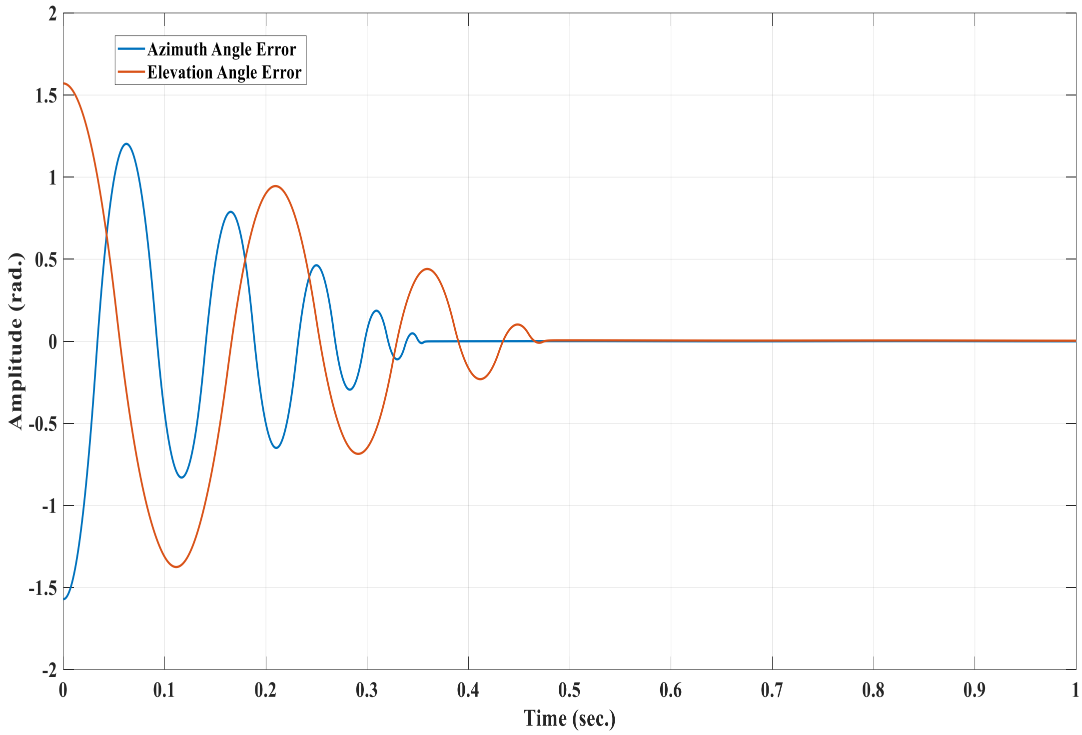

Figure 8. Error function of the trajectories versus time.

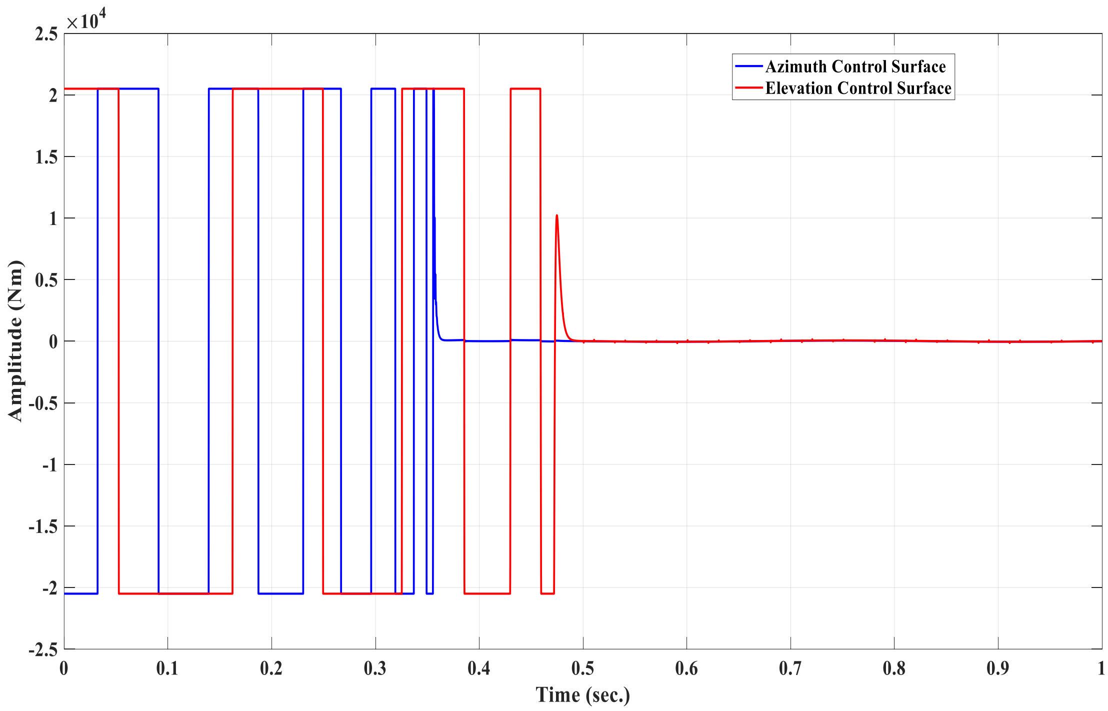

Figure 9. Joint torques versus time.

To sum up, the simulation results affirm that the adaptive backstepping feedback control law is a potent and viable strategy for controlling the weapon-pointing path of a helicopter gun-turret system. Its combination of efficiency, robustness, disturbance rejection, and high precision makes it an attractive option for complex control tasks, particularly in the defense sector where these attributes are highly valued.

5. CONCLUSION

The primary aim of this study is to explore the application of robotics in the control of weapon pointing systems, specifically concentrating on the functionality of a helicopter gun turret. It also aims to develop a systematic approach to thoroughly investigate and efficiently control the complex interactions and dynamic coupling between the azimuth and elevation axes of the gun turret. This approach is crucial for achieving precise and responsive control over the turret's movements. The utilization of an imaginary robot model for formulating the control strategies of the turret system provides valuable insights into the complex dynamics of the gun turret. Understanding these dynamics is fundamental to developing an effective control system.

One of the key strategies employed in this study to enhance the control system's performance is the reduction of the nonlinearity in the feedback control. This is achieved by decomposing the robot's inertial matrix, a technique that simplifies the control problem. The decomposition of the inertial matrix helps manage the system's complex dynamics, leading to a control strategy that is not only simpler but also well-suited for real-time implementation. Such a streamlined control system is essential for operational scenarios where quick and accurate responses are critical. The study further advances by employing a state-augmented adaptive backstepping control method. This method is used both for simulation purposes and to demonstrate the practical effectiveness of the approach. Adaptive backstepping is especially well-suited for systems with high levels of uncertainty and nonlinearity, making it an ideal choice for controlling a helicopter gun turret system.

Comprehensively, the study addresses the challenges associated with the control of gun turrets, including system modeling, updating model parameters, and the design and implementation of adaptive backstepping turret controllers in the face of disturbances and parameter variations. The results of this study also demonstrate that the proposed control system can effectively maintain the desired trajectory angle with negligible steady-state error, even in the presence of gun-barrel disturbances. Additionally, the system exhibits an acceptable settling time. Crucially, the proposed approach proves its efficacy in controlling the helicopter gun turret drive, even under challenging conditions of disturbances and parameter uncertainties.

Briefly, this study marks progress in weapon-pointing systems, paving the way for numerous future research opportunities. Key areas for future exploration include the development of advanced sampling techniques, which could enable more accurate modeling of turret dynamics and improve overall model precision. Furthermore, incorporating machine learning algorithms may also offer enhanced predictive capabilities for system behavior under diverse conditions, leading to increased control accuracy and scalability. The integration of the proposed control system with autonomous pointing systems represents another exciting research direction, promising a unified solution for targeting accuracy and autonomy. Additionally, advancements in Human-Machine Interface (HMI) solutions could greatly enhance operational efficiency and safety, ensuring seamless communication between operators and the turret system. Investigating the scalability of the proposed control system could also extend its application to various weapon systems and platforms across land and marine systems.

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