FRACTIONAL ORDER FEEDBACK CONTROL OF NONLINEAR AERIAL SYSTEMS

DOĞRUSAL OLMAYAN HAVA SİSTEMLERİNİN KESİR DERECELİ GERİBESLEMELİ KONTROLÜ

Murad A. YAGHI

Prof. Dr. Mehmet Önder EFE
Supervisor

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This work titled "Fractional Order Feedback Control of Nonlinear Aerial Systems" by **MURAD YAGHI** has been approved as a thesis for the Degree of Doctor of Philosophy in Computer Engineering by the Examining Committee Members mentioned below.

Assist. Prof. Dr. Murat AYDOS

Head ....

Prof. Dr. Mehmet ÖNDER EFE

Supervisor ....

Prof. Dr. Coşku KASNAKOĞLU

Member ....

Assoc. Prof. Dr. Ahmet Murat ÖZBAYOĞLU

Member ....

Assist. Prof. Dr. Adnan ÖZSOY

Member ....

This thesis has been approved as a thesis for the degree of Doctor of Philosophy in Computer Engineering by Board of Directors of the Institute of Graduate School of Science and Engineering on ……./……./……..

Prof. Dr. Menemşe GÜMÜŞDERELİOĞLU

Director of the Institute of
Graduate School of Science and Engineering

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- I did not do any distortion in the data set
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12 / 11 / 2019

MURAD YAGHI

Murad

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MURAD YAGHI

ABSTRACT

FRACTIONAL ORDER FEEDBACK CONTROL OF NONLINEAR AERIAL SYSTEMS

Murad YAGHI

Doctor of Philosophy, Department of Computer Engineering

Supervisor: Prof. Dr. Mehmet Önder EFE

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In this dissertation, a system of Fractional Order Proportional Integral Derivative controller is introduced and implemented to a radar guided missile in order to track a high-speed flying target. Many novel intelligent tuning techniques are proposed and implemented to this controller and each of these tuning methods is examined by a number of performance metrics such as 2-norm, ∞-norm, radar tracking performance, angle of attack during flight, normal acceleration efficiency and the missile hitting accuracy expressed by the value of miss distance. Some of these tuning methods are tested under the effect of noise and error sources. Also, these tuning methods have been compared with other standard methods from the literature. The simulation results proved the effectiveness of these tuning methods especially the novel neural H_2/H_∞ optimization technique associated with genetic algorithm achieves an excellent tracking performance with a very low value of miss distance as well as a very smooth and effective control of the missile during the whole flight time, and especially at the vicinity of impact where the behavior of the missile becomes very aggressive.

Keywords: Neural tuning, genetic algorithm, radar-guided missile, intelligent tuning, H_2/H_∞ optimization, fractional order PID controller.

ÖZET

DOĞRUSAL OLMAYAN HAVA SİSTEMLERİNİN KESİR DERECELİ GERİBESLEMELİ KONTROLÜ

Murad YAGHI

Doktora Bilgisayar Mühendisliği

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Bu tezde, yüksek hızlı bir uçuş hedefini takip etmek için bir radar güdümlü füzeye bir Kesir Derceli Düzen Oransal İntegral Türev denetleyici sistemi tanıtılmış ve uygulanmıştır. Birçok yeni akıllı ayarlama tekniği bu denetleyiciye önerilmiş ve uygulanmıştır ve bu ayarlama yöntemlerinin her biri 2-norm, ∞-norm, radar izleme performansı, uçuş sırasındaki saldırı açısı, normal hızlanma verimliliği ve kaçırma mesafesinin değeri ile ifade edilen isabet doğruluğu gibi birçok performans ölçümü ile incelenmiştir. Bu ayarlama yöntemlerinden bazıları, gürültü ve hata kaynaklarının etkisi altında test edilmiştir. Ayrıca, bu ayarlama yöntemleri, literatürdeki diğer standart yöntemlerle karşılaştırılmıştır. Simülasyon sonuçları, bu ayarlama yöntemlerinin etkinliğini göstermiş, özellikle genetik algoritma ile ilişkili yeni sinirsel H2/H∞ optimizasyon tekniği çok küçük bir kaçırma mesafesi elde etmiş, aynı zamanda tüm uçuş süresi boyunca ve özellikle çarpışmaya yakın iken füzenin saldırgan olduğu durumda pürüzsüz ve etkili bir kontrolün yanı sıra mükemmel bir izleme başarımı sergilemiştir.

Anahtar kelimeler: Sinirsel ayar, genetik algoritma, radar güdümlü füze, akıllı ayar, H_2/H_∞ optimizasyonu, kesirli düzen PID denetleyicisi

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SYMBOLS AND ABBREVIATIONS

Symbols

K_i	Integration gain
λ	Integration order
K_p	Proportional gain
μ	Derivation order
K_d	Derivation gain
H_2	2-Norm
H_∞	∞-Norm

Abbreviations

FOPID	Fractional Order Proportional Integral Derivative
PID	Proportional Integral Derivative
MD	Miss Distance
LOS	Line of Sight
GA	Genetic Algorithm
PSO	Particle Swarm Optimization
PN	Proportional Navigation
PNG	Proportional Navigation Guidance
ZN	Ziegler-Nichols

1. INTRODUCTION

1.1. Overview

1.1.1. Missile Definition

Missile is defined as a weapon that could be shot at target. Thus, an arrow moving toward an animal is a missile. The animal could avoid the missile by moving away from the flight course of the arrow (missile). If the arrow has been equipped with some kind of intelligent system that could track the animal during flight and overcome the maneuvering ability of the bird (target), then, the missile in this case is called a guided missile. Usually, any guided missile is equipped with an energy source that is responsible for providing the movement force (propulsion system), and intelligent system responsible for providing the missile with the target position (guidance system) and a tracking system responsible for providing the missile with an effective maneuvering ability while flying toward the target (control system) (Debnath, 2016b).

1.2. Aims and Contributions

Missile hitting accuracy is a control problem that many researchers are investigating in order to optimize it. Due to that, scientists proposed a lot of performance metrics for testing the accuracy of the missile, and miss distance of the missile is considered an important metric that measures the missiles' hitting accuracy.

From literature, the value of miss distance (MD) is "the minimum distance between a guided flying object and its intended target site during their intersection" (K. Y. Guo, Qu, Feng, & Sheng, 2016). The proposed Proportional Navigation (PN) is employed for controlling and guiding the aerial systems as well as tracking a particular fast-moving target. PN guidance is reported as the most used technique which is employed for missile navigation (Zhou Weiwen, Liang Xiaogeng, & Jia Xiaohong, 2010). The research conducted by this dissertation produced 7 peer reviewed papers, where 6 of them have been published in 6 prestigious international conferences in different countries, and one of them in a top-grade journal “IEEE Transactions on Industrial Electronics”.

1.3. Dissertation Outline

In Chapter 2 we investigated some previous works related to missile guidance and navigation systems. In Chapter 3 we introduced some basic concepts related to the missile navigation and guidance systems. In Chapter 4 we proposed a dual fractional order feedback control system. In Chapter 5 we introduced a Neural FOPID system. In Chapter 6 we introduced a FOPID system that is working under the effect of disturbances. In Chapter 7 we introduced an intelligent weighted technique based on H_2/H_∞ optimization method for tuning a radar guided missile equipped with fractional order PID controller. In Chapter 8 we introduced an adaptive sliding mode FOPID controller used in three-loop autopilot guidance system. Chapter 9 summarized the main conclusions produced by this dissertation.

2. LITERATURE REVIEW

A bias term is presented by (Erer, Tekin, & Özgören, 2016) and implemented into the PN guidance. The purpose of the implemented design is to enhance the course tracking performance and colliding angle accuracy of the controlling system designed for intercepting stationary target. The proposed controller is influenced by error signal and noise which is related to the incidence angle.

In our research instead of stationary target, we assumed a high-speed moving target.

The research presented by (Radhika, Parthasarathy, & Kumar, 2016) introduced an approximation procedure that employs Kalman for PN guidance. The purpose of the presented algorithm is to collide with a maneuvering target with least possible miss distance value.

The research proposed by (Su, Chen, & Li Kebo, 2016) introduced an optimized guidance system to compute the acceleration demand needed by the missile in order to follow a maneuvering target. The outcomes of their paper proved the efficiency of the introduced technique for computing the required acceleration which yielded a low miss distance.

A new technique for analyzing the incidence angle by analyzing the rotation speed which is considered as an alternative for computing the incidence angle rather than the standard technique proposed by (Tyan, 2015) .

In (Yueneng & Ye, 2018), an adaptive sliding mode system that employs neural techniques is introduced and this proposed control system is implemented uncertain system. A neural network is employed to reduce the chattering effect. The results of this research proved the efficiency of the introduced system in reducing the chattering effect.

Instead of these previously mentioned techniques, we integrated the fractional order PID controller to modify the acceleration demand in order to achieve a better mis distance value against highly maneuvering target which resulted in much more accurate miss distance value.

In (Raj & Ganesh, 2015), the authors inspected the effect of noise which affects the navigational guidance system. They introduced a new procedure that employs digital fading memory filters in order to increment the smoothness of the system which is exposed to uncertain effects. The results of the simulation proved the superiority of this procedure over the well-known Kalman filters.

In (Davanipour, Javanmardi, & Goodarzi, 2018), a self-tuning proportional integral derivative control system employs fuzzy wavelet neural system is introduced and integrated to a nonlinear plant. The introduced system were able to handle the disadvantages of the PID control system effectively when handling plants that has unknown parameters or affected by uncertain or unpredictable environmental change.

In (Yang, 2018), a sliding mode control technique that employs a nonsingular terminal with time-specified is introduced. The introduced system is integrated within a robotic airship in order to track a trajectory. The simulation outcomes elaborated the efficiency of the proposed control scheme which effectively avoided the singularity problem which is existed within sliding mode controllers.

(Golestani, Ahmadi, & Fakharian, 2016) introduced a new guidance system to solve the problem of tracking a maneuvering target. The dynamics of the autopilot model have been implemented as a transfer function of the first order. The results of simulation for the proposed control system showed promising performance and effectiveness for the introduced guidance system against maneuvering targets.

In our research, instead of linearizing the autopilot dynamics, we used an intelligent tuning technique for our fractional order PID that doesn’t require any linearization and the resulted fractional order PID controller proved to have much more accuracy against the maneuvering target which has a miss distance value near to zero.

(H. Sun, Yu, & Zhang, 2016) created an optimized control to examine the effect of the non-linear tracking and decoupling that exists within the roll motion. The improved system is implemented using flight path linearization control design and an enhanced control technique that established by separating the time-scale. The results of this research proved the efficiency of the proposed adaptive system in maintaining the tracking ability, robustness and accuracy of the missile which is exposed to uncertainty, noises and external disturbances.

In (Su et al., 2016), an enhanced guidance law is introduced for the problem of approximating the acceleration demands of the PN controller. The experimental results proved the efficiency of the introduced controller.

(Kim, 2016) showed a PID control scheme that is integrated to the proportional navigational guidance of a missile. The aim of employing this controller is to enhance miss distance of the PN system, however, the PN system is described as a non-linear plant, and the performance of the PID for such non-linear systems might be unsatisfactory. For that reason, we proposed the employment of FOPID which considered to have better performance compared with the integer order one.

Some of the previously mentioned methods that employs the standard PID controller require to linearize the system at multi operating points, and use a specialized PID controller for each operating point. However, it has been proved in literature that one Fractional Order PID is usually sufficient for dealing with nonlinear systems unlike the Normal PID controller. Therefore, we used a single Fractional order PID in most of our proposed designs and proved the accuracy of this system in stabilizing the missile during the whole flight time.

(Raj & Ganesh, 2015), examined the noise and disturbances influence on PN system. To enhance the signals quality, they proposed a specialized memory system, that is assumed to have better efficiency than Kalman filters.

In the research introduced by (Viswanath, Krishnaswamy, & Deb, 2015), a study on utilizing the LOS angular rate and the distance formulated by the missile and the target is introduced to be employed in the PNG system by creating nonlinear equations. In this study, the researchers concluded that the target’s acceleration is obscure and it should be computed by a specific observation system, the stability of the control system is verified by calculating the miss distance value, which showed a value of approximately zero.

(Cho, Kim, & Tahk, 2016) investigated the problem of maneuvering targets. They have introduced a model of short-range missile and it’s assumed to have the same target’s acceleration. In that research, an adaptive controlling system is implemented to calculate the tangential portion for the acceleration of the target. The suggested guidance process is simulated against other guidance systems by removing the influence of noise, and the outcomes yielded better system that the other simulated methods.

The research introduced by (Golestani et al., 2016), contains a guidance system that employs a controlling loop in order to collide with a target that has an evasion capabilities. The introduced fractional order system proved to have better efficiency over the integer one for this problem. In this study, the dynamics of the autopilot system is investigated as a transfer function of the first order. The capabilities of this introduced guidance law is verified by testing the system against targets with high evading capabilities.

In (Qilun et al., 2016), a dual stage method is proposed for handling cooperative attacks, for that purpose, a cooperative law procedure is employed on many missiles and they left to communicate with each other. Proceeding to this stage, the missiles were allowed to disconnect with each other, and they tried to collide with the target without any form of cooperating between themselves. The test outcomes verified the capabilities of the proposed law for intercepting the target.

In (Feng, Wang, Liu, & Cai, 2017), the author analyzed three variables that influence the missile’s tracking accuracy. The variables that were studied by these scientists were the latency of the information, the deviation of the proportional guidance coefficient, and the noise existed within the measurements. The resulted simulations confirmed that the impact of these parameters on the tracking accuracy of the radar is extraordinary.

In (Wang, Lin, Wang, & Cheng, 2010), the author introduced comparisons between three navigational guidance systems in terms of miss distance value, these systems are: BP, VP, and PN. The comparison between these systems is employed when these systems are exposed to some noise such as target glint, heading error and angular noise. They have also studied the implementation of these systems and the influence of these variables on the miss distance value. The outcomes of this research confirmed that the VP and BP laws produce more accurate miss distance values than applying the proportional navigation guidance just when the missile is affected by target glint and angular noise.

(Zhe, Jiabin, Chunlei, & Hongye, 2017) introduced a new control scheme based on proportional integral derivative controller in conjunction with fuzzy control system that is employed to a radar. This combined system proved the ability of the fuzzy system to increases the robustness of a proportional integral derivative system in controller a radar under the influence of noise.

(Lin & Lin, 2014) showed a new intelligent technique that employs neural network techniques for guiding a missile that is exposed to noise. These error factors include target maneuver, fading noises and glint. The introduced law was simulated against the standard PN law. It is verified by the outcomes that the introduced intelligent technique produced better miss distance for all scenarios.

In our work, we have used many intelligent tuning techniques such as particle swarm optimization, genetic algorithm, and neural tuning techniques and applied it to our FOPID system. We have also compared between these techniques and introduced a novel neural based tuning method that provided a very accurate tuning for the fractional order PID.

(El-Sousy & Abuhasel, 2016) introduced a smart tuning scheme based on H2/H∞ technique used to control a two-axis trajectory. Three controlling types were presented that employed a special type of neural networks called (SORFWNNC). Two controllers with H_2/H_∞ process as well as a third one was employed to optimize the robustness of the system. The SORFWNNC technique is employed to be the main controlling system to evaluate the dynamical parameters as well as the disturbances and noise. the H_2/H_∞ controller is used to minimize the quadratic error and the robust type controller is designed to tackle the error of approximation. The experimental simulations verified the efficiency of the proposed system in following a reference in the existence of disturbances and noises.

In (Pan & Shen, 2016), the H_2/H_∞ based system is implemented to helicopter with 3-DOF. The H_2/H_∞ controlling strategy is employed with a weighting strategy for the parameters to compensate for the variations in the elevation angle. By employing these control laws, the dynamics efficiency as well as the controlling precision are both enhanced.

In (Sumardi, Sulila, & Riyadi, 2017), (PSO) algorithm is used in order to optimize a PID controller which is employed to a UAV system. The performance of the employed procedure is examined without and with the presence of disturbances. The simulation outcomes proved the accurate ability of the introduced system within flight.

(Babu, Das, & Kumar, 2017) the gradient decent algorithm is employed to enhance PID parameters of control system online that is employed to UAV system. The introduced control system is examined with waypoint navigation system, and with the help of leader follower controller.

The research in (Emam & Fakharian, 2016) introduced a mixed H_2/H_∞ robust tuning procedure that is implemented to a feedback system. This controller is employed to control a quadrotor unmanned aerial vehicle. The controlling signals are affected by noises as well as error sources. To optimize the H_2 and H_∞ based control procedure, the Linear Matrix Inequalities (LMI) is implemented to enhance the system, which is considered a multi-objective convex problem. The simulation results of the controlling strategy resulted in excellent efficiency especially in the presence of disturbances and noise.

In (Lee, Lee, Kim, Moon, & Jun, 2016) a research on adaptive autopilot intended to control a skid-to-turn missile. In this research, the state-dependent Riccati equation is used along with the neural networks (NN). The inertial and velocity parameters of the system is supposed to be varying with time and an autopilot system is employed with two-loop implementation to control the yaw, pitch and roll motions. The controlling system is implemented by SDRE method for following the reference, and the adaptive control method is implemented by NN approach to manage the uncertainty presented during optimization. The efficiency of the proposed control scheme is verified and demonstrated by numerical simulation.

In (J. Sun & Liu, 2018) a robust optimal control for controlling the longitudinal dynamics of the missile under disturbances is introduced using adaptive dynamic procedure. The variables are modeled using smooth functions, then nonlinear disturbances are designed. The output of the disturbances is observed and a controller with integral sliding mode is implemented to cancel the influences of the disturbances and the approximation error for the unknown variables to ensure smoothness of the system. The adaptive dynamic method is used to implement the adaptive optimal controller with novel weight update law. The stability and performance of the closed-loop system and the estimated weight efficiency in stabilizing the system is guaranteed by using Lyapunov's method. The effectiveness and feasibility of the introduced control system are verified using the longitudinal of the missile dynamics.

The research in (Z. Guo, Zhou, & Guo, 2017) focuses on designing a robust autopilot system for controlling a bank to turn (BTT) type using a proposed dual layer sliding mode adaptive control system. The model is supposed to be exposed to external disturbances along with uncertainties. The constructed control system is a dual layer system in which one layer is responsible for driving the system to the requested sliding surface in certain time, while the job of the other layer is to reduce the control gain value. The proposed controlling method is compared with the classical one named as super-twisting method. The results showed promising performance along with high robustness to the proposed controlling system.

In (Tian, Lin, Wang, & Li, 2017) the stability of three-loop autopilot feedback system based on angle of attack (AOA) is applied on rolling missiles that is exposed to parasitic effect which is caused by the radar radome slope. The analysis results of the parasitic effect showed that another feedback loop is existed in the navigation guidance control system, which will dramatically affect the dynamic of the missile and will degrade the rolling stability of the missile. Using differential equations which are implemented in complex form, the stability conditions for the three-loop autopilot system with angle of attack (AOA) feedback loop is obtained and the simulation results showed the effect of the proposed stability condition compared with the conventional design.

In (Zhao, Shi, & Zhu, 2018) a new method for building autopilot system by an adaptive control system is used to tackle the uncertainties presented in the system and the variables of the moment. By this research a coupled and nonlinear six degree of freedom (6 DOF) structure is built and used to compute the effectiveness of the introduced adaptive autopilot system in the flight time. Then a method based on linear matrix inequality (LMI) and square up strategy is introduced to implement the autopilot system with an adaptive feedback output law is implemented to the 6 DOF model which proved to have stable tracking ability for system presented with uncertainties.

In (Ra, Kim, & Suk, 2017) an adaptive controlling with sliding mode is presented for controlling a skid to turn type missile that is exposed to uncertainties. By this research, the velocity of the missile and the air density are considered to be fast varying, and the aerodynamic coefficients are implemented using look-up tables. Numerical simulations applied on skid to turn missile with high maneuvering ability proved the effectiveness of the tracking performance for the proposed model compared to the linear model.

In (Padhi, Sirisha, & Sarkar, 2014) a nonlinear autopilot system implemented to a tactical flight vehicle is designed and analyzed for surface to air application. By this research the lateral of the autopilot is designed using the principle of dynamic inversion with time scale separation. The autopilot control process for roll motion is designed using back stepping technique. The test outcomes verified the efficiency of the introduced nonlinear pursuer, which simulated using six degrees of freedom applied for the evader and pursuer engagement.

(Hartzstein, 2016) studied the glint noise as a major source of noises that affects the radar system. By this investigation, the averaging process is not efficient for canceling this noise, and due to that, the scientists applied new law which depends on creating some weights and averaging them. By this technique the noises produced by large targets can be removed and canceled.

In (Solomon Raj & Krishna, 2015), Kalman filter is introduced to improve tracking procedures applied for aggressive and slow targets. The tracking radar system was developed based on these tracking algorithms and simulation aimed to find minimum tracking error.

In our work, we introduced the fractional order PID system that works as an accurate and efficient controller as well as a noise suppressor, we examined three noises and error types: Receiver noise, Radome aberration error, and time delay. The simulation results proved that our proposed system proved to have a very effective controlling as well as noise suppression properties.

3. BACKGROUND

3.1. Missiles Classifications

In literature, there are many ways of classifying guided missiles. The classification process of guided missiles is based on their properties such as range, type of target, control system type, aerodynamics, propulsion system, type of guidance system, launching system.

According to the target type which the missile is prepared to counter, the missile systems could be classified into:

- Anti- missile
- Anti-tank/anti-armor
- Anti-helicopter/ Anti-aircraft
- Anti-personnel
- Anti-ship/anti-submarine
- Anti-satellite

Another popular classification method is based on launching method. According to this classification type, the missiles could be divided into:

- Surface-to-surface-missiles (SSM)
- Surface-to-air missiles (SAM)
- Air-to-surface missiles (ASM)
- Air-to-air missiles (AAM)

Although Surface-to-surface missiles are usually used for ground-to-ground, it also could be used from ship to another one. Missiles that are used under the sea usually shot from submarines are considered as surface-to-surface missiles (SSM).

Depending on launching method, missiles could be classified as:

- Aircraft/helicopter-borne
- Land mobile (wheeled vehicle or tracked vehicle)
- Shoulder fired / tripod launched
- Space based (Star Wars concept)

According to the used guidance system, missiles could be classified as:

- Inertial navigation guidance
- Homing guidance
- Beam rider guidance
- Command guidance

According to the aerodynamic system used to control the missile, a missile is called:

- Tail controlled
- Wing controlled
- Canard controlled

Based on the trajectory type of the missile, the missiles could be divided into:

- Cruise missile
- Ballistic missile

A missile is called ballistic missile when most of the operating range of the missile is outside the atmosphere. In this working range, the only force exerted on the missile's body is the earth gravity. A missile is called cruise missile if the entire working range of the missile in inside the atmosphere which usually have constant speed and height. Some kind of missiles could have both types, by which the missile could have some of its working range in the ballistic mode, and then it could change to cruise mode during terminal part.

There is also classification based on the propulsion method used to fire the missile, according to this classification we have:

- Scramjets
- Ramjets

- Gas turbine engine

Also, there are other types of propulsion techniques that are still under research, but until now there is no specific kind of missiles known for using these techniques. Some of these propulsion techniques that are under development are: nuclear, ionic, and plasma propulsion systems.

3.2. Missile Guidance Systems

Guidance system is responsible for deciding the movement direction of the missile, this usually has to be computed in a very short time (1/50 second) during the flight time of the missile. There are many guidance techniques applied on the missiles, the main guidance types are:

3.2.1. Command Guidance

By this method, the instantaneous locations of the missile and target are computed at ground station, and then its transmitted to the missile by the mean of wire link, fiber optics and radio signals. The wire link could be wound on a spool which is placed on the missile's body, and then it's unreeled while the missile flies toward the target. This method is usually used in surface to surface anti-tank missiles, which the distance is less than 4 kilo meters. The radio signals transmitting method is used when the missile movement is relatively fast, and that is usually applied for anti-aircraft missiles. Fiber optics are employed when the velocity of missile is less than Mach 1 (the sound velocity), in other words, lower than 300 m/s, so, a TV camera could be placed at the nose of the missile, and fiber optics are used to carry the information obtained by the missile to the launch station which it can be processed and then sent back to the missile by the same link. The exact positions of the missile and target are computed at the ground station which can locate the instantaneous locations of the missile and target using infrared sensors, TV, or radar located on a ground station, and then the information is transmitted to the missile. So, the deflection of the missile from the path between the launcher and the missile, which is also called the line of sight (LOS). This LOS is corrected by the missile actuators.

One of the disadvantages of using this type of guidance is it can only handle a specific number of missiles, and therefore it can’t be used for multi-target situations. The advantage of this type of guidance is that there is just small number of guidance devices needed to by the missiles’ body, as most of the guidance computations that involve target tracking and path planning are done at the ground station. So the missile will have more space for warhead, or the size of the missile will be reduced which will reduce the overall cost of the missile (Palash Choudhari, Varun Karthikeyan, & Anoop Madhavan, n.d.).

3.2.2. Beam Rider System

By this system, an antenna is used to point at a target by radiating a beam of energy toward that target, then the missile is fired toward that beam. After the missile enters the beam area, the control system associated with the missile will work on keeping the missile at the center of that beam. During flight time, if the missile deviated from the center of the beam, then the displacement error is calculated and then the control system on the missile will work on bringing the missile’s body to the center of the beam until it hits the object.

The most important advantage of this type of guidance system, is its simplicity, as there is no complex equipment needed for guidance. However, the drawback of this system is that during terminal phase, the missile needs high lateral acceleration to hit the target (Debnath, 2016a).

3.2.3. Stellar Guidance

This type of guidance utilizes celestial bodies as a reference for guiding the missile, the stellar guidance is usually established with the inertial guidance system.

3.2.4. Inertial Guidance

By this navigation system, computers, accelerometers and gyroscopes are used to guide the missile. The purpose of the accelerometer is to provide readings about the change in the velocity of the missile (acceleration).

Gyroscope measures the turning rate of the missile. The computer processes the information gained from the accelerometer and the gyroscopes, and then send it to the guidance system to the missile’s navigation system.

The inertial navigation systems could be classified into the following categories:

- Strap down guidance systems.
- Gimbaling guidance systems.

In gimbaling inertial guidance system, three gimbal-mounted gyroscopes are used to provide a reference frame for the missile’s yaw, pitch, and roll rotations.

The accelerometers measure the velocity rate (acceleration) in each one of these directions, and by integrating the acceleration, the velocity is obtained, another integration is implemented to obtain the exact position of the missile.

In the strap down inertial guidance system, three accelerometers are placed on the missile, each one of them is placed in the direction of one of the missile’s axes, gyroscopes are employed to provide readings about the turning rate of the missile instead of providing a stable platform as in the gimbaling inertial guidance system. The readings for the accelerometers are then fed to the computer which performs double integration. The first integration is used to gain the velocity form the acceleration, and the second integration is used to gain the distance from the velocity. Also, an integration could be performed on the gyroscopes readings to obtain the direction (angle) from the turning rate of the missile. So, the exact missile’s location could be determined (Charles Stark Draper, n.d.).

One of the main advantages associated with the inertial guidance system is that there are no electromagnetic emissions from the missile, which might be detected by an anti-missile and then used against it.

3.2.5. Homing or Seeker Guidance

This guidance type is usually applied for short range missile, by which the missile utilizes the reflected or emanating signals from the target. Using these signals, a LOS is formed by the missile and the target, and then the transmission of the commands are started in order to rotate the missile toward the target and keep it on the line of sight.

Homing guidance could be divided into the following types:

- Passive homing guidance
- Active homing guidance
- Semi active homing guidance

In active homing guidance, both the receiver and the signal source are placed on the missile itself, the missile radiates the electromagnetic waves form the source toward the target, then it receives the reflected signal by the receiver. So, the missile will compute the line of sight, and then generate commands to the control system to follow this LOS until the missile hits the target. In active homing, the missile is not dependent on the signals transmitted from a ground station neither from the target, instead it generates all signals that it needs and then receive the reflected one.

In semi active homing system, the source of the signals is placed on a ground station, and the ground station emanates the signals toward the target, then the reflected signals from the target are received by a receiver placed on the missile and the missile will compute the LOS formed by the target and the missile.

In passive homing guidance, neither the missile nor the ground station emanates the required signals for the missile, instead the target itself emanates those signals and the missile receives these signals by the receiver and generates the required guiding commands to track the source of these signals (target). By comparing the inertial guidance with the homing guidance, the inertial system is found to have good accuracy for long-range missiles in case that the target is a known coordinate on the earth, but when the target is unpredictable such as air craft, cruise missile, or any other target that its location is unknown at the launch time of the missile. So, in order to intercept such kind of targets, a real time sensing of the location of the target, a fast reaction time is required from the defending missile.

The most accurate one over all the other mentioned guidance systems above is the homing guidance, by which the target information quality increases as long as the missile got near to the target, while in the other guidance systems, the signal quality of the target decreases as the missile closes in.

sometimes more than one guidance system could be applied on the missile depending on the phase of guidance. There are three major guidance phases:

- Launch phase.
- Mid-course phase.
- Terminal phase.

3.3. Missile Sensors

The purpose of the guidance system in the missile is to track a target. There are many methods used to locate the target and feed the missile with information regarding the position of that target. Some of these methods are: radio or radar beams, light, heat, television, Loran and the magnetic field of the earth.

electromagnetic sources also could be used to aid in guiding the missile, in this case an antenna with a receiver together are used as a sensor and installed in the missile’s body to catch the signals which are used to guide the missile toward the target. If other than electromagnetic waves used for sensing the target, then other types of sensors should be used, but all of them should act as providing the missile with information regarding the target position.

There are many factors affects the choice of the used sensors, some of these factors are: operating conditions, maximum operating range, minimum required accuracy, size and weight of the sensor, the type and speed of the target, and the viewing angle.

3.4. Flight Controller

The process of choosing the right controlling type is dependent on many such as: packaging constraints, cost and overall system mission. Also the type of flight controller could be influenced by the flight phase of the missile, as for each flight phase, a different suitable flight control could be chosen. For example, when using the ship- or ground-launched missile, the flight control system that is used during boost phase could be too much different from the flight control system that is used for intercept phase. The following contains an overview of flight control systems and when each one of them might be used.

3.4.1. Acceleration Control System

This type of flight control systems is usually used in endoatmospheric applications, which is used to track the acceleration demands perpendicular to the missile. By this flight control system, the aerodynamic surfaces used to control the missile such as the tail fin is taken as the controller input, then the acceleration and pitch angular rate are measured by the IMU in order to feed it back to the autopilot system. The force produced by the deflection of the aerodynamic surface which controls the missile is small on the tail, but this force is amplified on the missile’s airframe due to the lever arm applied distant from the center of mass of the missile. This will induce a moment that is responsible for rotating the missile and producing angle of attack which is necessary for lifting the missile. Figure 3.1 shows the equations that might be applied in the autopilot to produce the commands of the deflection angle based on the demanded acceleration and the measurements of the pitch rate (q) and the measured acceleration of the missile which are fed back to the control system. As seen in the figure, the error calculated by finding difference of the measured acceleration and the demanded one, then it is entered to the inner loop of the controller. Then it is used for controlling the rate of change of the missile’s pitch. The mathematical processes appear in the figure include integrations with respect to time which could be done for an analog autopilot system using specialized circuitry, or using numerical difference equations on computer for digital autopilot system. The controller gains are selected to keep the robustness of the closed-loop flight controller. and consistent with the design specifications such as actuator limits, as well as achieve the required response speed. The feedback control system presented in Figure 3.1 is an initial design that we might begin with, but other features should be added to make it more suitable for real missile control systems such as adding noise filters to attenuate the noise cause by IMU and the missile vibration.

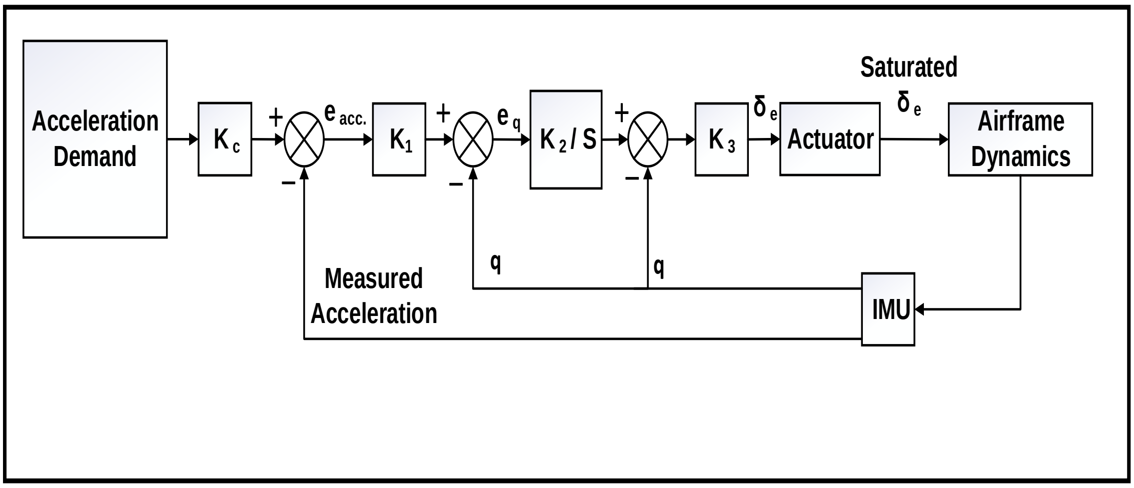

Figure 3.1. Control of acceleration.

This block diagram demonstrates the classical approach to the implementation of an acceleration control autopilot. As the figure shows, the difference between the measured acceleration and the scaled input acceleration command is multiplied by the gain in order to create a pitch rate signal. The difference between the effective pitch rate signal and the readings of pitch rate signal is entered to a gain and then integrated. After this process, the resulting value from the integration is differenced with the measured rate of pitch and then entered to a gain in order to create the control signal that could possibly achieve a desired tail-deflection angle. With this process, the purpose of providing a gain to the input acceleration command is to provide zero steady-state error associated with the constant acceleration command inputs. After that, some aspects could be considered for the final autopilot design, such as adding noise filters as well as actuator command limits. This structure is called the three-loop autopilot system.

3.4.2. Attitude Controller System

Figure 3.2 is another control method for autopilot that is used for controlling the attitude of the missile. By this controlling method, the attitude of the missile could be modified by changing the thrust deflection angle, which is actuated by jet tabs or nozzles. The structure of this autopilot control type is following the same of the previous autopilot controller presented in Figure 3.1, but the outer loop of the control system contains the pitch-angle instead of the acceleration as a feedback.

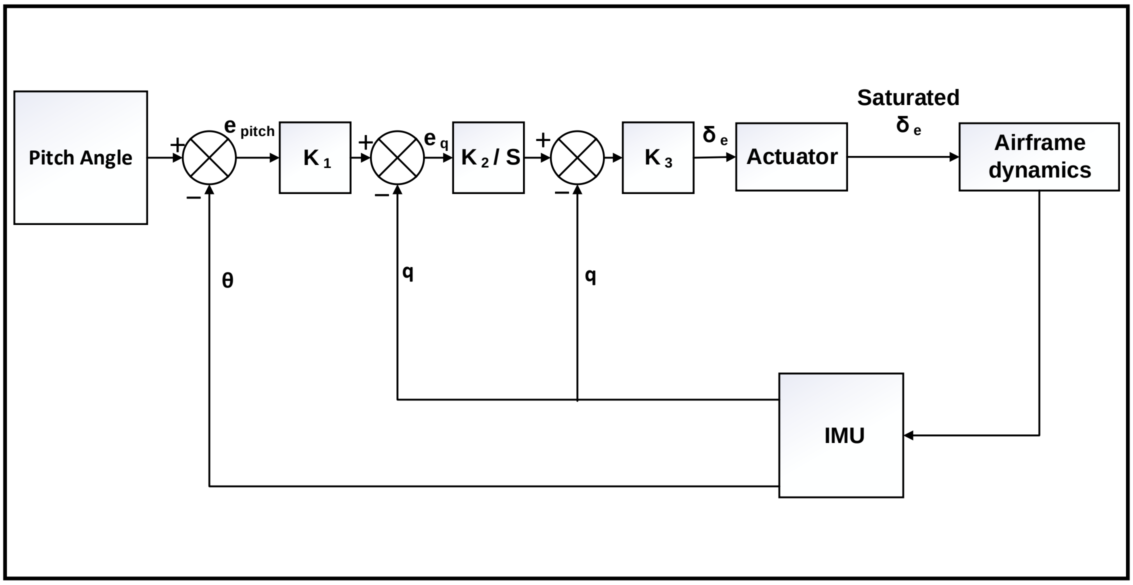

Figure 3.2. Control of attitude.

3.5. Proportional Navigation

Proportional navigation is considered as a guidance system that works on finding a normal acceleration (a_m) that has a relationship with the distance between the Line of Sight (LOS) and the aerial system, so, the missile movement direction will be on the direct path toward the target. In other words, by the proportional navigation system, the missile will always be on the LOS and when the target rotates, the missile will have the same rotation rate of the LOS. This could be more elaborated as presented in Figure 3.3 which elaborates the kinematics of the PNG system where the missile point location is far from the LOS. A normal acceleration a_m is exerted on the missile for aligning the LOS and the missile together. This lateral acceleration is related with the distance separating the LOS from the missile.

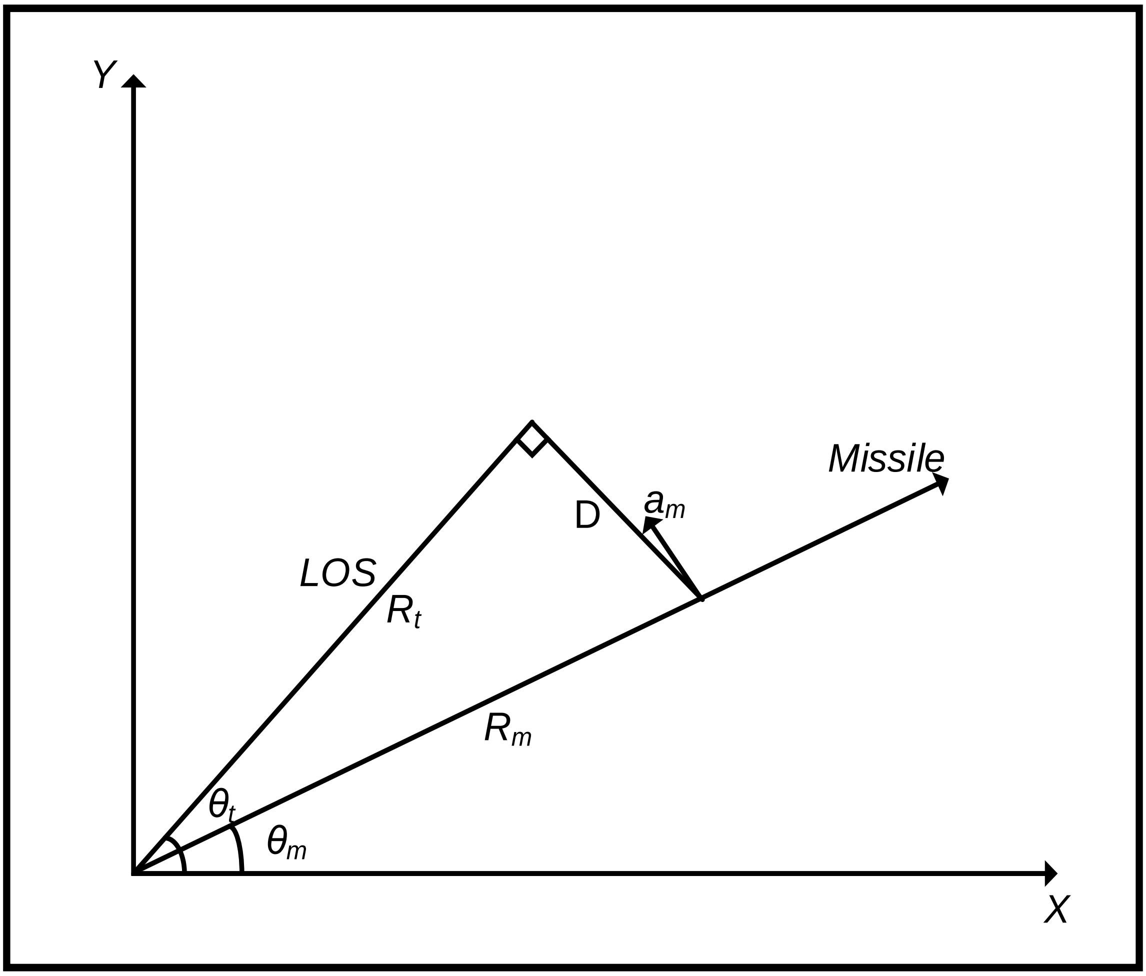

Figure 3.3. Kinematic model for the PNG.

The normal acceleration value a_m could be calculated using equations (1) and (2) as follows:

$$a_m = KD \tag{1}$$

$$a_m = KR_m sin(\theta_t - \theta_m) \tag{2}$$

where *D* is the distance separating the LOS from the missile, *K* represents a constant value, θ_m is the angle formed by the reference axis and the missile, θ_t is defined as the angle formed by the reference axis and the target.

The kinematic model of the PN system with stationary tracker applied for the target and the missile is presented by Figure 3.4.

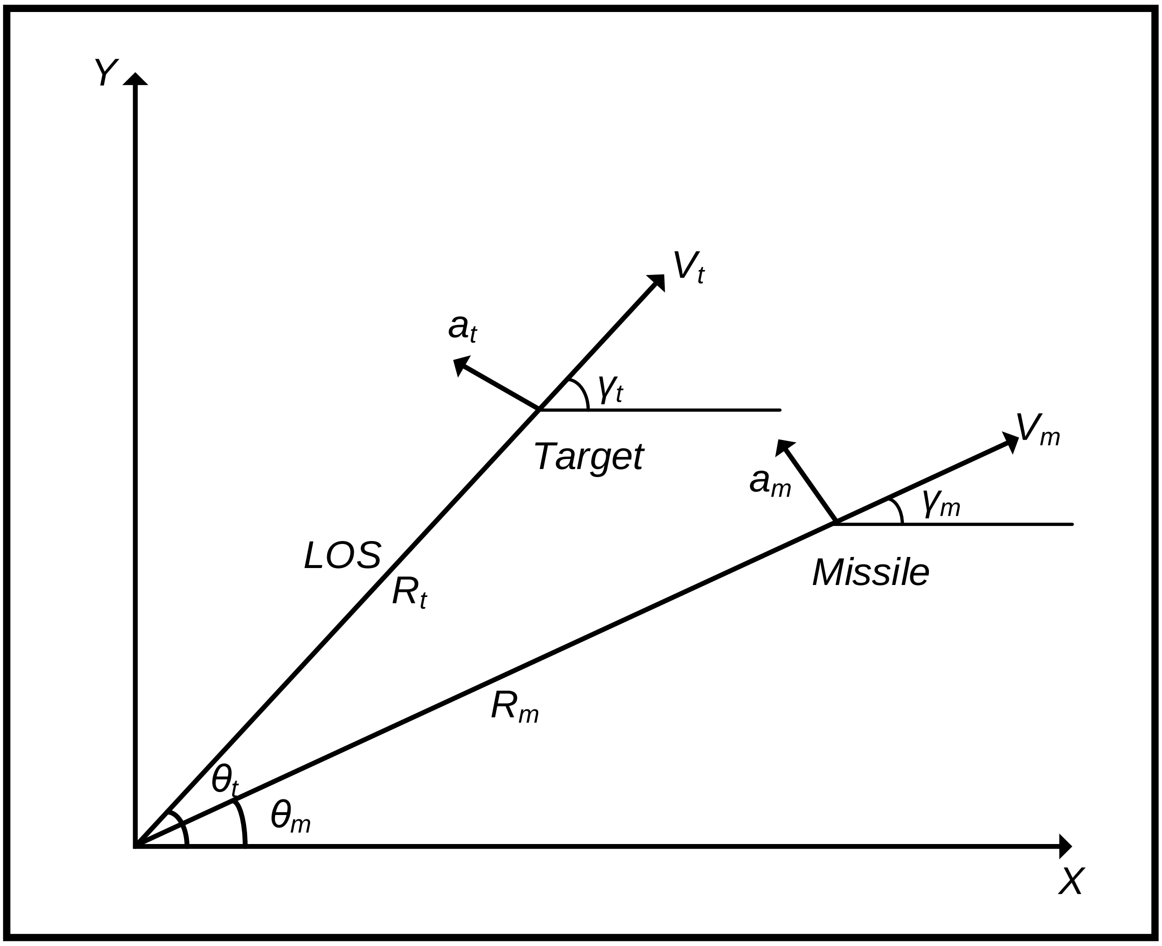

Figure 3.4. Kinematic model of the proportional navigation with relative to a stationary tracker.

Missile kinematics are elaborated in the equations below:

$$\frac{dR_m}{dt} = V_m cos(\gamma_m - \theta_m) \tag{3}$$

$$R_m(\frac{d\theta_m}{dt}) = V_m sin(\gamma_m - \theta_m) \tag{4}$$

$$V_m(\frac{d\gamma_m}{dt}) = a_m \tag{5}$$

where R_m is the distance existed from the tracker to the missile, θ_m represents the angle formed by reference axis and the missile, a_m is the lateral acceleration exerted by the missile's body, γ_m is defined as the angle formed by the direction of movement of the reference axis and the missile's body, V_m is defined as the missile's velocity. The equations of kinematics for the target are elaborated in the following equations:

$$\frac{dR_t}{dt} = V_t cos(\gamma_t - \theta_t) \tag{6}$$

$$R_t(\frac{d\theta_t}{dt}) = V_t sin(\gamma_t - \theta_t) \tag{7}$$

$$V_t(\frac{d\gamma_t}{dt}) = a_t \tag{8}$$

Where V_t is the target's velocity, R_t is the distance formed from the target to the tracker, θ_t is the angle existed by the reference axis and the tracker, a_m is the lateral acceleration exerted on the target's body, γ_t is the angle formed by the reference axis and the missiles' movement path.

To align the LOS and the missile with each other, a specific lateral acceleration a_m should be exerted on the missiles' body as elaborated by these equations:

$$a_m = (d(R_m(\frac{d(\theta_t - \theta_m)}{dt}))/dt) + (\frac{dR_m}{dt})(\frac{d(\theta_{t-}\theta_m)}{dt}) \tag{9}$$

$$a_m = R_m\left(\frac{d^2(\theta_t - \theta_m)}{dt^2}\right) + \left(\frac{dR_m}{dt}\right)\left(\frac{d(\theta_t - \theta_m)}{dt}\right) + (\frac{dR_m}{dt})(\frac{d(\theta_t - \theta_m)}{dt}) \tag{10}$$

$$a_m = R_m(\frac{d^2(\theta_t - \theta_m)}{dt^2}) + 2(\frac{dR_m}{dt})(\frac{d(\theta_t - \theta_m)}{dt}) \tag{11}$$

By substituting $V_m = \frac{dR_m}{dt}$ in (11) we get,

$$a_m = 2V_m(\frac{d(\theta_t - \theta_m)}{dt}) + R_m(\frac{d^2(\theta_t - \theta_m)}{dt^2}) \tag{12}$$

This is the final equation that we could use for finding the normal acceleration for a missile with stationary tracker.

3.6. Dynamics Equations of the Missile.

The dynamics equations of the missile are designed using Simulink. To calculate the location and motions of the missile, the moments and forces applied on the missile should be obtained first, in order to do that, the following equations could be used for that purpose:

$$F_z = C_z(0.5\rho V^2 S_{ref}) \tag{13}$$

$$F_x = C_x(0.5\rho V^2 S_{ref}) \tag{14}$$

$$M = (C_m + q)(0.5\rho V^2 S_{ref} * D_{ref}) \tag{15}$$

Where V is the missile's movement velocity, M is the pitch moment exerted by missiles' body, F_x is the missile's exerted force on the x-axis, F_z is the missile's exerted force on the z-axis, C_x and C_z are considered as coefficients that are stored in a lookup table, the value of these coefficients are related to the missile's pitch angle and missile's speed, S_{ref} is reference of the missiles' cross-sectional area, D_{ref} is the missiles' circular body diameter. Then, the moment and forces are applied in order to acquire the exact location of the missiles' body as shown in the following equations:

$$A_z = \frac{F_z}{m} - qv_z - gsin(\theta) \tag{16}$$

$$A_x = \frac{F_x}{m} - qv_x - gsin(\theta) \tag{17}$$

$$\dot{\theta} = q \tag{18}$$

$$\dot{q} = \frac{M}{I} \tag{19}$$

Where θ is the missile's attitude, A_x is the x-axis missile's acceleration, A_z is the z-axis missile's acceleration, m is the mass of the missile's body, q is the missile's rotation rate, v_x is the velocity exerted on the x-axis, v_z is the velocity exerted on the z-axis, I is the missile's inertia while g is the force of gravity that affects the missile.

3.7. Fractional Calculus

It is a mathematical science that computes the differentiation and integration in a non-integer order and obtaining its definition by approximating it using integer order functions. The famous PID controller is known to be one of the most controlling type employed in industrial applications. This is because of the high availability for many procedures specialized for parameters tuning of the controller, also applying this controller to many kinds of industrial systems is an easy thing to achieve. In control systems theory, the definition of the normal PID could be evolved to fractional order type by employing fractional orders derivation and integration as elaborated in the following equation:

$$C(s) = \frac{D(s)}{U(s)} = k_p + \frac{k_i}{s^{\lambda}} + k_d s^{\mu} \qquad (20)$$

where μ and λ are the fractional orders of differentiation and integration respectively. The normal PID controller design process contains tuning of three parameters, however, the fractional order PID contains two more parameters to be tuned.

The fractional calculus history began in 1695 when G. de L'Hospital sent a letter to G. Leibniz and asked him to explain the fractional order derivation (e.g. $d^{1/2}/dx^{1/2}$), regarding that question, G. Leibniz answered by: "it will lead to a paradox, from which one day useful consequences will be drawn" (Gonzalez & Petras, 2015). As a consequence of these letters, many mathematicians began to search on this field. Among those scientists, there are Liouville and Euler who introduced many significant contributions to the fractional calculus field. However, the investigation conducted on the fractional calculus principles was rare until recent decades where the relationship between integrals and derivatives are shown by the theory of fractals and chaos, (David, Linares, & Pallone, 2011). Fractional calculus could be defined in order to generalize the integer order integration or derivation by presenting the differintegration operator. This new operator is denoted by ${}_{\mathrm{a}}\mathrm{D}_t^{\alpha}$ and it makes the derivation and integration to be implemented with non-integer order. In this operator presentation, α is defined as differintegration order, while *a* is the initial value and *t* is the variable over which the differintegration is conducted. The definition of the differintegration operator with in terms of derivation or integration is elaborated in the following equations:

$${}_{\mathrm{a}}\mathrm{D}_t^{\alpha}\mathrm{y(t)} = \begin{cases} \dfrac{d\mathrm{y(t)}}{dt^{\alpha}}, \alpha > 0 \\ \mathrm{y(t)}, \alpha = 0 \\ \displaystyle\int_a^t (\mathrm{y}(\tau)d\tau)^{\alpha}, \alpha < 0 \end{cases} \qquad (21)$$

There are several definitions for this operator in the literature for approximating the differintegration operator; the most famous approximations for this operator are presented by three widely used methods. Riemann-Liouville (RL) as shown in the following equation presents the first one of these approximations:

$$ {}_{\mathrm{a}}\mathrm{D}_{t}^{\alpha}\mathrm{y(t)} = \frac{1}{\Gamma(n-a)}(\frac{d}{dt})^{n}\int_{a}^{t}\frac{y(\tau)}{(t-\tau)^{\alpha-\mathrm{n}+1}}d\tau \qquad (22) $$

Grünwald-Letnikov (GL) presents another commonly used approximation method, which is an approximation in the discrete time for the differintegration operator. The Grünwald-Letnikov approximation could be defined in the following equation:

$$ {}_{\mathrm{a}}\mathrm{D}_{t}^{\alpha}\mathrm{y(t)} = \lim_{h\to 0}\left(\frac{1}{h^{\alpha}}\right)\sum_{m=0}^{\left[\frac{t-a}{h}\right]}(-1)^{m}\frac{1^{\eta}(\alpha+1)}{m!\,\Gamma(\alpha-\mathrm{m}+1)}y(t-mh) \qquad (23) $$

While both (GL) and (RL) are considered to be good but recently (Caputo definition) the third one is considered to be better for many reasons such the ease of applying this method to industrial applications where the initial conditions have only integer orders (David et al., 2011). The differintegration approximation introduced by Caputo approximation could be shown in the following equation:

$$ {}_{a}\mathrm{D}_{t}^{\alpha}\mathrm{y(t)} = \frac{1}{\Gamma(n-a)}\int_{a}^{t}\frac{y^{(n)}(\tau)}{(t-\tau)^{\alpha-\mathrm{n}+1}}d\tau \qquad (24) $$

The transfer function for this operator is implementable using Laplace transform and this could be defined as $L(D^{\beta}) = s^{\beta}$, where L expresses Laplace transform operation while s represents Laplace variable (Efe, 2011). These mentioned techniques are not the only techniques used for defining the fractional order, in literature there are many other famous techniques such as Oustaloup's approximation which has a very high degree of accuracy, therefore we chose this technique to implement our FOPID controller as elaborated in this dissertation. it’s better to use the FOPID controller rather than the integer one because of the advantages that it has in terms of performance, robustness and stability (Pradhan, Patra, & Pati, 2016). Fractional order PID also capable of handling the system variation and uncertainties. It has also the ability to deal with the disturbances of the load. FOPID can reject and cancel the environmental noises more efficiently than the integer one (Edet & Katebi, 2016). Fractional order PID also shows an outstanding performance when there are time delays existed within the system. Moreover, when using the PID for dealing to control a nonlinear system, we should linearize this system at multi points, and then assign a specialized integer order PID to handle the control at each of these points. However, its stated that one fractional order PID could be able to handle such a problem alone in many cases. (Shah & Agashe, 2016).

3.8. Noise and Error Sources

missile tracking and hitting accuracy is of the most research topics that is taking the interest of the researchers around the world. Miss distance value is considered one of the most significant criteria that measures the performance of missile tracking and hitting accuracy. However, missile accuracy that is dependent on miss distance (MD) can be decreased by many factors. signals and communication issues are examples of these factors that affects the tracking and hitting accuracy of the missiles. Solving these problems is very important for the defender missile, otherwise it will not be able to achieve its assigned mission for intercepting flying targets in real time with high accuracy. To overcome these problems that belongs to the communication issues, some procedures are presented in the literature and applied for solving these issues. In most of these applied procedures, signal filtering is of the most followed procedure that is intended to solve the effects of the disturbances. Using filtering procedures is very useful for radar signals especially when there are refractions or delays affects the received signals. However, these filtering approaches are not intended to deal directly with the tracking performance of the missile, but using special kinds of controlling systems could decrease the noise effects, increase the tracking performance of the missile, and decrease the time delay influence on the response of the missile. This will lead to better target tracking hitting accuracy as well as lower miss distance (MD) values.

3.8.1. Missile Radome Aberration Noise

In the design process of homing missiles, a radome is implemented at top of the missile over the radar location to provide some protection for the missile against air drag forces that is caused by the movement of the missile. The electromagnetic signals produced by the radar is usually passed through this radome. But the electromagnetic signals could face refractions when passed by this radome, that is, if the radome shape is anything other than hemispheric, the signals will be refracted, if the of the radar radome is hemispheric, that’s the best case for electromagnetic signals where the signals will not face any refractions, but the radome itself and the speed of the missile will increase the value of drag forces dramatically. To overcome this problem, the best thing to do is to design the radome to be not hemispheric, but this will give wrong measure of the LOS angle, and so, the missile will not be directed to the real location of the target, so it will miss the target. therefore processing the signals could be a solution to this phenomena so the real location of the target will get corrected and known without error (Seo & Tahk, 2015).

3.8.2. Time Delay

The existence of time delay causes serious problems that might affects the tracking performance of the missile. As known, the missile defense system should always work in real time. And any delay in the response could cause some catastrophic problems which will make the missile completely useless, as it will not be able to do its mission by tracking the target and intercepting it. This delay could be caused by many factors, such as computational and processing time needed to process the signals reflected from the target to extract the information related to the location of the attacker. Also, a delay could happen because of the dynamic response of different mechanical parts of the missile, such as the motors that deflect the fins. Sometimes the time delay is added intentionally to the system, as it could decrease the effect of the received noisy signals, but it should always remain within specific acceptable rages to not degrade the responsiveness of the missile.

3.8.3. Receiver Noise

Receiver noise could be divided into many subtypes such as receiver active noise, glint noise, fading noise and receiver passive noise. Some of these noise types are considered as range independent, while some others are considered as range dependent. in this dissertation the value of 6.5×10^{-8} rad^2 / Hz is used for simulating the power density of the noise as an angular range independent white noise (Yanushevsky, 2008).

4. Dual Fractional Order Feedback System

By this dissertation, a system of dual Fractional Order PID is presented and implemented to navigational system of a missile. the objective of this control is to accurately guide the missile until it hits a flying target. The Dual controlling system is presented and implemented into the missile's body guided by PN system. This novel implementation of dual controlling system is supposed to increase the effectiveness of the PN Guidance by making the value of miss distance as low as possible. For each of the dual FOPID system, there are 10 parameters that need to be tuned for stabilizing the missile, and by using Dual FOPID system, it results for 10 parameters to be tuned. Genetic Algorithm (GA) is used as the main tuning procedure for the proposed controlling system. The proportional navigation (PN) is used in controlling a defending missile against a target by guiding the defending missile until it collides with the attacker. Many metrics have been introduced to measure the accuracy and the performance of the introduced controlling procedure for guiding the missile such as: the time period taken by the missile from launch time until the impact time, also the minimum distance formed by the target and the missile, which is known as miss distance accuracy.

4.1. Tuning and Designing the Control System

By this section, a dual FOPID controller system is presented. Figure 4.1 shows the standard PN system model taken from MATLAB with some modifications. And figure 4.2 shows the introduced dual Fractional Order PID controlling mode integrated with the PN device. As shown in Figure 4.1 the missile's error information about location is produced by finding the difference of the target location and missile's location.

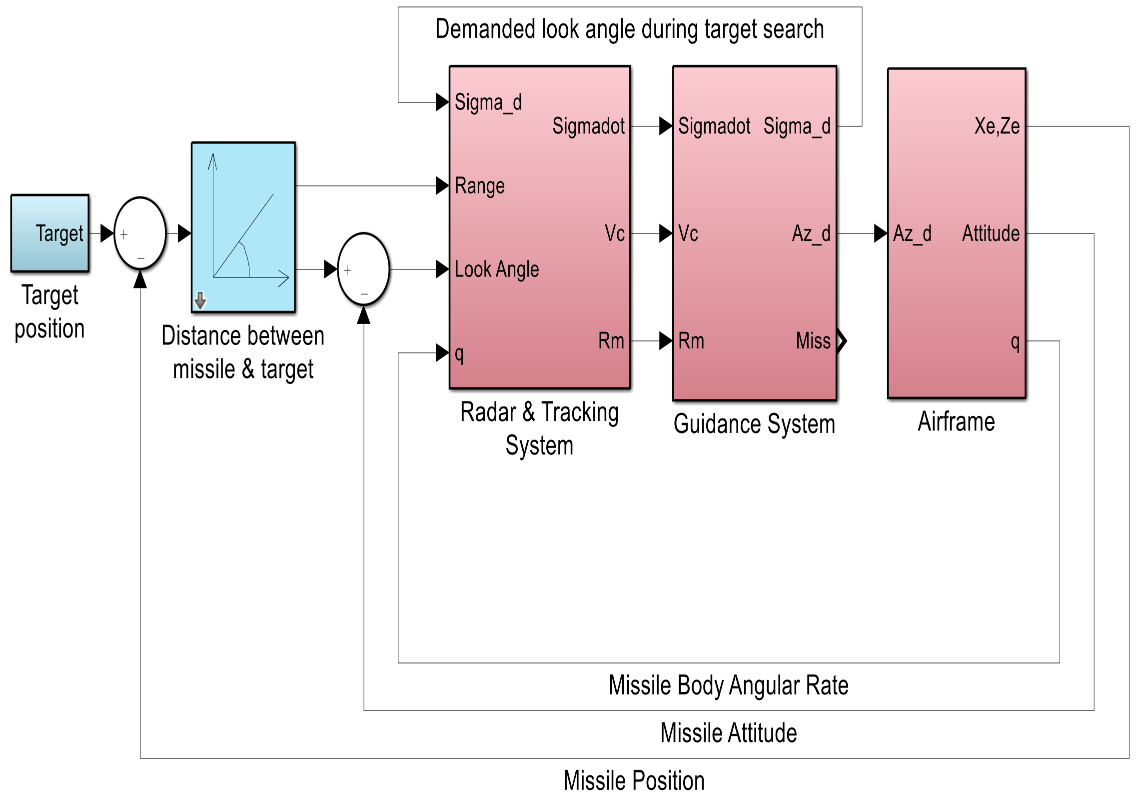

Figure 4.1. Conventional guidance system.

In the implemented design the error signal is entered into the Fractional Order PID control system. This FOPID control system designed by using Dual FOPID controllers, the first one is used for controlling the missile direction by considering the signal measures the X-axis of the missile’s location, and another one that uses the signals of the Y-axis of the missile’s location. The necessity for dual FOPID system is introduced and justified by the existence of different forces in the Y and X axis that acts on the missile, for example: gravity force is exerted on the Y-axis only.

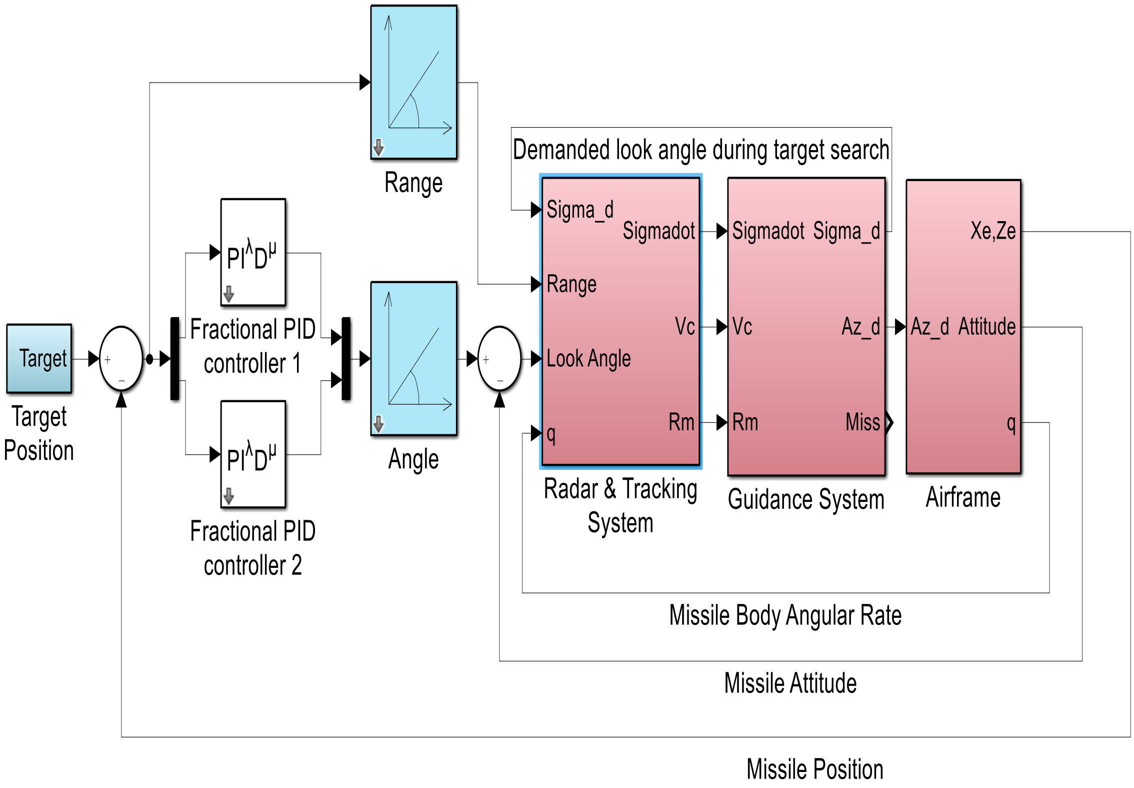

Figure 4.2. Dual FOPID controller.

Genetic algorithm is used for tuning the proposed FOPID dual control system. In the simulation outcomes, the dual FOPID controller with its 10 parameters have been tuned after producing 66 generations. The produced values of the proposed dual FOPID controller are introduced in Table 4.1.

Table 4.1. Parameters for dual FOPID controller.

Controller Parameter	**First FOPID Controller**	**Second FOPID controller**
K_p	0.674	0.739
K_i	0.385	0.186
λ	0.617	0.574
K_d	0.736	0.202
μ	0.490	0.992

4.2. Target and Missile Flight Path

Figure 4.3 presents the flight path of the missile by employing the PN controller inside the conventional controlling device. Figure 4.4 presents the PN system using the introduced Dual FOPID controller. The flight path of the target on these figures is not changing.

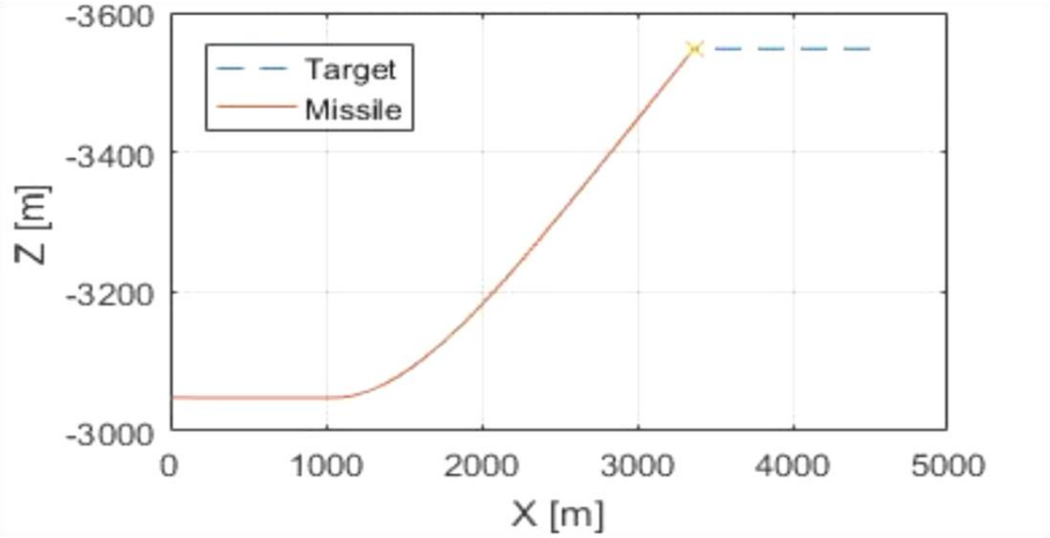

Figure 4.3. Target and missile flight path by employing standard PN controller.

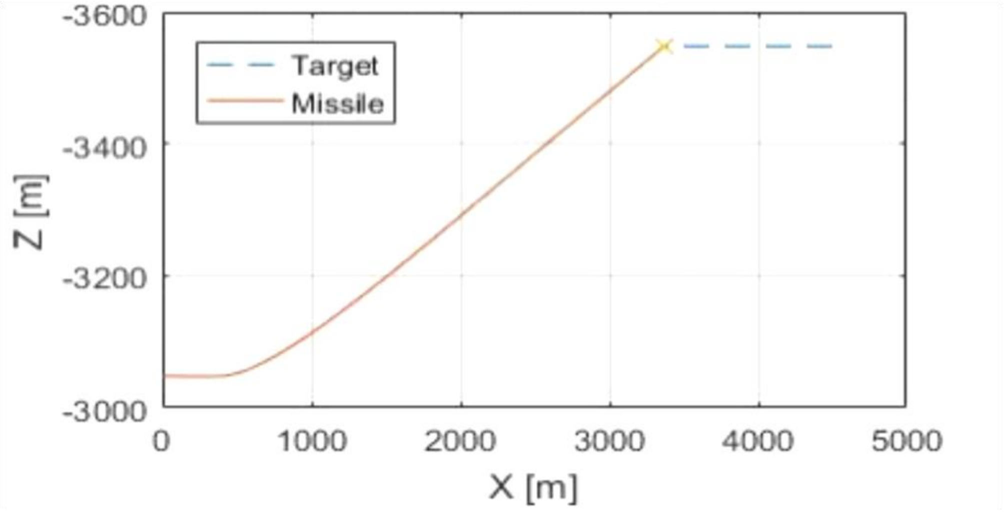

Figure 4.4. Target and missile flight path by employing dual fractional order PID.

The previous figures also present the distance that the attacker traveled before colliding with the missile. that proves that the missile controlled by the standard PID needed more time to be on the right path toward the target while the FOPID one took lesser time. The simulation results showed that the missile collided with the target after 3.46 sec. using the conventional control system, while using the proposed dual FOPID guidance system, the intersection occurred at 3.45 sec. Although the time difference appeared to be small, but this could lead to a big difference in the crossed distances because of the very high speed of the missile.

Figure 4.5 shows that the missile using the conventional proportional navigation system needs approximately a second to align the look angle with the gimbal angle. Figure 4.6 elaborates that true look angle is aligned with the gimbal angle of the radar system approximately the whole time.

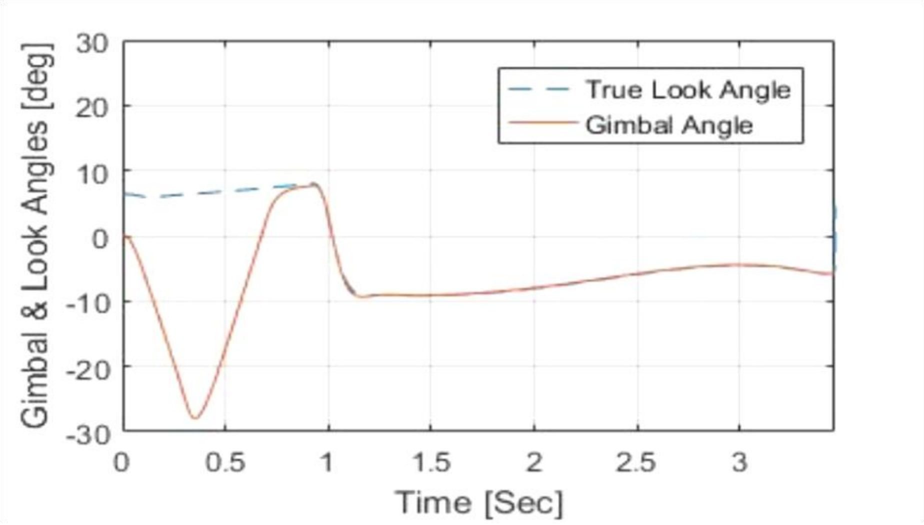

Figure 4.5. Look angle and gimbal angle by employing standard PN system.

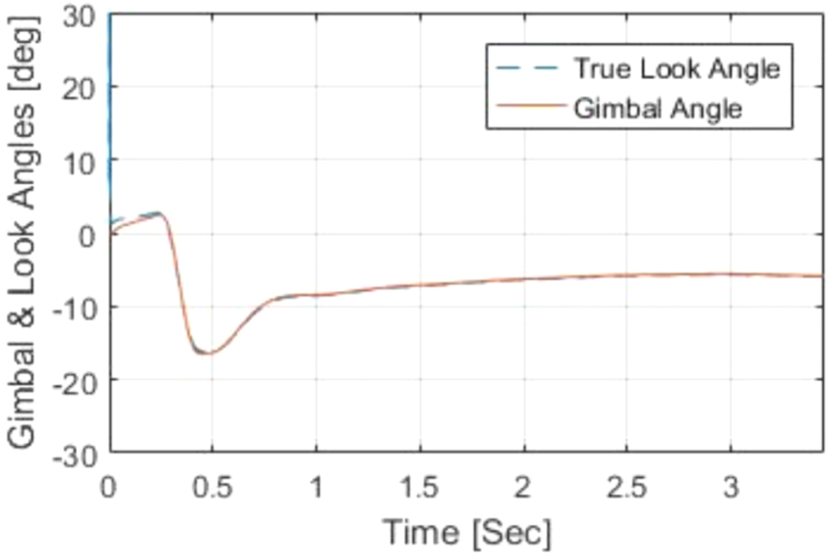

Figure 4.6. Look angle and gimbal angle by employing fractional order PID system.

4.3. Miss Distance Performance

The miss distance for both conventional and Dual Fractional controllers were computed. The computed miss distance presented a huge increment in the miss distance performance of the PN system using the presented Dual Fractional Order PID system over the standard one. The miss distance value for the Dual

FOPID controller was about 0.0009 while for the standard system it was 0.2682. This proves that the Dual FOPID system has higher performance than the standard system. This huge improvement is because the applied forces on each of the X and Y axes are different and by applying dual fractional order system, each one of the controllers will work on stabilizing the missile dynamics on each axis.

4.4. Summary

In this chapter, a novel controller system consisting of dual fractional order PID system is presented and employed to the proportional navigation controller. The necessity for this dual system is justified by the different forces exerted on each axis of the missile’s, for example, the gravity force is acting on just a single axis of the missile. The outcomes of the simulation proved that the introduced Dual controlling system resulted in higher performance on the intersection time between the missile and target and a higher ability for colliding with the target with higher miss distance performance.

5. Fractional Order PID Controller for a Missile under Disturbances

5.1. Design and Tuning the Controller

Figure 5.1 presents the standard radar system, while the introduced fractional order system along with the considered error sources is elaborated in figure 7.2

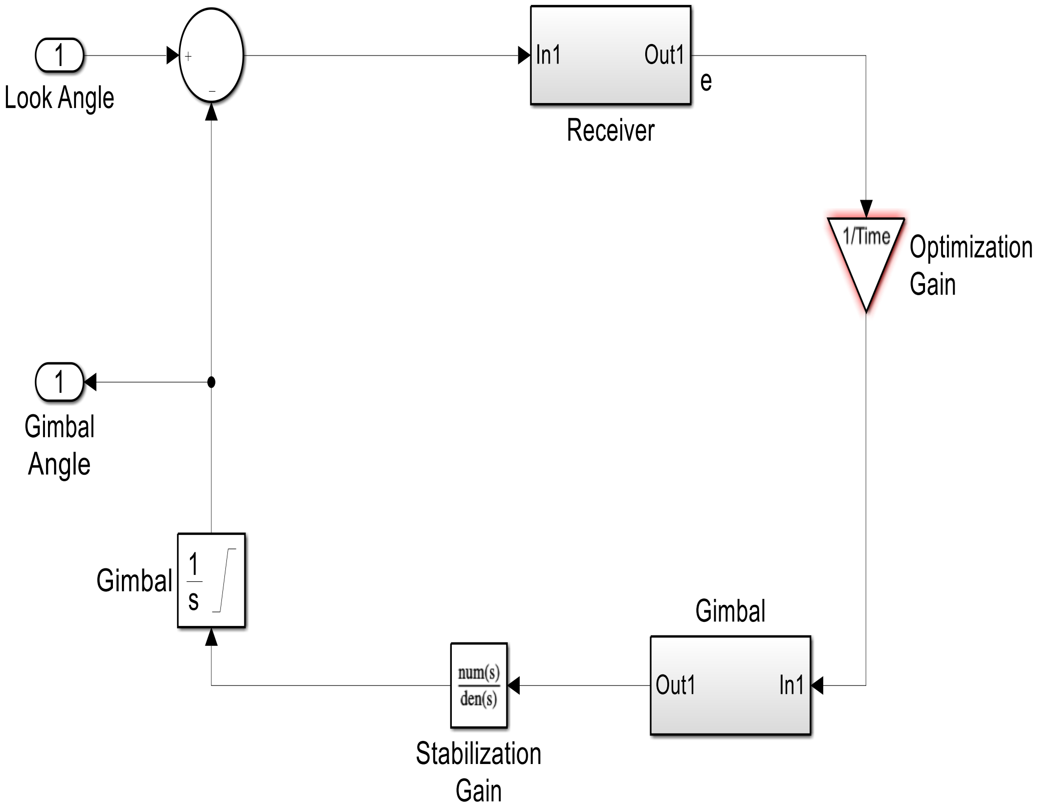

Figure 5.1. The conventional radar system.

The error signal in the introduced FOPID controller elaborated in Figure 5.2 is implemented by subtracting the radar rotation angle from the line of sight (LOS). This error signal is then adjusted by the FOPID system. The output of the FOPID controller is sent to the receiver. We have introduced a band limited noise that affects the quality of observation. These signals that enter the receiver is then divided by a suitable for achieving a better feedback information. The signal is then integrated to obtain the radar gimbal angle. The influence of time delay is also introduced to the system which affects the output of the controller that enters to the receiver. Finally, a radome aberration error is introduced which in turns changes the computed gimbal angle. This error is introduced as a linear approximation of the radar gimbal angle and also affects the output of the controller that enters to the receiver.

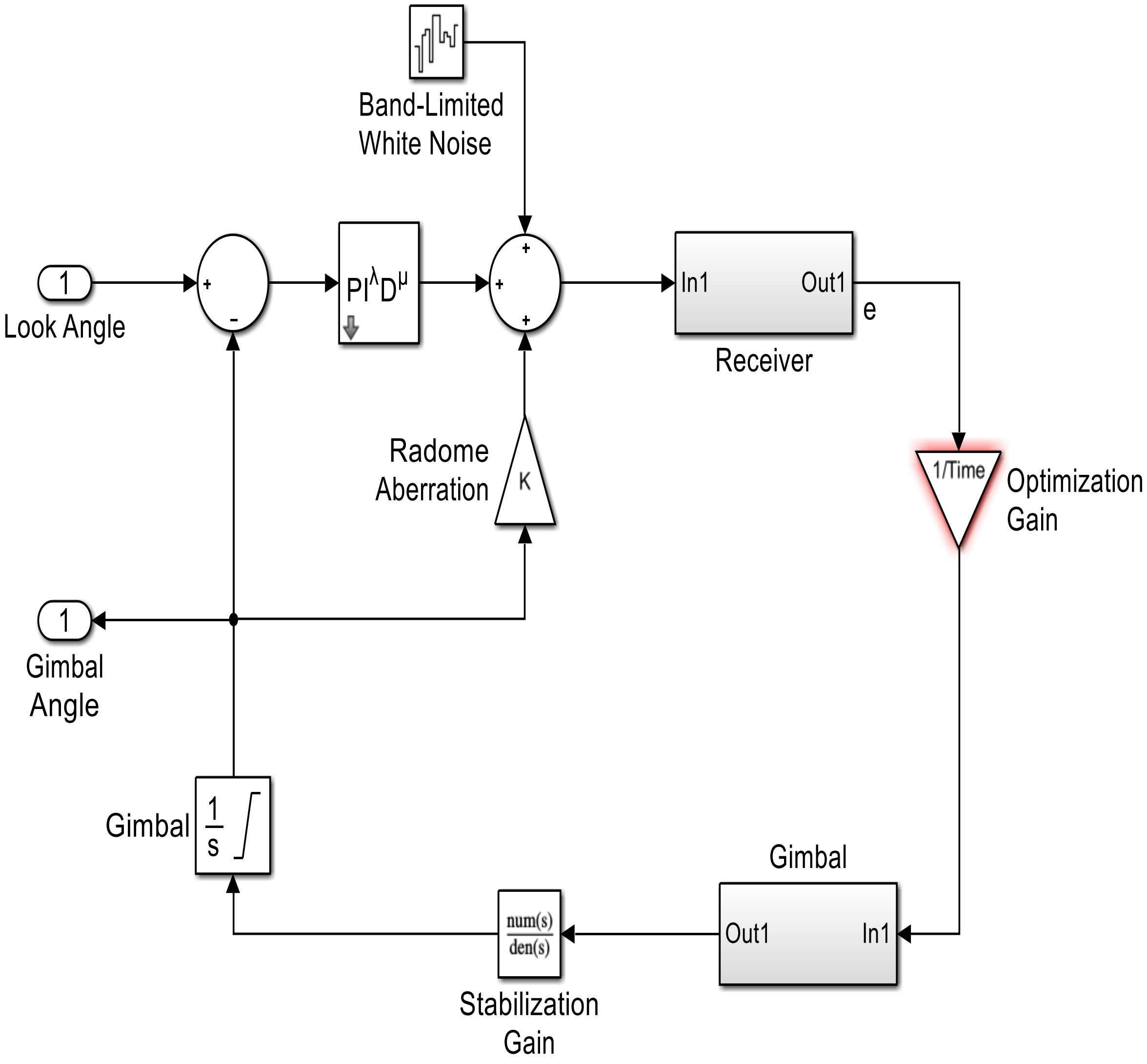

Figure 5.2. The proposed FOPID model.

5.1.1. Using GA for the FOPID Optimization

Genetic Algorithms is employed to optimize the fractional order PID parameters. These parameters are K_p, K_i, K_d, μ and λ. The fitness function of the GA is computed utilizing the miss distance, so, the GA looks for the best parameters that result in a lower miss distance value, so the missile could collide with the target at high accuracy. The produced fractional order PID parameters from this process are presented in Table 5.1.

Table 5.1. The parameters of the FOPID produced by GA.

Parameter	**Value**
K_p	0.859
K_i	0.257
λ	0.643
K_d	0.098
μ	0.075

The introduced FOPID was simulated against the standard controller, in which error sources and noises are considered. The performance of both systems has been tested in terms of incidence and of the missile, miss distance and normal acceleration.

5.2. Time Delay Error

The error of time delay is usually presented because of the reaction time needed by the gimbals. In the experimental test, the time delay is introduced prior to computing the gimbal angle, as presented in Figure 5.2. The time delay was about 0.005 s. When simulating this time delay along with the standard system, the miss distance value was recorded as 10.52 m, while using the introduced FOPID the recorded miss distance resulted by the missile was observed as 8809 m. Also increasing the time delay will result in higher miss distance value. Figure 5.3 and Figure 5.4 presenting comparisons of the introduced FOPID and the standard one in terms of the behavior of normal acceleration and the behavior of the incidence angle during flight time. The presented figures show that the existence of time delays highly affecting the standard system, as it showed a lot of oscillations everywhere after the end of the 1st second, and that is the time when the target has been found by the radar system. Using the introduced FOPID, the time delay effect is reduced, also the FOPID is able to smooth the plant much more than the standard one. The applied normal acceleration needed to rotate the missile is less during flight time, so, we can confirm that there is less power needed by the fractional order PID system to rotate the missile towards the target in the existence of time delay.

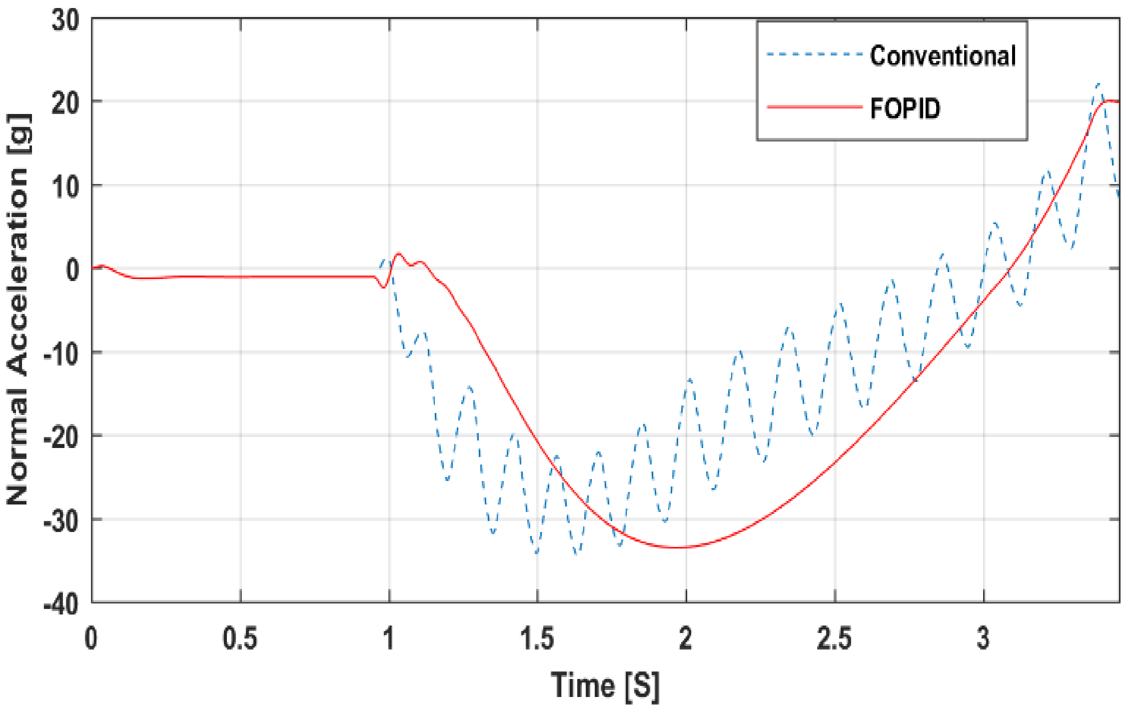

Figure 5.3. lateral accelerations comparison with time delay.

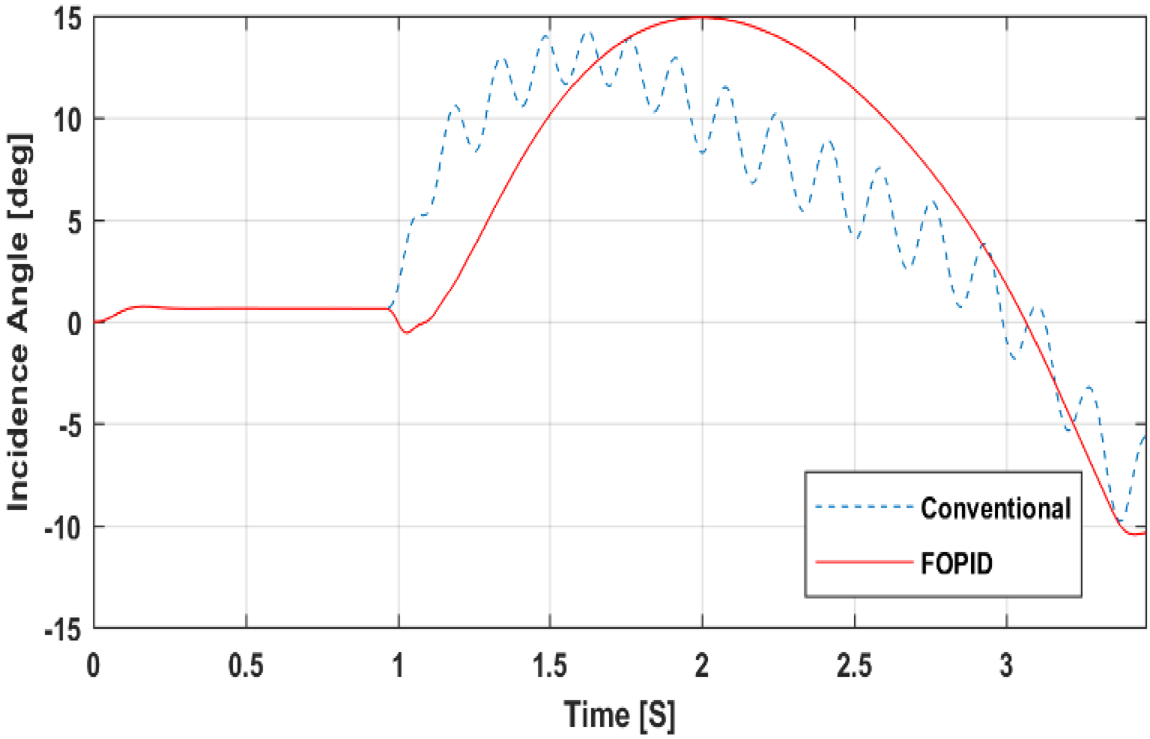

Figure 5.4. Incidence angles comparison with time delay.

5.3. The Noise of Radome Aberration

The noise of Radome aberration is introduced and modeled with a relationship to the missiles’ gimbal angle. The estimated radome gain is -0.04, and the registered miss distance by applying the standard PID was 38.8 m, while after applying the introduced FOPID system, the registered miss distance was shown as 0.8703 m. by this we can verify that the introduced fractional order PID is more useful in reducing the error value of radome aberration. Figure 5.5 and Figure 5.6 simulate the noise of radome aberration exerted on the incidence angle of the missile as well as the normal acceleration during flight time. For the standard system, many oscillation points are shown after the 1st second, and this is when the target has been detected. While using the fractional order PID the behavior tends to be more stable. These results supported by the simulation graphs proved the ability of the introduced fractional order PID for stabilizing the missile and reducing the influence of radome aberration error.

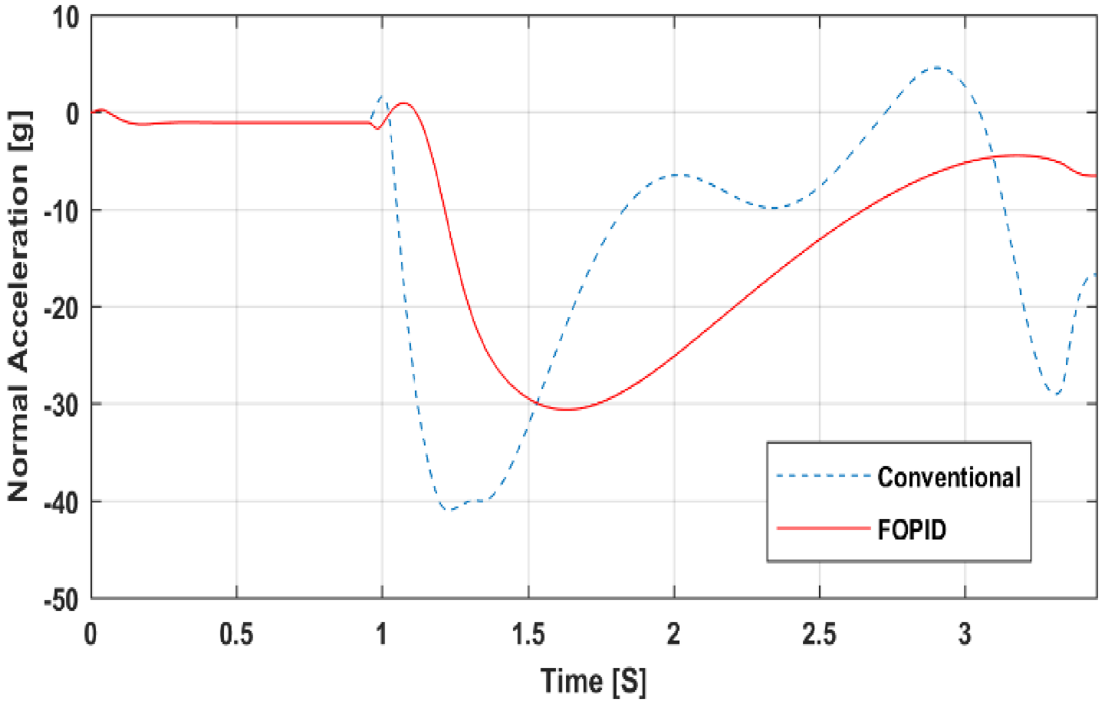

Figure 5.5. simulation of normal accelerations exerted to radome aberration noise.

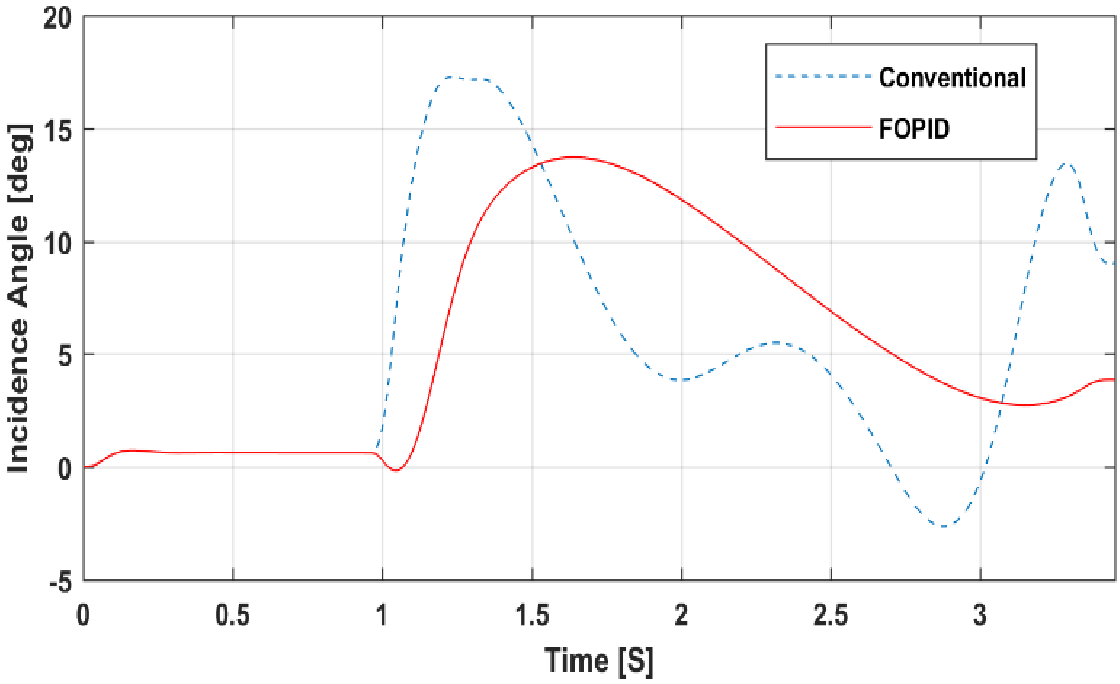

Figure 5.6. simulation of incidence angles due to radome aberration error.

5.4. Receiver Noise

A receiver white noise has been introduced with a power of 6.5×10^{-8} rad^2/Hz (Yanushevsky, 2007) as clarified in Figure 5.7. It has a mean of 0 and a variance of 6.5×10^{-8}. The miss distance value recorded by the standard system in the existence of noise was 20.5 m while for the FOPID controller the recorded miss distance observed as 3.7 m.

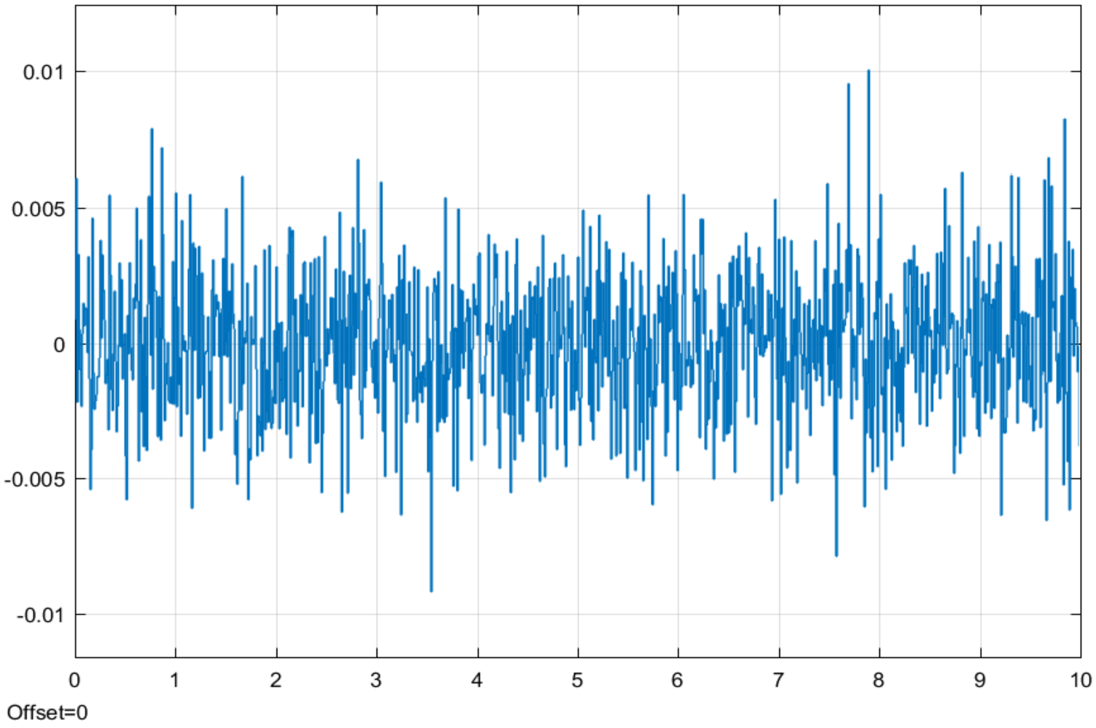

Figure 5.7. White noise exerted on the radar system.

It's clear from these results that the introduced FOPID is able to decrease the effect of receiver noise and produce a lower miss distance value compared with the standard PID system.

5.5. Summary

Radar guided missile systems controlled by the standard PID controller as well as the fractional order PID are introduced. This Radar guided missile has been simulated in the environment that is affected by many error sources and noise. There are three kinds of error and noises that affects the proposed radar guided missile which are: radome aberration error, receiver noise and time delay. Fractional order PID system is introduced and simulated side by side with the normal PID controller which are affected by error and noises. These systems were compared in terms of incidence angle behavior during flight time, miss distance value, and normal acceleration. The outcomes of this research proved the ability of the introduced FOPID in surpassing the standard PID for reducing the time delay effect. Also, the fractional order PID system was better in keeping the missile more stable during flight as well as making it more accurate in hitting the target compared with the standard PID system. Fractional order PID system also proved to have better efficiency in reducing the influence of radome aberration error. Also, the efficiency in reducing the white noise effect of the receiver was not apparent in terms of incidence angle and the value of normal acceleration during flight, but it proved to have better accuracy and more hitting accuracy by using the proposed FOPID compared with the standard system under the effect of the receiver noise.

6. Intelligent Weighted H_2/H_∞ Fractional Order Tracker Optimized for Radar Guided Missile

By this chapter, an intelligent weighted H_2/H_∞ tuning strategy is proposed to solve the near impact stability problem of the radar guided missile. It is well known that PNG controller is the most used system for controlling radar guided missiles and tracking high-speed targets. One of the most critical problems found in the radar guided missiles is controlling the missile near the colliding location which is responsible for missile to miss its target. There are many scientists who addressed this problem, and one of the proposed solutions found in the literature is by integrating a PID controller into the system. This process increased the performance of the tracking system near the impact region, however, it's well known that the missile's dynamics are nonlinear, and the PID system exerts only a linear behavior, and in order to use PID control for nonlinear system, the trivial method is by choosing multi-points from the operation range of the plant, and then linearizing the plant at each one of these points. After that, a specific PID is customized for each operating point. However, using a nonlinear control system such as the fractional order PID should result in more performance for the tracking system than the conventional PID especially near the impact region, and using one fractional order PID might be enough for such systems (Shah & Agashe, 2016). In the process of customizing a control system for tracking applications such as homing missiles or unmanned aerial vehicles. Either the control system will be customized for smooth tracking, which has a side effect of degrading the maneuvering ability of the missile, but will have smooth behavior during flight time, or it will be customized to gain high agility and maneuvering ability at the cost of degrading the stability during flight time (Bolandi, Rezaei, Mohsenipour, Nemati, & Smailzadeh, 2013). Recently, the mixed H_2/H_∞ optimizing technique is getting high interest in feedback controllers because of the outstanding properties that it exerts on these systems. The principle of H_2 is about acquiring the overall controlling efficiency by averaging over all working points, while the principle of H_∞ is based on obtaining a guaranteed efficiency that has a minimum value to achieve for all working points of the system. For a radar-guided missile, the flight time near the impact region only accounts for a small portion of the whole flight time. Therefore, when applying the trivial H_2 or H_∞, the controlling performance will not take near impact region performance into consideration, as it accounts for only a very small portion of flight time, which gives a higher chance to missile to miss its target, even when the missile was stable during most of the flight time. To overcome this issue, we proposed a weighted mixed H_2/H_∞ tuning algorithm. By this algorithm, range dependent weights will be implemented to the mixed H_2/H_∞ tuning procedure, and thus gives high weights to the mixed H_2/Hf_∞ tuning procedure, while the missile approaches the target. This weighting algorithm will stabilize the fractional order PID controller for the whole flight time, while also concentrating on stabilizing the controller close to the colliding location. There are outcomes in the literature that works on optimizing the H_2 and H_∞ based tuning procedure.

PSO method is used to minimize the second and infinity norms to have good stability to the missile while flying and especially near the impact region. The introduced tuning method implemented to fractional order PID controller is simulated against the traditional ZN method employed on the conventional PID. The simulation outcomes proved the efficiency of the fractional order control along with its proposed tuning method over the conventional one.

6.1. Design the Controlling System

In this chapter, a weighted mixed H_2/H_∞ tuning technique is used along with miss distance constraint to tune a FOPID. The intelligent tuning procedure is implemented to the FOPID using PSO method to obtain the five parameters of the FOPID controller, which results in minimum miss distance, H_2, and H_∞ values. The proposed fractional order control system is simulated and simulated against the standard PID controller, which used the conventional ZN strategy, as it is often used to tune the normal PID.

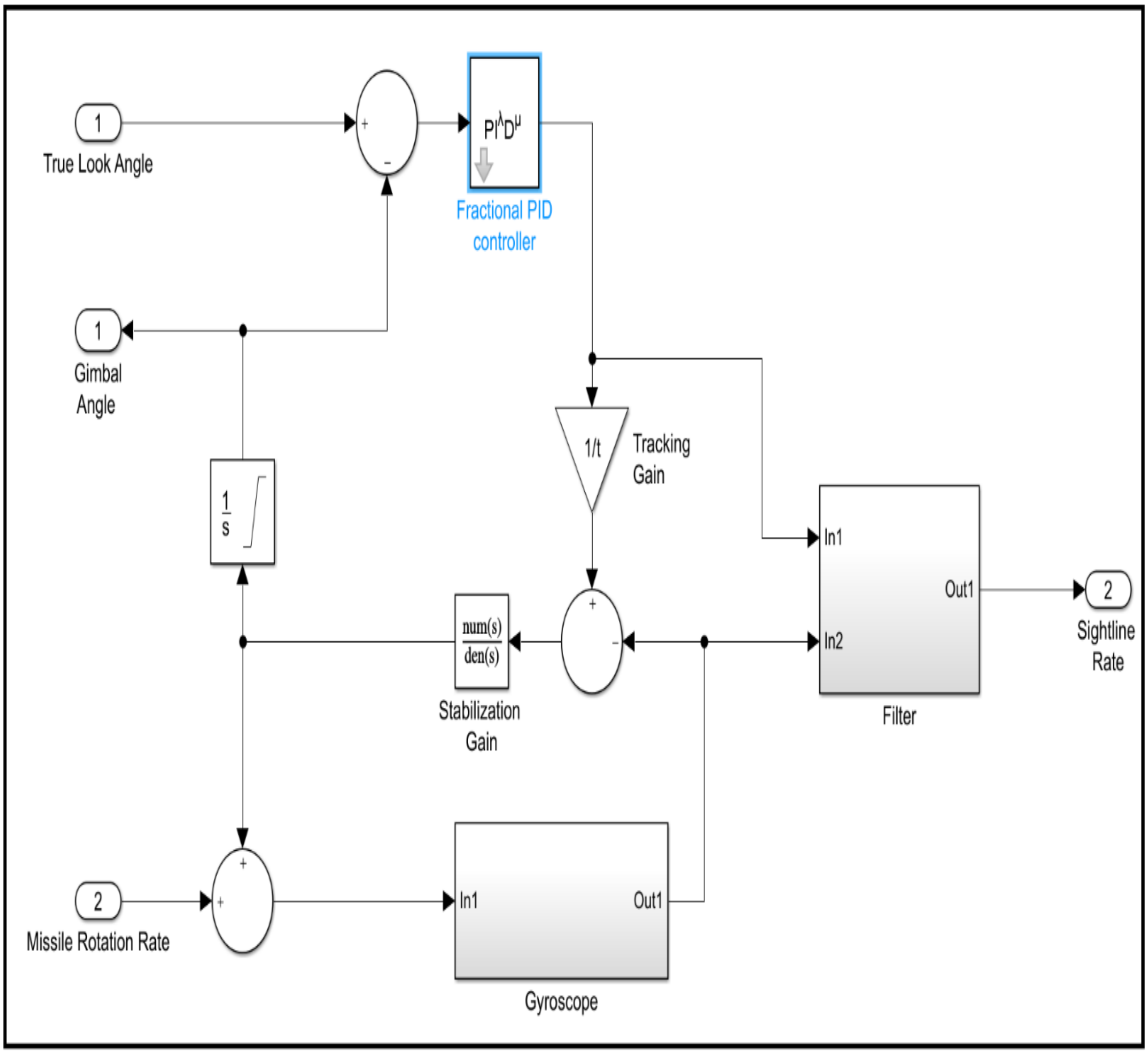

Figure 6.1. The radar control system.

6.2. The Standard PID System

Ziegler-Nichols tuning process is implemented to the conventional PID controller. The tuning strategy is started by acquiring the system response where the gimbal the systems output is the gimbal angle, and the systems input is the look angle. After that, the transfer function of the system is calculated as elaborated below:

$$T(s) = \frac{2513s^2+2.2\times10^6 s+9.9\times10^8}{s^4+879.6s^3+3.9\times10^5 s^2+5.2\times10^7 s+1\times10^9}, \qquad (25)$$

From this transfer function, the parameters of the PID are calculated using the ZN strategy. The resulted parameters using the Ziegler-Nichols are presented below:

Table 6.1. PID parameters acquired by Ziegler Nichols method

Parameter	**Value**
K_p	78.6901
T_i	0.0050
T_d	0.0012

6.3. The Proposed Fractional order PID

The introduced controller is applied using FOPID. The proposed system is then simulated using the toolbox designed by: (Tepljakov, Petlenkov, Gonzalez, & Petras, 2017). Oustaloup's approximation strategy is employed to approximate the FOPID. PSO method is employed for tuning the parameters of the proposed FOPID (K_i, λ, K_p, μ and K_d). In the tuning process, the fitness function of the PSO is defined to optimize the values of H_2 and H_∞ in order to decrease them to very low values. After that, we divide the error vector by the distance, thus, the error values of the feedback system near the target will have high weights. Due to that, the controller will be optimized and tuned for the space closed to the intersection point of the missile and the target. The fractional order PID parameters generated by this process are presented in Table 6.2.

Table 6.2. Fractional order parameters generated by mixed H_2/H_∞ tuning process

Parameter	**Value**
K_p	0.8821
K_d	0.0219
μ	0.0105
K_i	0.0100
λ	0.1324

6.4. Results of Simulations

The introduced fractional order controller is simulated against the normal PID in terms of trajectories motion, stability of the incidence angle, miss distance, acceleration demands as well as the radar ability to track the true look angle.

6.4.1. H_2/H_∞ and Miss Distance

Miss Distance is defined as the shortest distance from the target to the missile. The miss distance for the standard PID controller is observed as 6.278; so, we can confirm that the missile missed the target. The second norm value H_2= 11.2946 and the infinity norm value H_∞= 0.7973. However, our proposed FOPID controller showed a good performance of the miss distance value which was 0.0019. The infinity norm H_∞= 0.6005, and the second norm H_2= 0.0016. Thus, the stability and accuracy of our fractional order PID in guiding the missile is proved.

6.4.2. The Flight Course for Missile and Target

The course of the missile and target for the standard system is shown in Figure 6.2. In this figure, the path that the missile follows is not straight, especially when it gets close to the colliding location where it shows unstable movement.

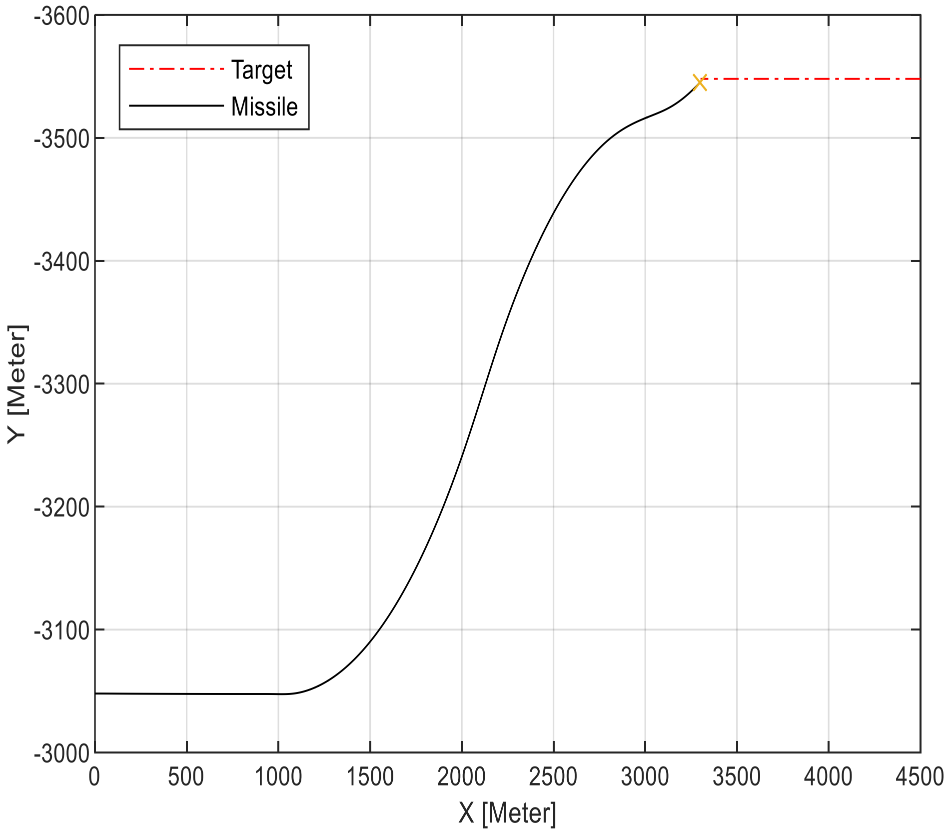

Figure 6.2. Flight course of missile and target for the conventional PID.

Figure 6.3 presents the course of the missile and target for the introduced fractional order PID. It is apparent that the flight course of the missile follows is approximately stable and straight especially near to the colliding location unlike the system equipped with the standard PID.

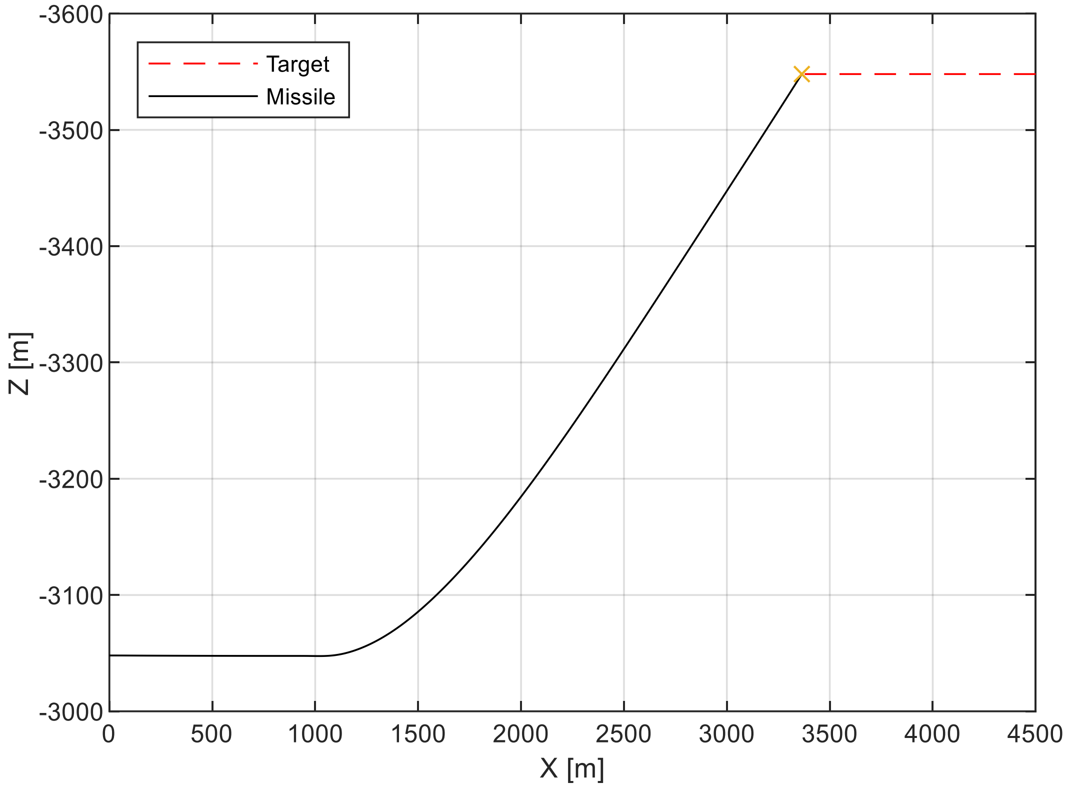

Figure 6.3. Flight course of missile and target for fractional order PID.

6.4.3. Incidence Angle

The Incidence angle also known as the angle of attack is known as the angle formed by the course direction of the missile and the reference line on the missiles' body. Figure 6.4 shows that the radar system found the target approximately at 0.7 seconds while the missile's incidence is changing to follow the target approximately at 0.9 seconds. It is also shown that the incidence angle is oscillating for system equipped with the standard PID with low stability during flight time as shown in Figure 4, while it is more stable and smoother for the proposed FOPID as presented in Figure 6.5.

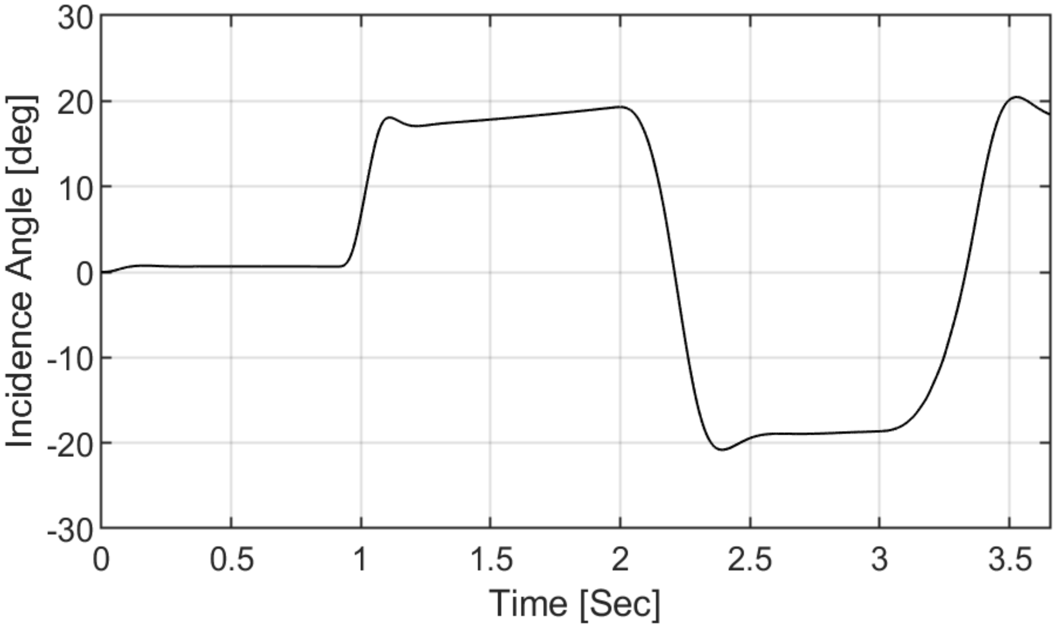

Figure 6.4. Incidence Angle of the conventional PID.

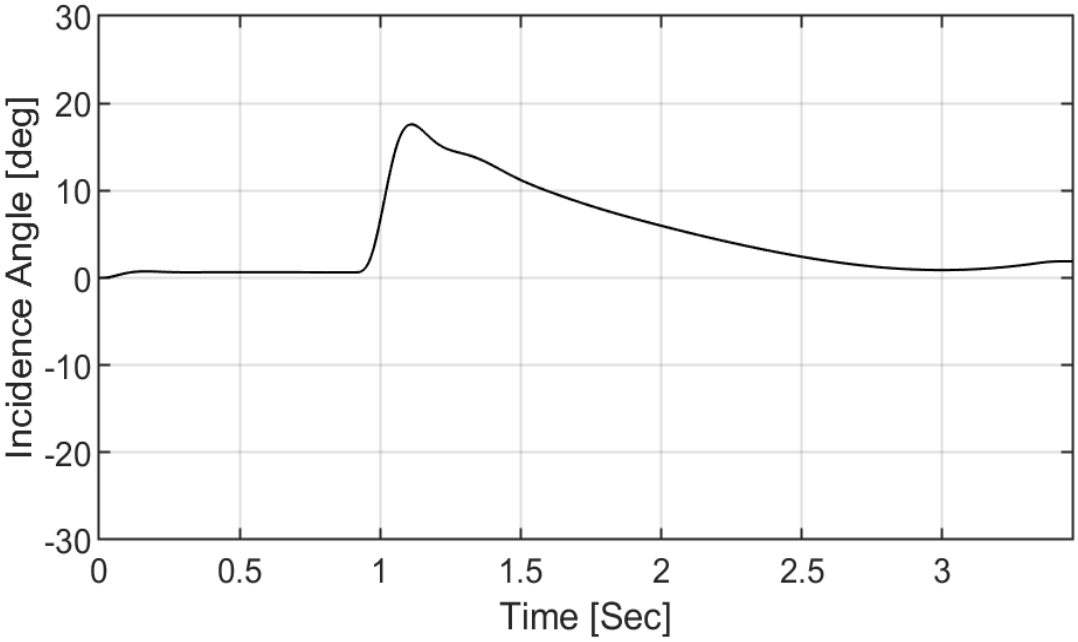

Figure 6.5. The incidence angle of the proposed fractional order PID.

6.4.4. Acceleration Demands

Acceleration Demand could be defined as the normal acceleration demanded to be exerted on the missile. This lateral acceleration is responsible for rotating the missile's body and aligning it with the line of sight. This acceleration demand has a huge impact on directing the missile towards the target and allowing the missile's body to hit the target accurately. Figure 6.6 elaborates that employing the standard PID the missile is generating an oscillating acceleration demand, which leads to an unstable and oscillating movement for the missile, while Figure 6.7 elaborates that employing the introduced fractional order PID, the acceleration demand shows smooth behavior to guide the missile towards the target.

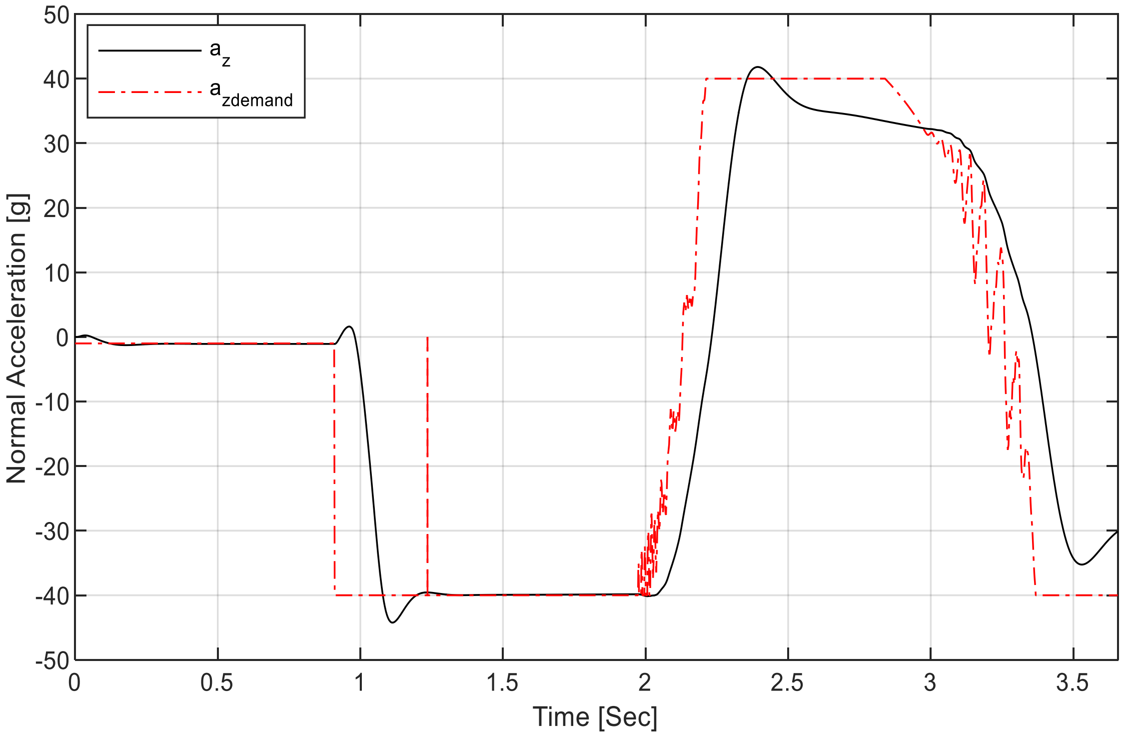

Figure 6.6. Normal acceleration for the conventional PID controller.

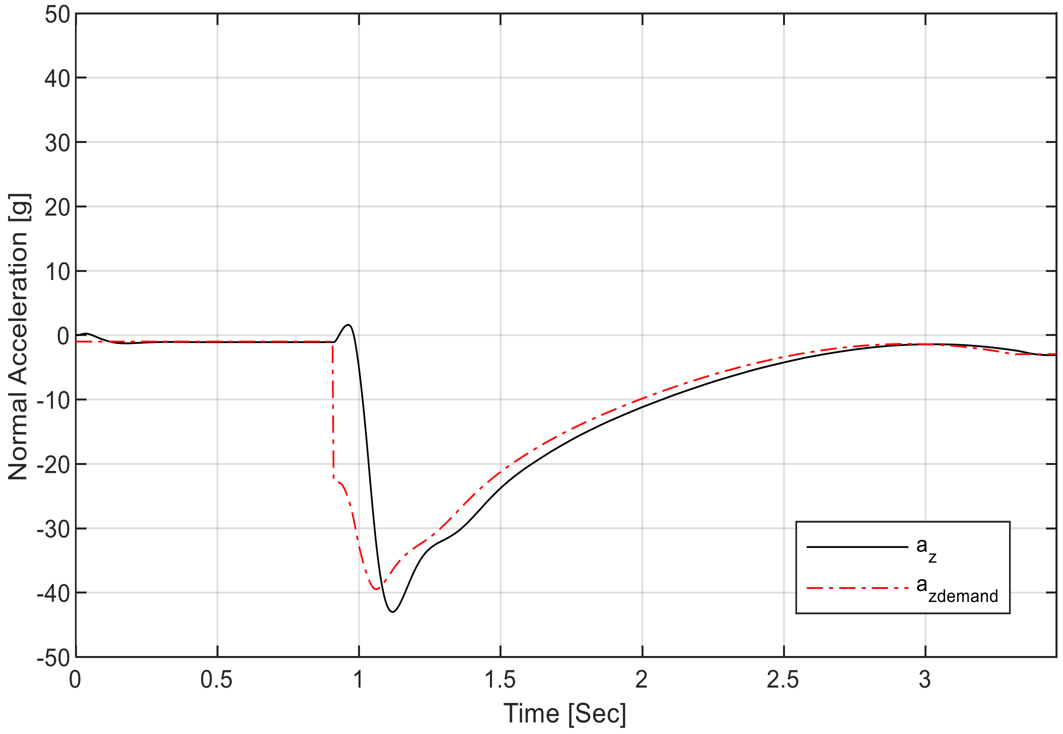

Figure 6.7. Normal acceleration for the proposed fractional order PID controller.

6.4.5. Gimbal and True Look Angles

True look angle is known as the angle formulated by the target and the reference axis, on the other hand, gimbal angle is formulated by the reference axis and the looking direction radar. As presented in Figure 6.8, the gimbal angle provides some oscillations before its alignment with the look angle direction. Also, after aligning with it, both of them are oscillating due to the unstable movement of the missiles’ body.

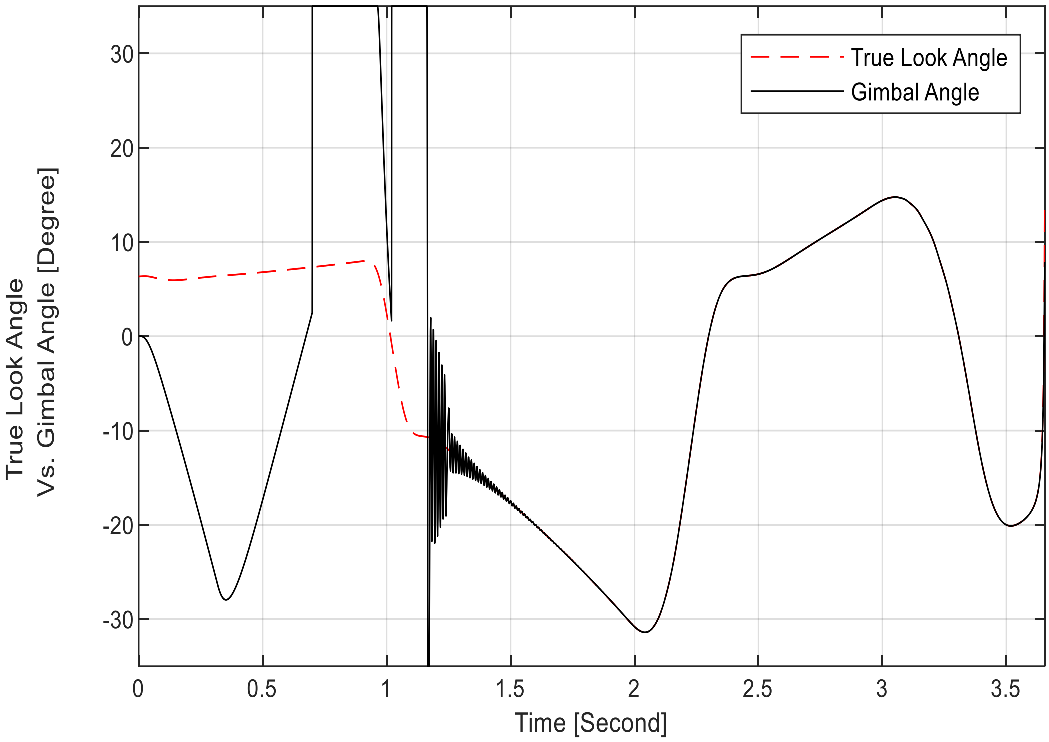

Figure 6.8. Gimbal angle vs. true look for standard PID.

The effectiveness of the proposed fractional order is shown in Figure 6.9. As elaborated in the Figure, the radar is directed toward the target's location approximately at 0.7 seconds. After that, the gimbal angle was able to track the look angle effectively. Thus, the performance of the proposed fractional controller for making the look angle aligned with the gimbal angle is confirmed.

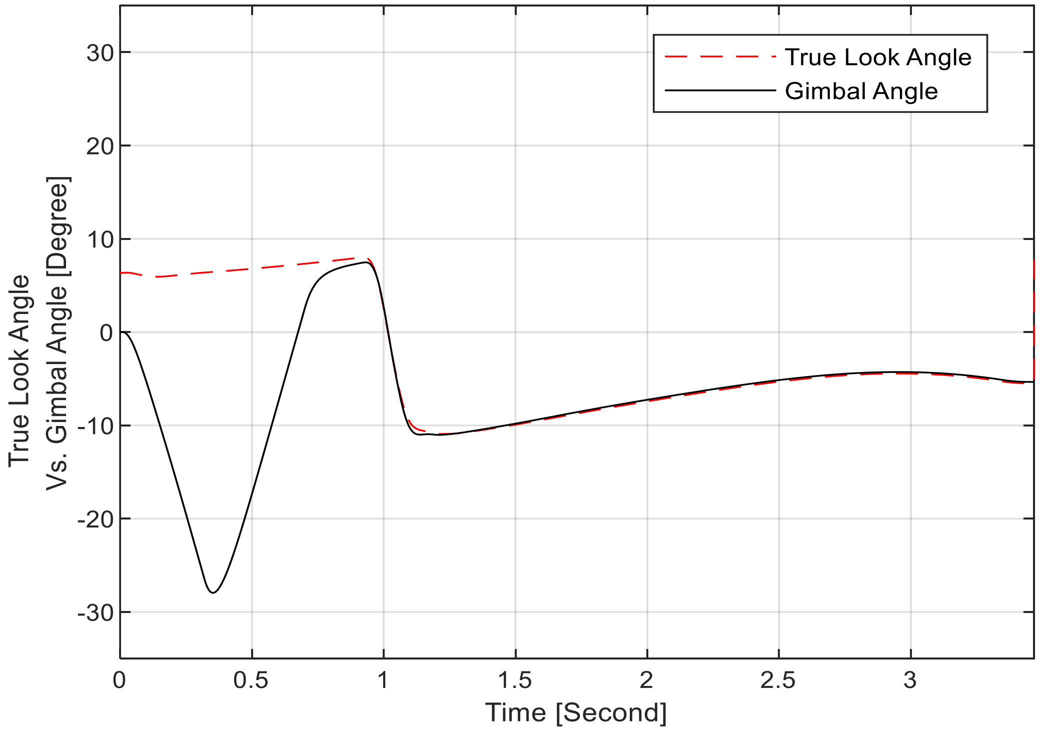

Figure 6.9. Gimbal angle VS. look angle by fractional order PID.

6.4.6. Effect of Noise

The proposed fractional order control system is tested under noise as shown in Figure 6.10. Even the demanded acceleration experienced noise effect, however, the control system suppressed that noise efficiently and the generated acceleration shows smooth behavior.

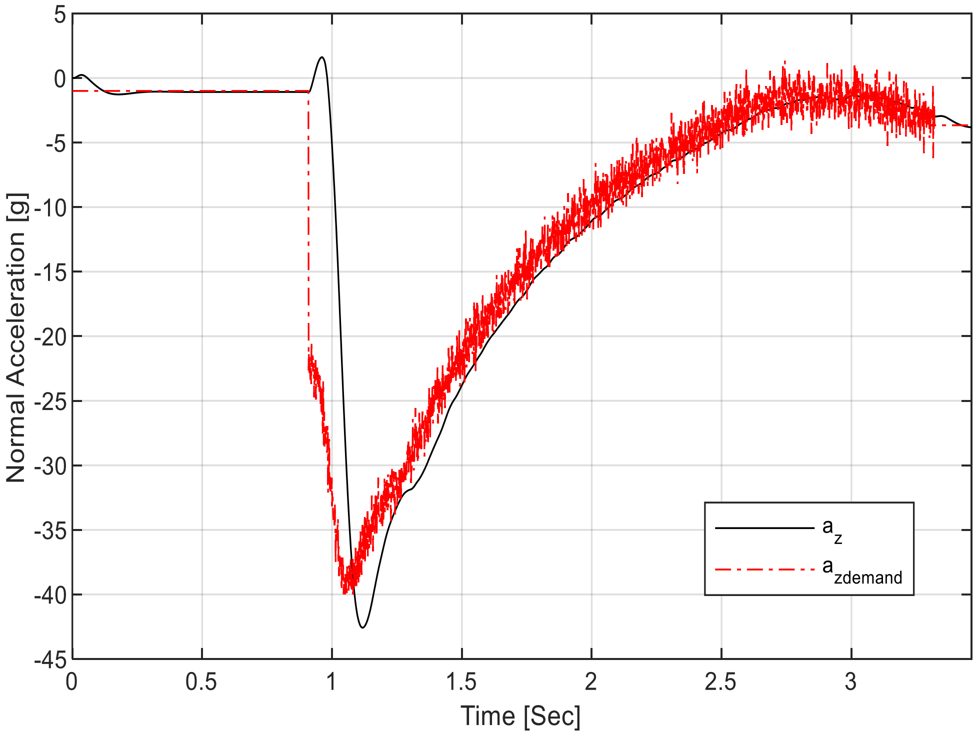

Figure 6.10. Noise effect on lateral acceleration for system equipped with FOPID.

6.5. Summary

By this chapter, a tuning method using weighted H_2/H_∞ based tuning is proposed and employed to FOPID. The presented algorithm based on H_2/H_∞ is introduced to deal with the stability of missile located near the colliding region, as the control efficiency of the missile becomes inefficient near the colliding location. PSO method is used for finding the optimal parameters of fractional order PID that is making the second norm H_2 and miss distance value as small as possible with guaranteed H_∞ value. The introduced control system is simulated with the normal PID, which employed ZN for tuning. The performance metrics that have been considered for comparisons were: second norm value, infinity norm value, miss distance, course of the target and missile, incidence angle, acceleration demands gimbal angle relative to the look angle. The outcomes of this showed the superiority of the introduced fractional order PID system in stabilizing the missile accurately specifically near colliding location with the standard tuning method. For future work, an adaptive fractional order PID to adapt with the density of air that changes it value during flight also with the laws of aerodynamics changes as the missile travels between different layers in the atmosphere.

7. Adaptive Sliding Mode Fractional Order Control Scheme for Three-Loop Autopilot System

7.1. Controller Design and Tuning

7.1.1. Conventional Three-Loop Autopilot

Figure 7.1 depicts the standard form of the three-loop autopilot system. The location of the target is obtained by a radar system implemented inside the missile, and the deviation of the missile from the right path toward the target is calculated. Then the lateral acceleration demand is calculated and sent to the autopilot control system as shown in figure. There are three gains needed to be tuned (G_1, G_2 and G_3) in order to achieve good tracking performance and to generate the fin demand needed to control the direction of the missile. Anti-windup gain is used to overcome the accumulated integration error caused by the limits of fin demand. The actual rotation rate as well as the actual lateral acceleration are measured by a set of gyroscopes and accelerometers and then fed back to the autopilot system.

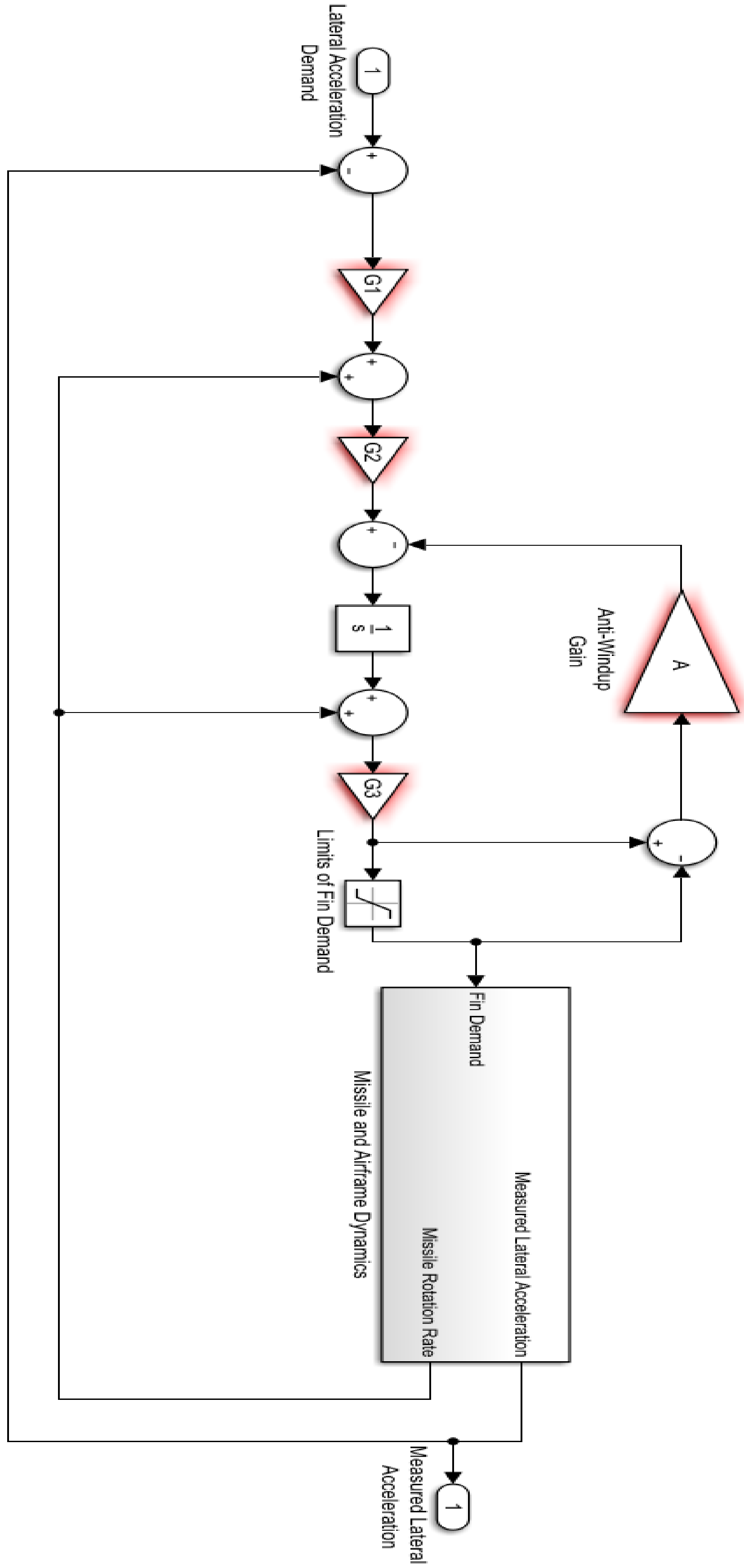

Figure 7.1. The conventional autopilot system.

7.1.2. Fractional Order PID Autopilot system

By this chapter, a fractional order controller is introduced and implemented into the three-loop autopilot. The introduced controller was simulated against the conventional three-loop autopilot system. The Oustaloup's fractional definition is employed for defining the proposed fractional controller and GA is employed to tune the scheduled fractional order autopilot system. In order to achieve good controlling performance without any observed sudden changes in the behavior of the system, mixed H_2/H_∞ based tuning technique is used. Miss distance value is also used to achieve good hitting accuracy at impact time. The H_2 norm or $\|u\|_2$ for a signal u(t), is yield by the following equation:

$$\|u\|_2 = \left(\int_0^\infty u(t)^2 dt\right)^{1/2} \tag{26}$$

where t ≥ 0. The physical meaning of obtaining the second norm H_2 of a signal u(t) is interpreted as obtaining a value relative to the whole energy exerted by the signal. The H_∞ for a signal u(t), is yielded by obtaining the maximum absolute value of its components, as expressed in the following equation:

$$\|u\|_\infty = \max_t |u(t)| \tag{27}$$

where t ≥ 0. The H_∞ is used to obtain the maximal possible amplification that could be yield at the output of the controller. The H_∞ is useful for controlling and stabilizing the plant with guaranteed efficiency for the all frequency spectrum (R. Toscano, 2013). Genetic algorithm is used along with H_2/H_∞ optimization process to search the space for the FOPID parameters which could stabilize the system by minimizing the values of the H_2, H_∞ and miss distance of the system.

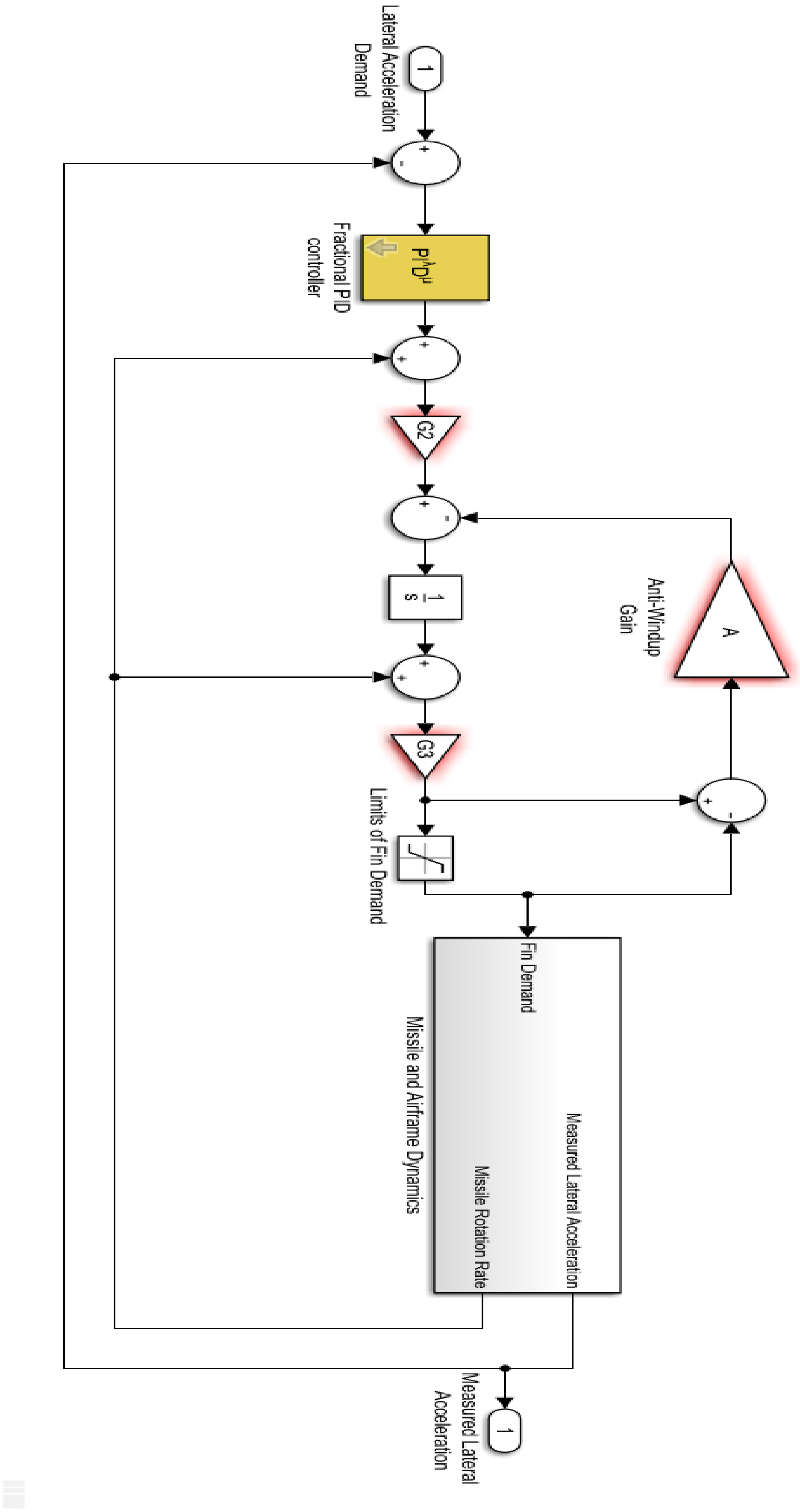

Figure 7.2. FOPID controller integrated into the autopilot.

7.1.3. Sliding Mode Fractional Order PID Autopilot system

The standard form of the gain scheduling with fixed-structure is expressed in Figure 7.3. By this conventional gain scheduling method (Gahinet & Apkarian, n.d.), the control problem is to find the gain parameters $K_1(\sigma)$, …, $K_n(\sigma)$ that could yield the intended performance of the system depicted in Figure 7.4. where P is non-linear plant.

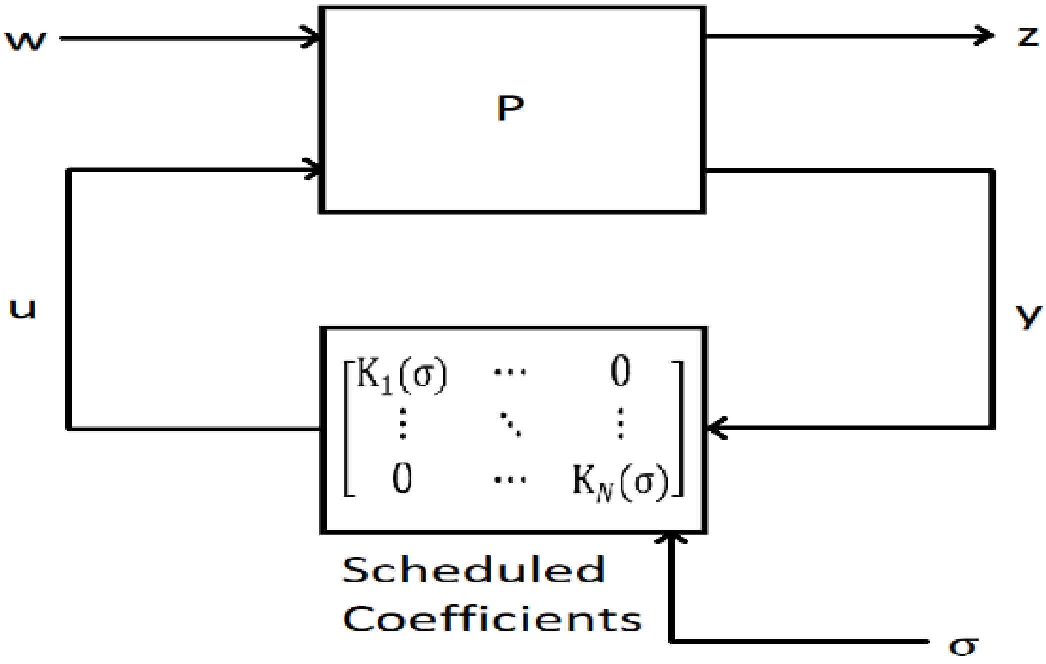

Figure 7.3. The standard form of the gain scheduling with fixed-structure.

Then, the plant P is linearized using Linear Parameter-Varying (LPV) method in order to obtain P(s,σ) which has the following form:

$$\dot{x} = A(\sigma)x + B_1(\sigma)w + B_2(\sigma)u \tag{28}$$

$$z = C_1(\sigma)x + D_{11}(\sigma)w + D_{12}(\sigma)u \tag{29}$$

$$y = C_2(\sigma)x + D_{21}(\sigma) + D_{22}(\sigma)u \tag{30}$$

where x denotes the model states, u is the input, y is the output signal, σ is scheduling variable vector, w is the disturbance input, z denotes the error signal, A(σ), B(σ), C(σ) and D(σ) are the controller gains matrices parameterized by the vector of the scheduling variable σ. To obtain this form, the dynamics of the plant should be linearized at specific operating conditions. As mentioned in literature, our autopilot model can be linearized using trim conditions in which $\dot{\alpha} = \dot{q} = 0$ for a range of speed and angle of attack (AOA) values (σ = (α, V)), then the scheduling procedure continues by (a) constructing a vector of finite number of operating points ($\sigma_1 . . . \sigma_M$). (b) Tuning the gains ($K_1 \ldots K_n$) for each of the operating points of the previously linearized plant P(s, σ). (c) The resulted gains are then interpolated to make it smooth and remove any sudden changes in the gains. Figure 7.4 shows an overview of the proposed gain scheduled controller applied for nonlinear radar guided missile. The nonlinear system takes the lateral acceleration demand ($A_{zdemand}$) and produces a lateral acceleration (A_z) which is measured and feedback to the controller. The value of the scheduled control parameters are function of the of the missile’s velocity and the incidence angle (V,α). There are 5 gain parameters scheduled and tuned which are (K_i, K_p, K_d, G_2, G_3) and 2 control parameters (μ, λ) that are tuned explicitly for the whole range of the 5 gain parameters (without scheduling).

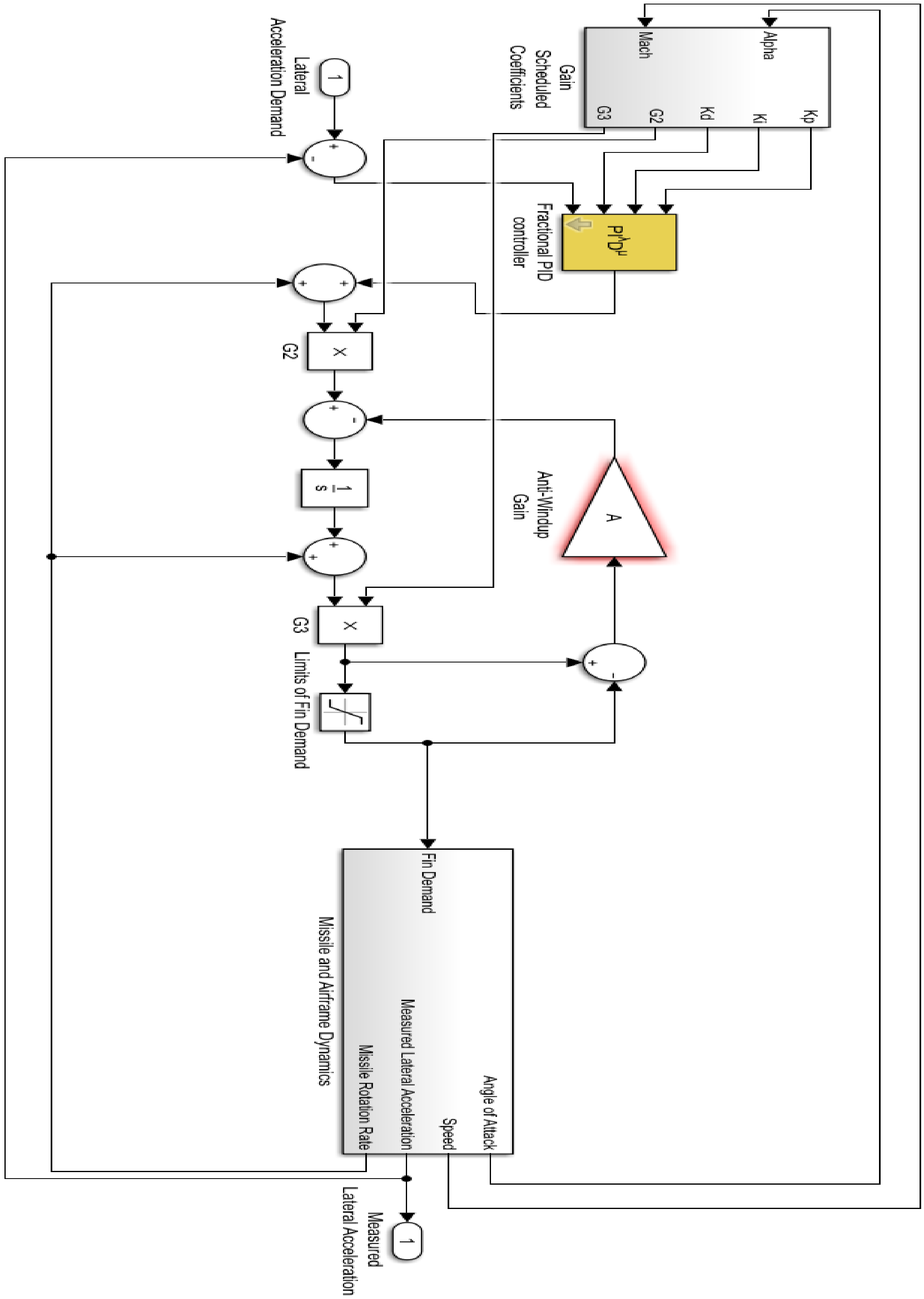

Figure 7.4. The proposed sliding mode fractional order controller integrated into autopilot system.

Linearization method is suitable for building a linear control system, however, when non-linear control system such as fractional order system is intended to be used as a controller, then linearizing the plant could degrade the performance of the fractional order controller. Also, when tuning a fractional order controller, an integer order control system might be obtained instead of fractional order one, knowing that integer order controller is very suitable for controlling linear systems. Therefore in the proposed controlled model, we will avoid linearizing the system, and genetic algorithm (GA) will be employed for tuning and scheduling the gains of the proposed fractional order three-loop autopilot controller (K_p, K_i, K_d, G_2 and G_3) as well as the fractional orders of the integration and derivation (μ and λ). The parameters used for the proposed scheduled control system are expressed in 2D matrices as below:

$$\sigma(\mathrm{m,n}) = \begin{bmatrix} (V_1,\alpha_1) & (V_1,\alpha_2) & \cdots & (V_1,\alpha_{n-1}) & (V_1,\alpha_n) \\ (V_2,\alpha_1) & (V_2,\alpha_2) & & (V_2,\alpha_{n-1}) & (V_2,\alpha_n) \\ \vdots & & \ddots & \vdots & \\ (V_{m-1},\alpha_1) & (V_{m-1},\alpha_2) & \cdots & (V_{m-1},\alpha_{n-1}) & (V_{m-1},\alpha_n) \\ (V_m,\alpha_1) & (V_m,\alpha_2) & & (V_m,\alpha_{n-1}) & (V_m,\alpha_n) \end{bmatrix} \tag{31}$$

$$\mathrm{Kp}(\sigma_{(m,n)}) = \begin{bmatrix} \mathrm{Kp}(\sigma_{1,1}) & \mathrm{Kp}(\sigma_{1,2}) & \cdots & \mathrm{Kp}(\sigma_{1,n-1}) & \mathrm{Kp}(\sigma_{1,n}) \\ \mathrm{Kp}(\sigma_{2,1}) & \mathrm{Kp}(\sigma_{2,2}) & & \mathrm{Kp}(\sigma_{2,n-1}) & \mathrm{Kp}(\sigma_{2,n}) \\ \vdots & & \ddots & \vdots & \\ \mathrm{Kp}(\sigma_{m-1,1}) & \mathrm{Kp}(\sigma_{m-1,2}) & \cdots & \mathrm{Kp}(\sigma_{m-1,n-1}) & \mathrm{Kp}(\sigma_{m-1,n}) \\ \mathrm{Kp}(\sigma_{m,1}) & \mathrm{Kp}(\sigma_{m,2}) & & \mathrm{Kp}(\sigma_{m,n-1}) & \mathrm{Kp}(\sigma_{m,n}) \end{bmatrix} \tag{32}$$

$$\mathrm{Ki}(\sigma_{(m,n)}) = \begin{bmatrix} \mathrm{Ki}(\sigma_{1,1}) & \mathrm{Ki}(\sigma_{1,2}) & \cdots & \mathrm{Ki}(\sigma_{1,n-1}) & \mathrm{Ki}(\sigma_{1,n}) \\ \mathrm{Ki}(\sigma_{2,1}) & \mathrm{Ki}(\sigma_{2,2}) & & \mathrm{Ki}(\sigma_{2,n-1}) & \mathrm{Ki}(\sigma_{2,n}) \\ \vdots & & \ddots & \vdots & \\ \mathrm{Ki}(\sigma_{m-1,1}) & \mathrm{Ki}(\sigma_{m-1,2}) & \cdots & \mathrm{Ki}(\sigma_{m-1,n-1}) & \mathrm{Ki}(\sigma_{m-1,n}) \\ \mathrm{Ki}(\sigma_{m,1}) & \mathrm{Ki}(\sigma_{m,2}) & & \mathrm{Ki}(\sigma_{m,n-1}) & \mathrm{Ki}(\sigma_{m,n}) \end{bmatrix} \tag{33}$$

$$\mathrm{Kd}(\sigma_{(m,n)}) = \begin{bmatrix} \mathrm{Kd}(\sigma_{1,1}) & \mathrm{Kd}(\sigma_{1,2}) & \cdots & \mathrm{Kd}(\sigma_{1,n-1}) & \mathrm{Kd}(\sigma_{1,n}) \\ \mathrm{Kd}(\sigma_{2,1}) & \mathrm{Kd}(\sigma_{2,2}) & & \mathrm{Kd}(\sigma_{2,n-1}) & \mathrm{Kd}(\sigma_{2,n}) \\ \vdots & & \ddots & \vdots & \\ \mathrm{Kd}(\sigma_{m-1,1}) & \mathrm{Kd}(\sigma_{m-1,2}) & \cdots & \mathrm{Kd}(\sigma_{m-1,n-1}) & \mathrm{Kd}(\sigma_{m-1,n}) \\ \mathrm{Kd}(\sigma_{m,1}) & \mathrm{Kd}(\sigma_{m,2}) & & \mathrm{Kd}(\sigma_{m,n-1}) & \mathrm{Kd}(\sigma_{m,n}) \end{bmatrix} \quad (34)$$

$$\mathrm{G2}(\sigma_{(m,n)}) = \begin{bmatrix} \mathrm{G2}(\sigma_{1,1}) & \mathrm{G2}(\sigma_{1,2}) & \cdots & \mathrm{G2}(\sigma_{1,n-1}) & \mathrm{G2}(\sigma_{1,n}) \\ \mathrm{G2}(\sigma_{2,1}) & \mathrm{G2}(\sigma_{2,2}) & & \mathrm{G2}(\sigma_{2,n-1}) & \mathrm{G2}(\sigma_{2,n}) \\ \vdots & & \ddots & \vdots & \\ \mathrm{G2}(\sigma_{m-1,1}) & \mathrm{G2}(\sigma_{m-1,2}) & \cdots & \mathrm{G2}(\sigma_{m-1,n-1}) & \mathrm{G2}(\sigma_{m-1,n}) \\ \mathrm{G2}(\sigma_{m,1}) & \mathrm{G2}(\sigma_{m,2}) & & \mathrm{G2}(\sigma_{m,n-1}) & \mathrm{G2}(\sigma_{m,n}) \end{bmatrix} \quad (35)$$

$$\mathrm{G3}(\sigma_{(m,n)}) = \begin{bmatrix} \mathrm{G3}(\sigma_{1,1}) & \mathrm{G3}(\sigma_{1,2}) & \cdots & \mathrm{G3}(\sigma_{1,n-1}) & \mathrm{G3}(\sigma_{1,n}) \\ \mathrm{G3}(\sigma_{2,1}) & \mathrm{G3}(\sigma_{2,2}) & & \mathrm{G3}(\sigma_{2,n-1}) & \mathrm{G3}(\sigma_{2,n}) \\ \vdots & & \ddots & \vdots & \\ \mathrm{G3}(\sigma_{m-1,1}) & \mathrm{G3}(\sigma_{m-1,2}) & \cdots & \mathrm{G3}(\sigma_{m-1,n-1}) & \mathrm{G3}(\sigma_{m-1,n}) \\ \mathrm{G3}(\sigma_{m,1}) & \mathrm{G3}(\sigma_{m,2}) & & \mathrm{G3}(\sigma_{m,n-1}) & \mathrm{G3}(\sigma_{m,n}) \end{bmatrix} \quad (36)$$

7.2. Simulation Results

7.2.1. Conventional Three-Loop Autopilot

In radar guided missile, a radar is usually implemented on gimbals inside the body of the missile, this radar is responsible for tracking the target and provide the missile with the exact location of the target continuously by controlling the gimbal angle. To achieve a better controlling efficiency, the gimbals have to be aligned with the look angle after the target is locked by the radar. Figure 7.5 shows the influence of using the conventional autopilot control system on the behavior of the radar system.

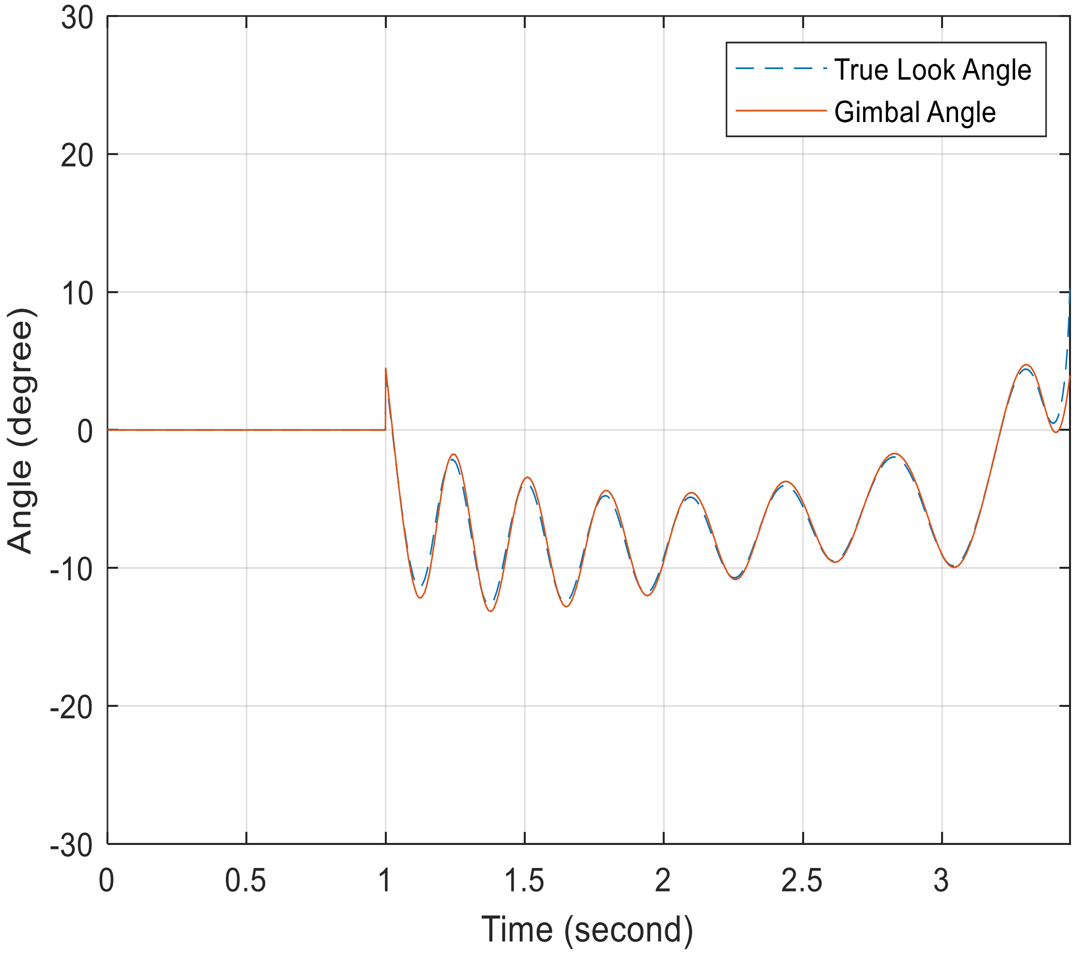

Figure 7.5. True look angle vs gimbal angle of the conventional autopilot system.

As seen in the figure, the gimbal angle is changing frequently in order to track the continuous changing of the true angle, the oscillation in the true angle along with the radar gimbal angle is due to the unstable movement of the missile. Despite these oscillations, the radar was efficiently tracking the true look angle formed by the target and the missile until the missile got near the target (vicinity of impact region) where the angle of the gimbals for the radar tracking system fell behind the true look as depicted in Figure 7.6.

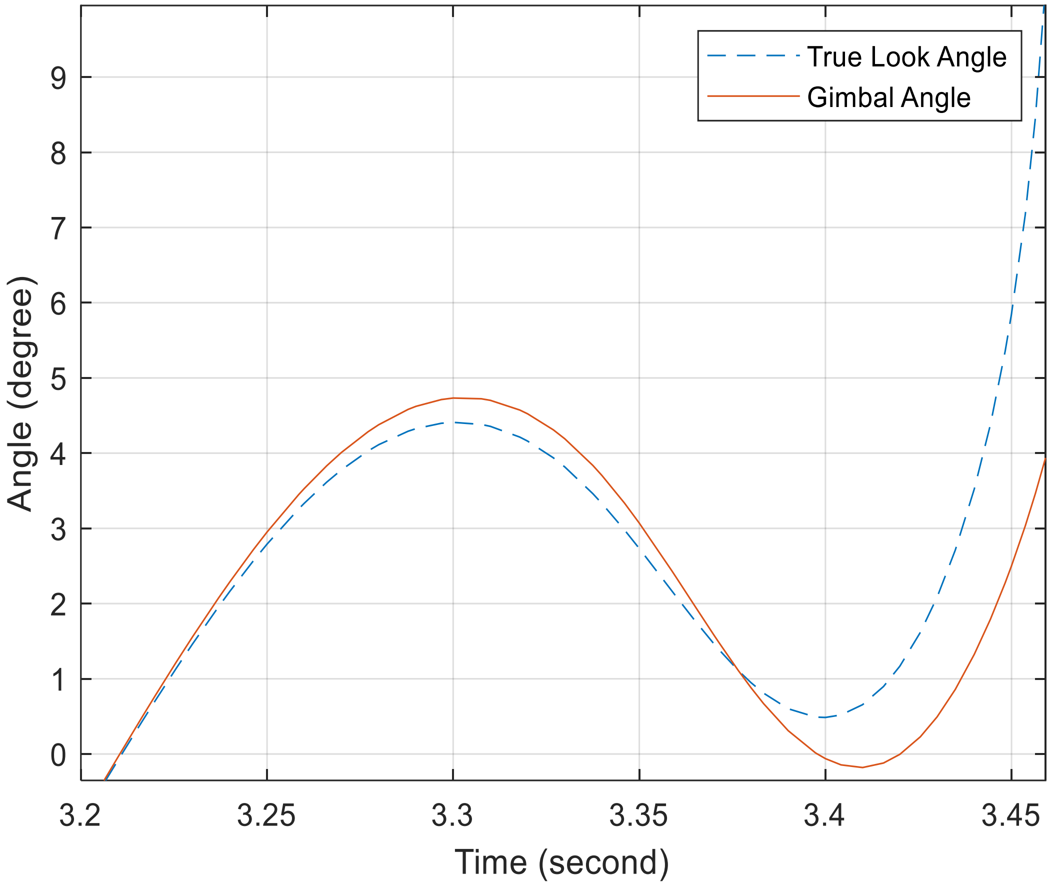

Figure 7.6. Vicinity of impact region for true look angle vs gimbal angle of the conventional autopilot system.

The behavior of the missile in term of angle of attack is also shown in Figure 7.7. The angle of attack is oscillating during the flight time, which emphasizes the oscillatory movement of the missile.

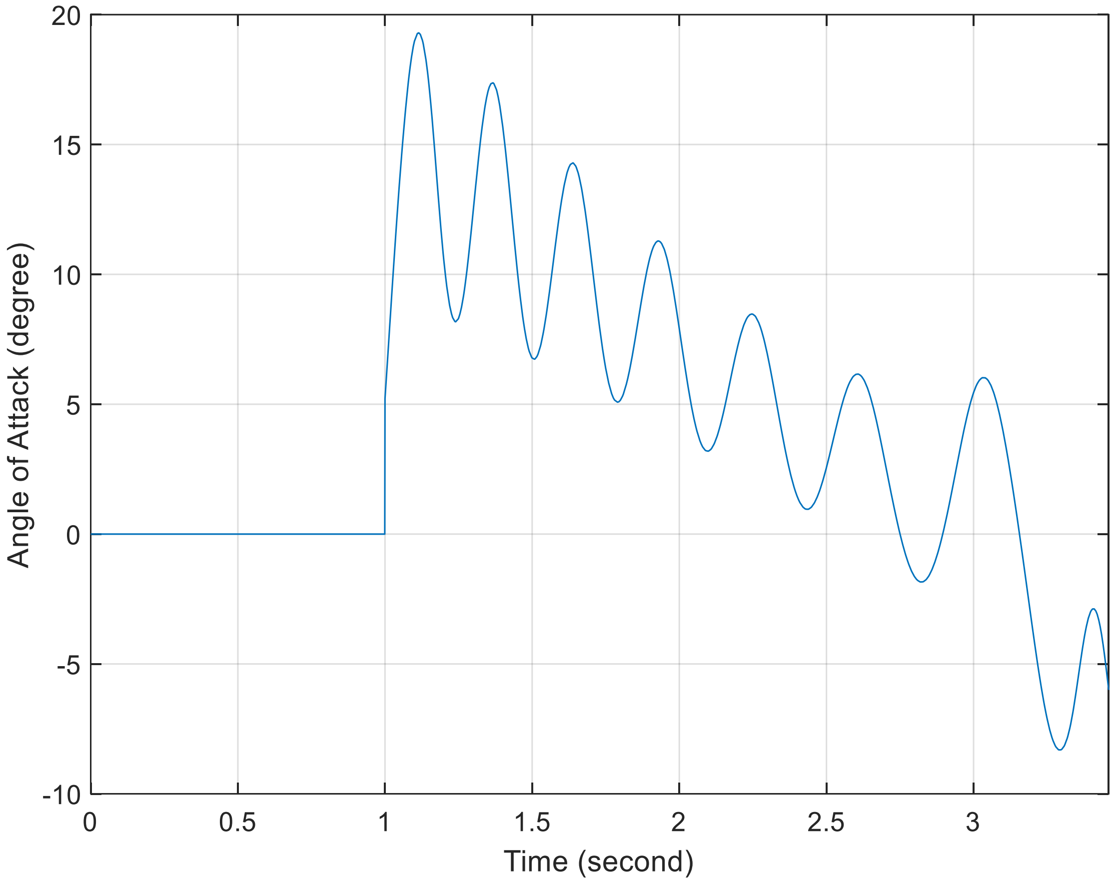

Figure 7.7. incidence angle of the missile for the conventional autopilot system.

Also, the changes in the amplitude of the oscillation increased dramatically near impact region as elaborated in Figure 7.8 which is a zoomed version of Figure 7.7 near the impact region.

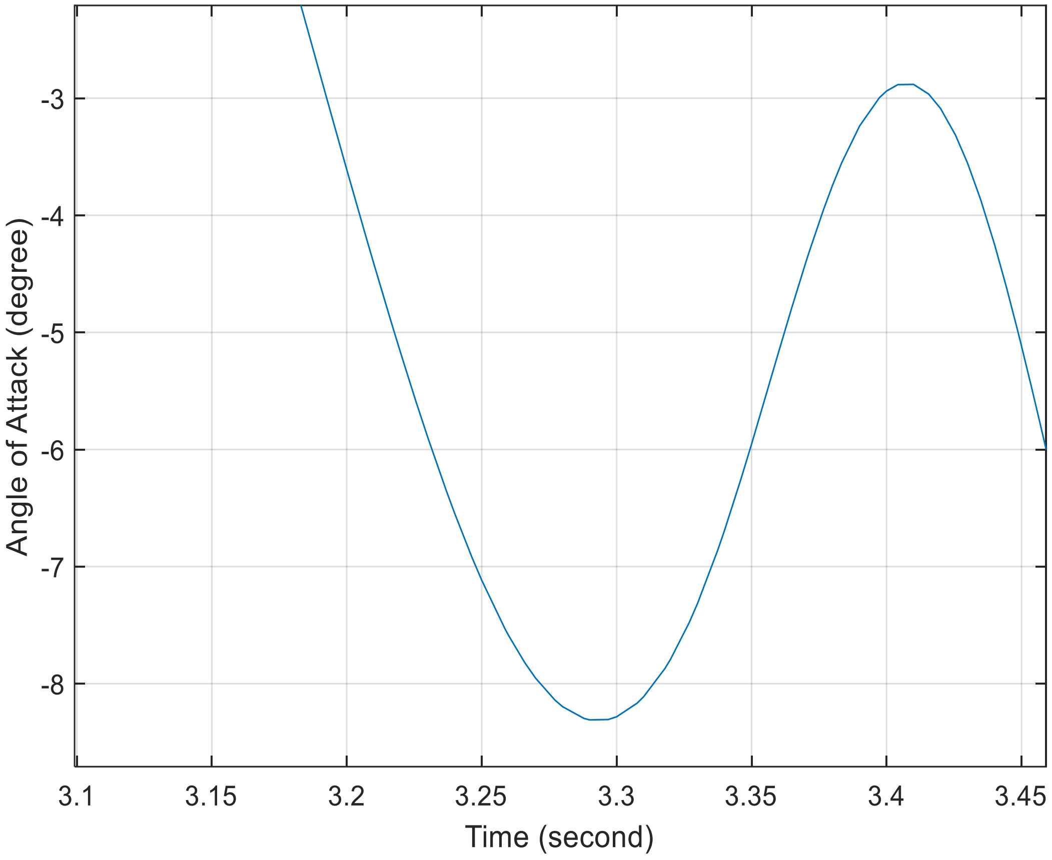

Figure 7.8. Vicinity of impact region for the angle of attack of the conventional autopilot system.

The autopilot system takes the normal acceleration as an input and then generates fin demands as an output. The normal acceleration is needed to keep the missile on the right track. The computation system in the missile uses the information regarding the position, speed and rotation angle of the missile to compute the deviation of the target from the missile, then the demanded normal acceleration is computed and sent to the autopilot system. The autopilot system uses the demanded acceleration to generate control commands to the moving parts of the missile such as its fins, which in turn generate the normal acceleration equals to the demanded acceleration required to put the missile on the right path. The demanded lateral acceleration needed to adjust the direction of the missile toward the target is shown in Figure 7.9. The demanded acceleration is oscillating most of the time which indicates continues need for correcting the movement direction of the missile during flight time.

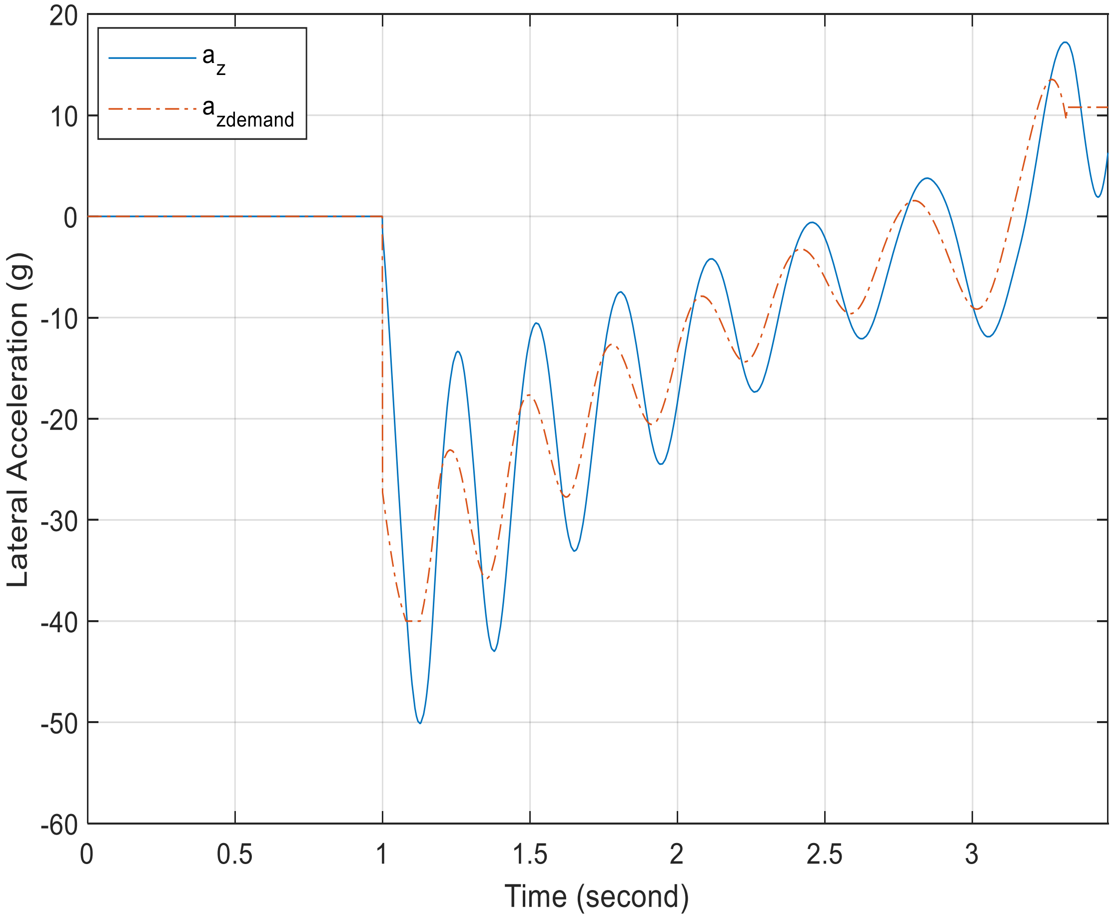

Figure 7.9. Lateral acceleration for the conventional autopilot system.

In addition, the normal acceleration fell behind the demanded acceleration most of the time and especially near impact region as shown in Figure 7.10 which provides poor controlling performance of the conventional autopilot for correcting the direction of the missile toward the target.

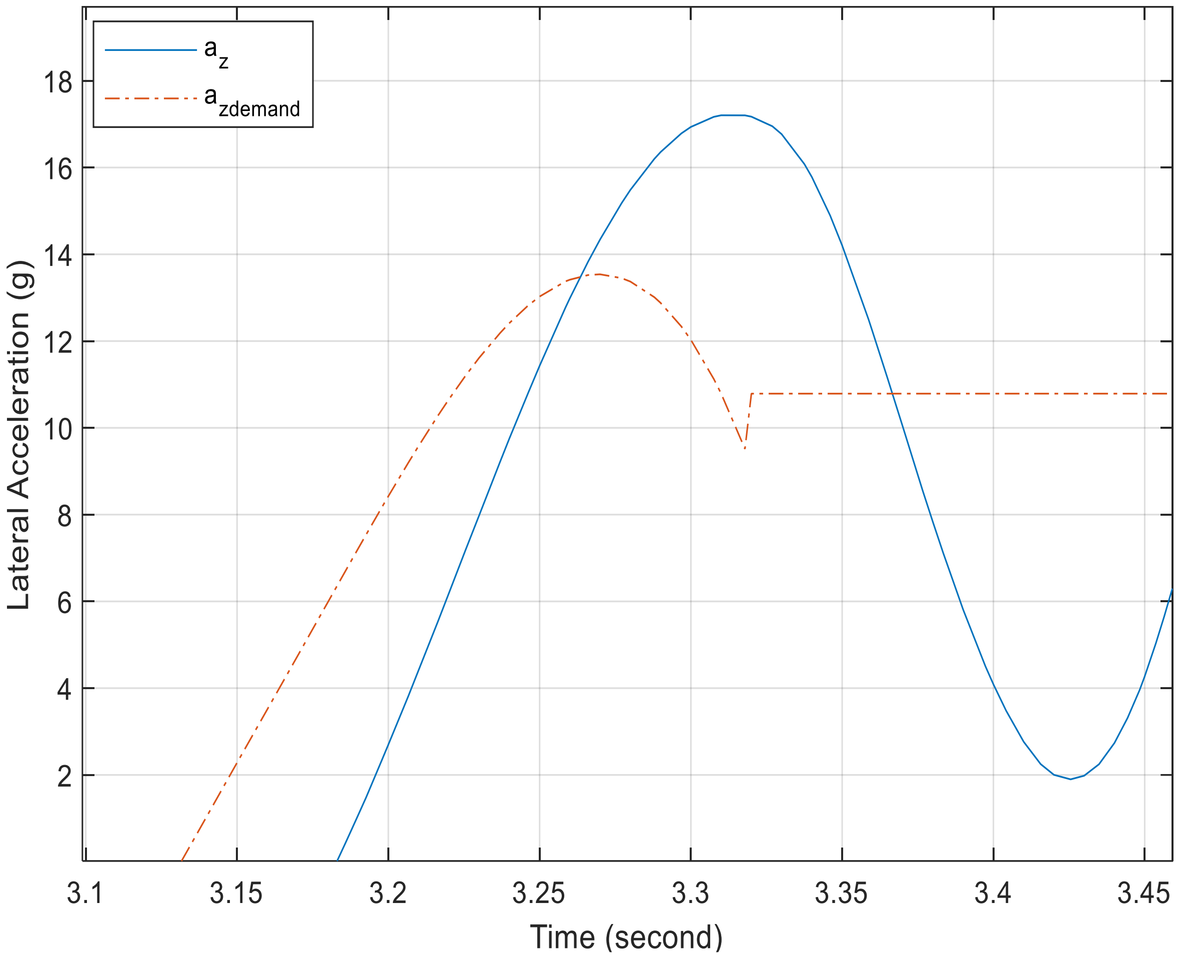

Figure 7.10. Vicinity of impact region for the lateral acceleration of the conventional autopilot system.

7.2.2. Fractional Order PID Autopilot system

The performance of the radar tracking system after implementing the fractional order PID is depicted in Figure 7.11.

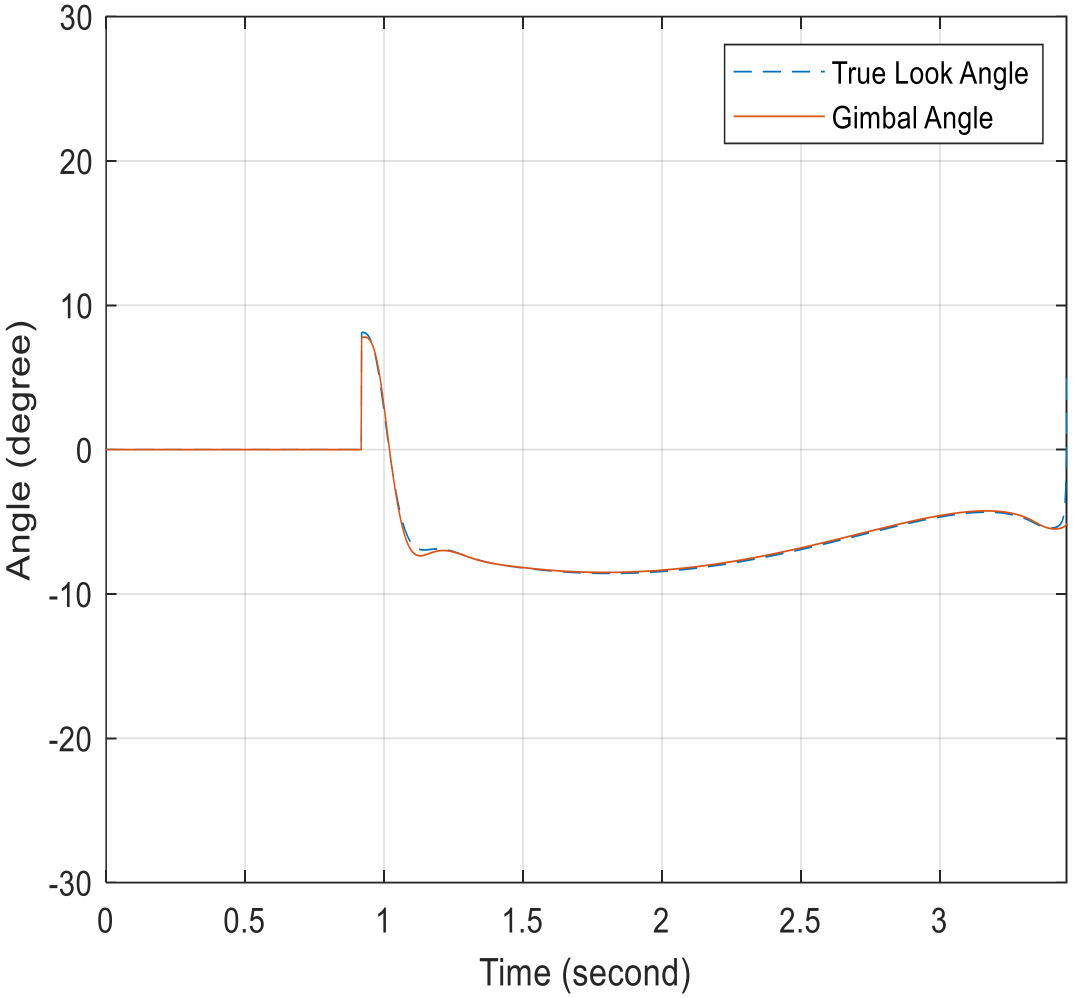

Figure 7.11. Gimbal angle against look angle of the fractional order integrated into autopilot system.

As seen in the figure, the behavior of the radar is almost stable, the radar tracked the target efficiently except in the vicinity of impact region, where the unstable movement of the missile near the impact region caused the gimbal angle of the radar system to fall behind the true look angle. A detailed plot of the vicinity of impact region is elaborated in Figure 7.12.

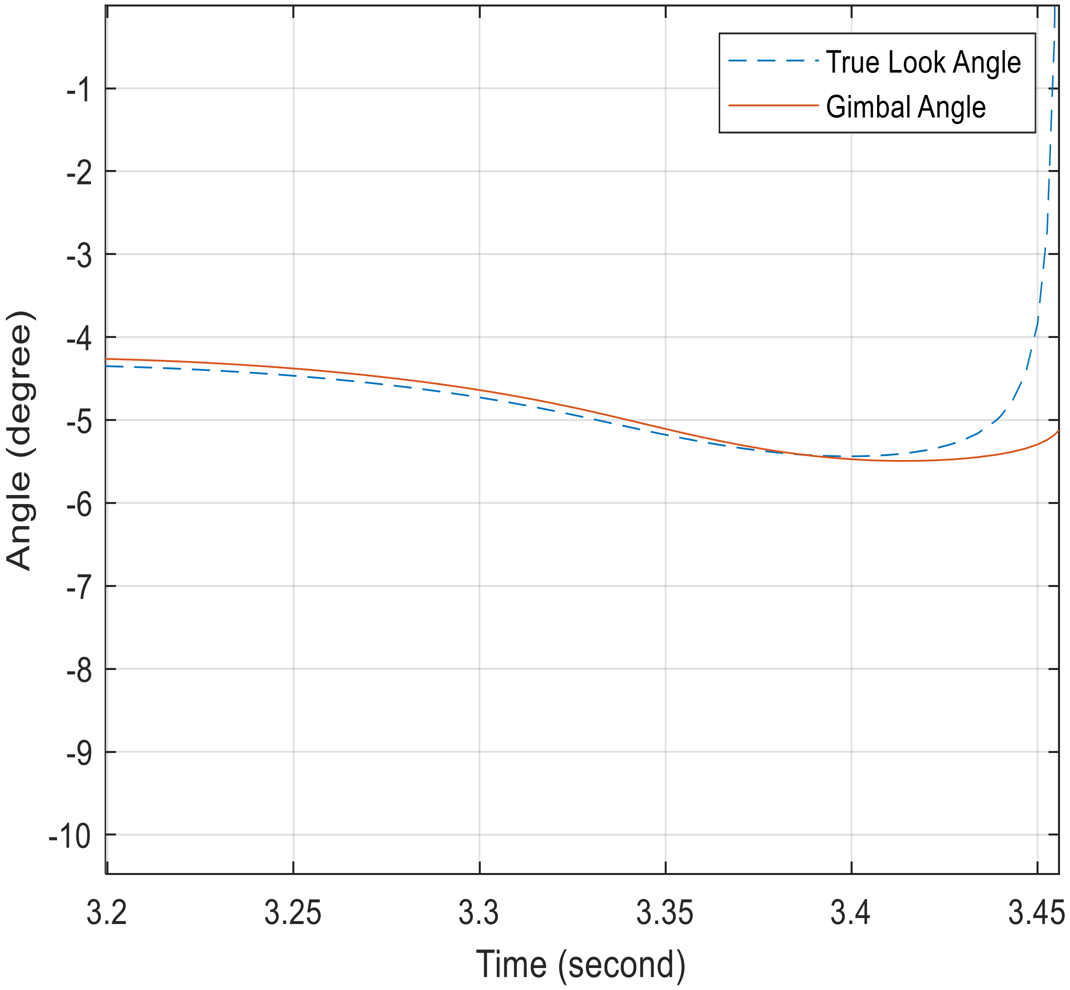

Figure 7.12. Vicinity of impact region for gimbal angle against look angle of the fractional order integrated into autopilot system.

The incidence angle of the missile is shown in Figure 7.13. The changing in the incidence angle using the integrated fractional order PID is very smooth during flight time compared with the conventional autopilot system, but during the terminal phase (vicinity of impact region), the autopilot control system showed unstable behavior in which it started to oscillate.

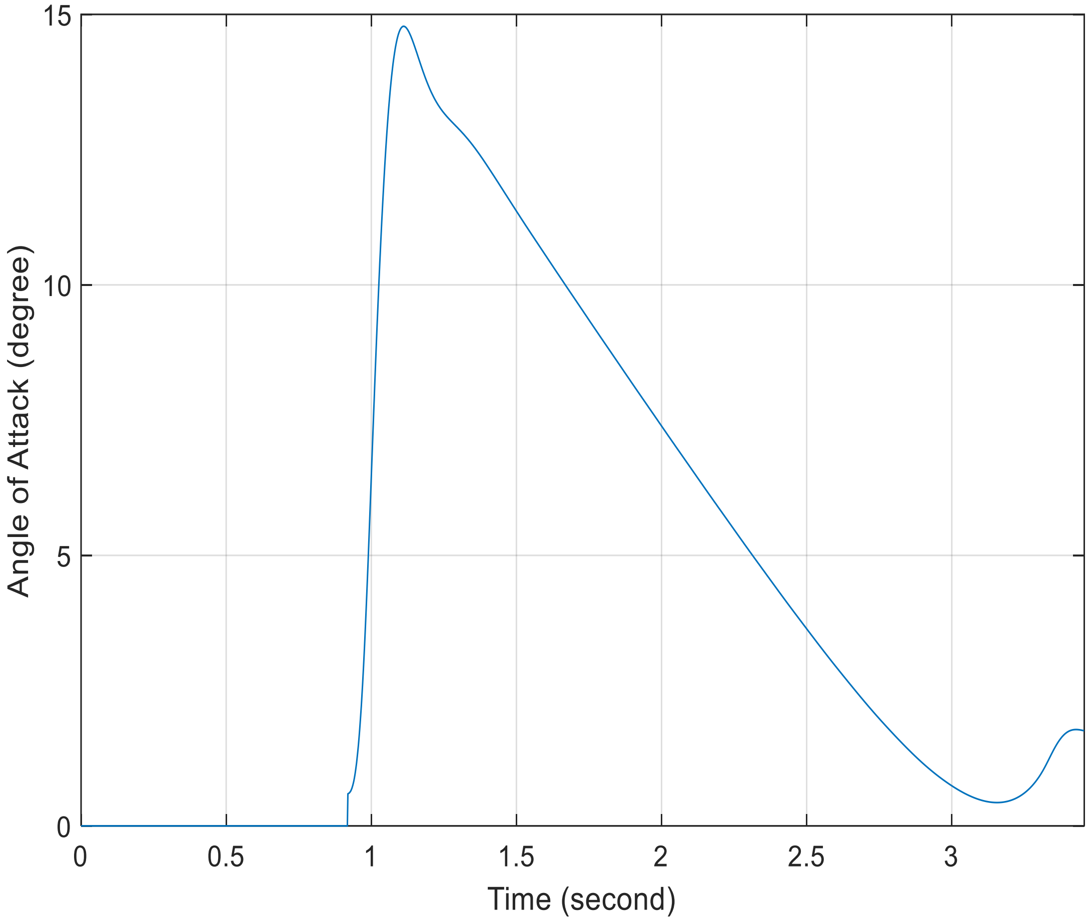

Figure 7.13. Speed and incidence angle of the missile for the fractional order PID integrated into autopilot system.

The behavior of the incidence angle near impact region is shown in Figure 7.14.

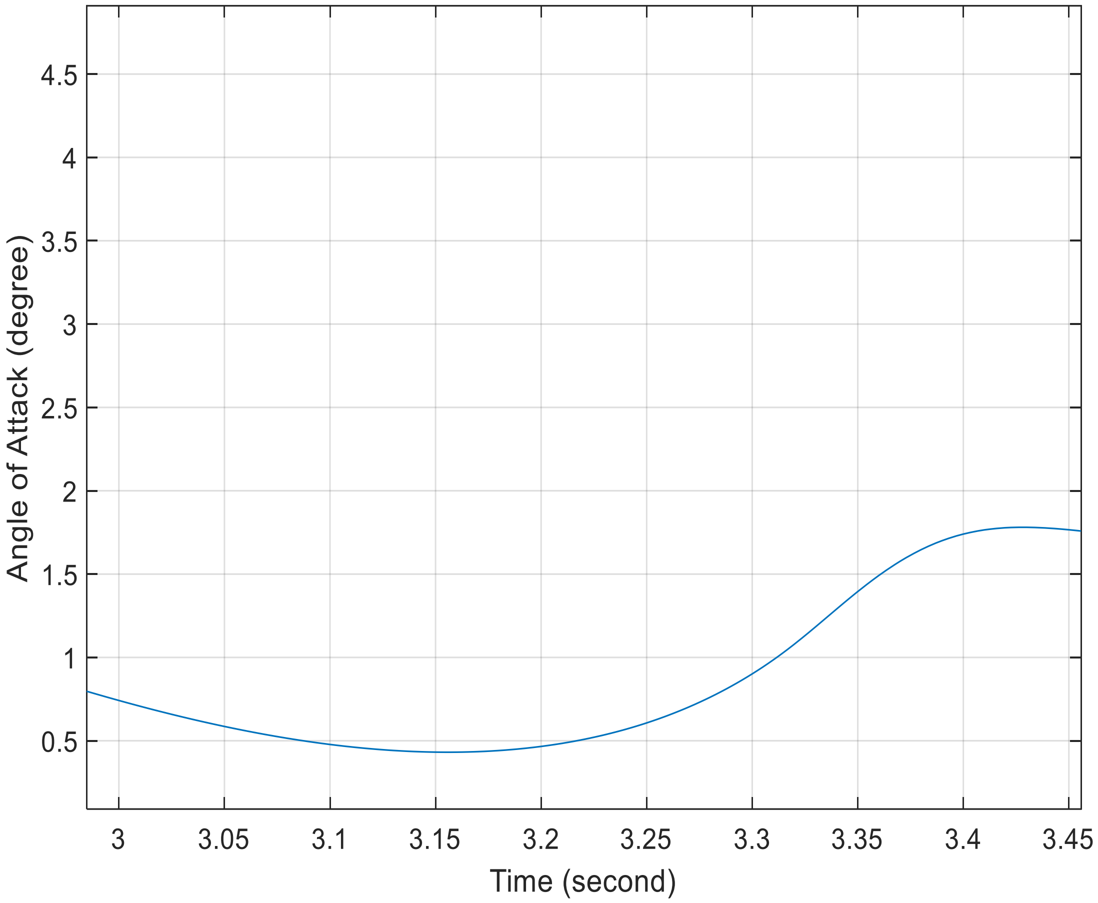

Figure 7.14. Vicinity of impact region for the angle of attack of the fractional order PID integrated into autopilot system.

The performance of the autopilot system for generating the required normal acceleration due to the autopilot is elaborated in Figure 7.15.

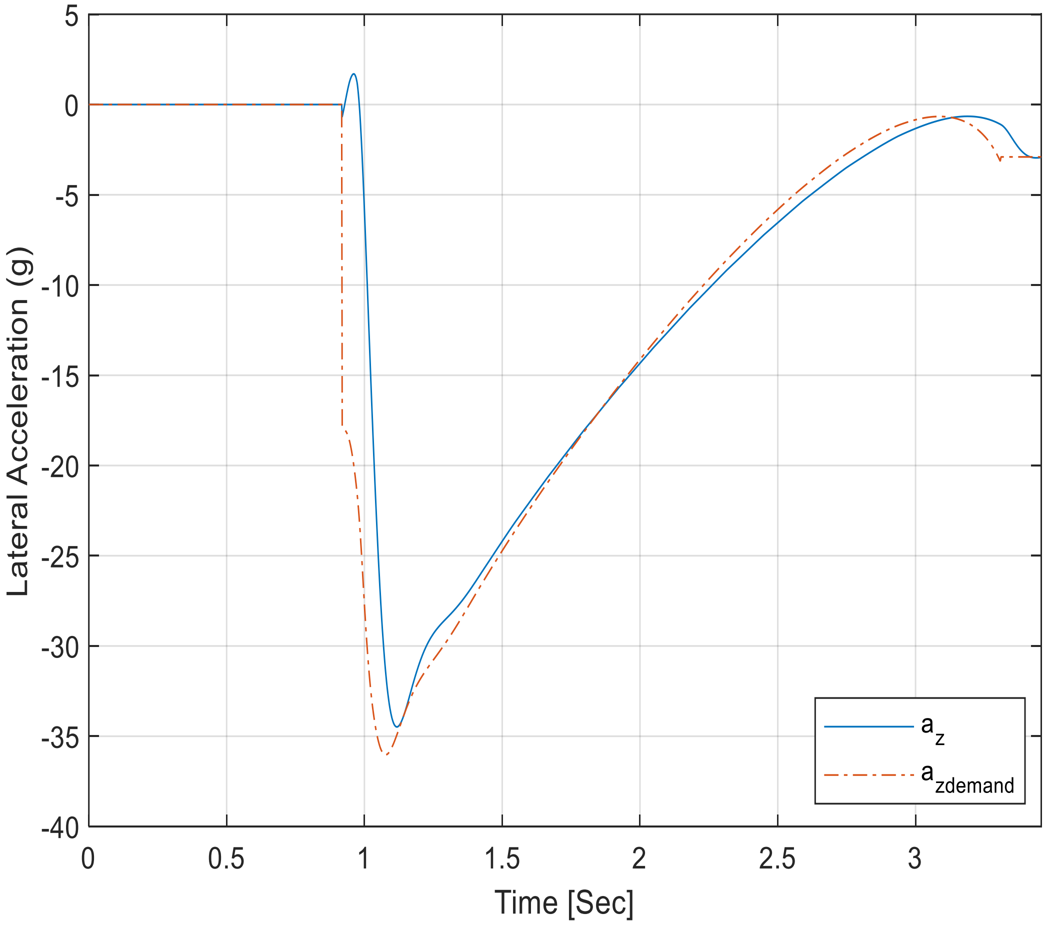

Figure 7.15. Lateral acceleration for the fractional order PID integrated into autopilot system.

All of these figures show good performance during flight time except for the vicinity of impact region. In the vicinity of impact region, the normal acceleration generated by the missile failed to follow the demanded normal acceleration that is computed by the missile computation device as elaborated in Figure 7.16.

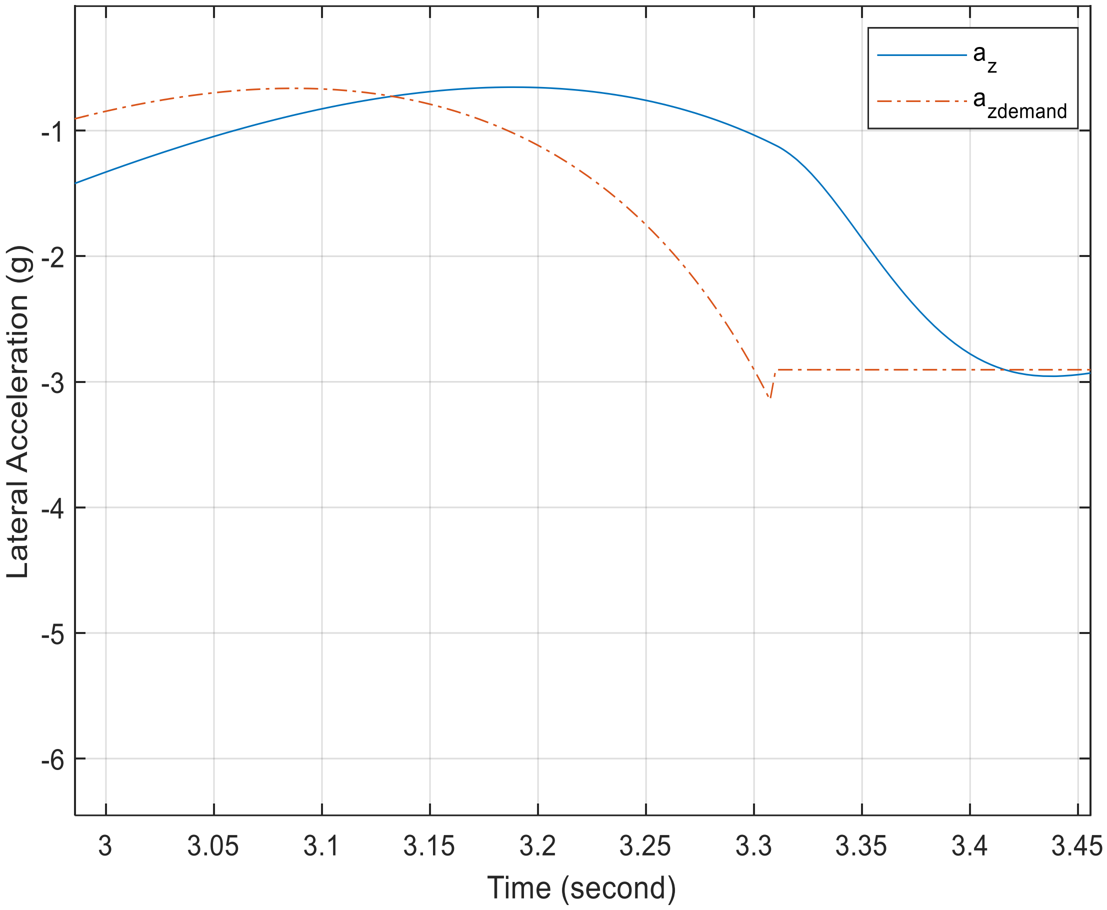

Figure 7.16. Vicinity of impact region for the lateral acceleration of the fractional order PID integrated into autopilot system.

7.2.3. Adaptive sliding mode Fractional Order PID Autopilot system

After implementing the proposed adaptive sliding mode fractional order PID, the efficiency of the radar system for following the true angle is depicted in Figure 7.17. Unlike the previous methods, this proposed autopilot system that depend on sliding mode control successfully stabilized the radar tracking system of the missile during the flight time and especially near impact region. As mentioned in literature, it has been found that the control parameters of the autopilot system are highly affected by the speed of the missile and the incidence angle of the missile during flight time, therefore the sliding mode fractional order PID takes the angle of attack as well as the speed of the missile as indices of the look up table to choose the right parameters for the FOPID controller during flight time. The resulted normal acceleration, angle of attack and speed of the missile due to the proposed sliding mode fractional order PID are stable during flight time and even near impact region as shown in figures below.

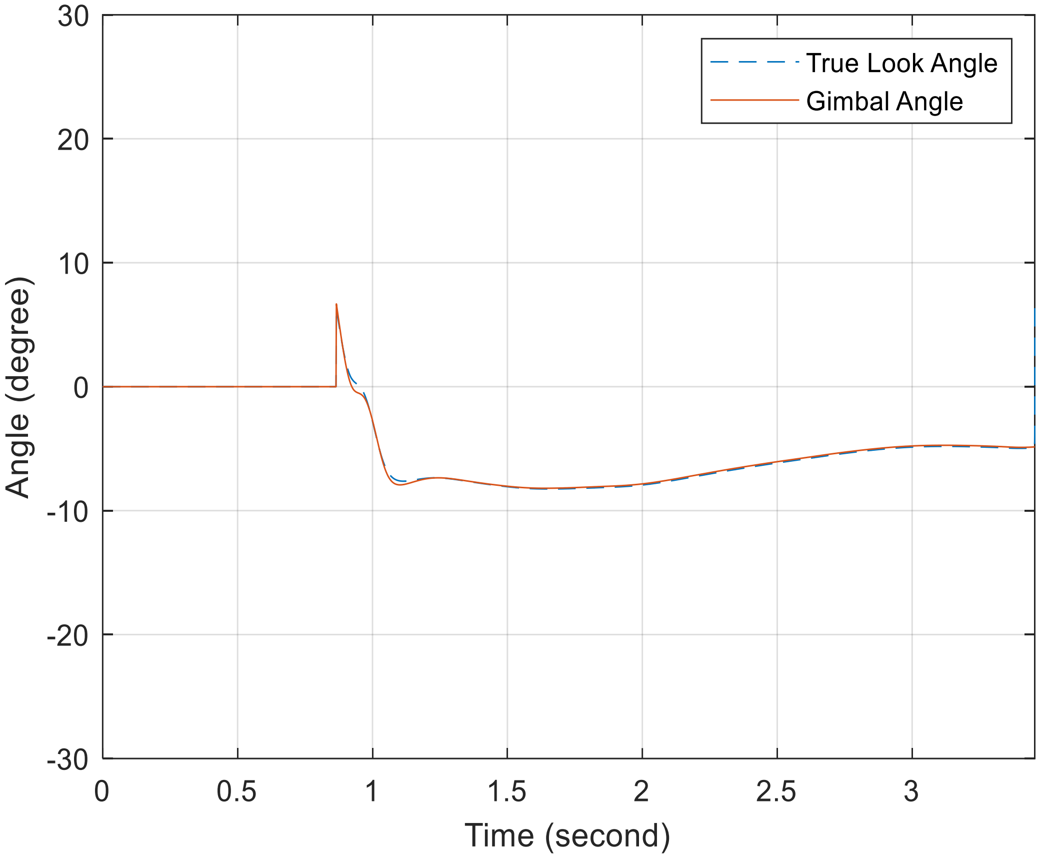

Figure 7.17. Gimbal angle against look angle of the sliding mode fractional order PID integrated into autopilot system.

As shown in the previous figure, in the FOPID system, the gimbal angle is able to track any changes in the look angle, and they were following the target efficiently without oscillations.

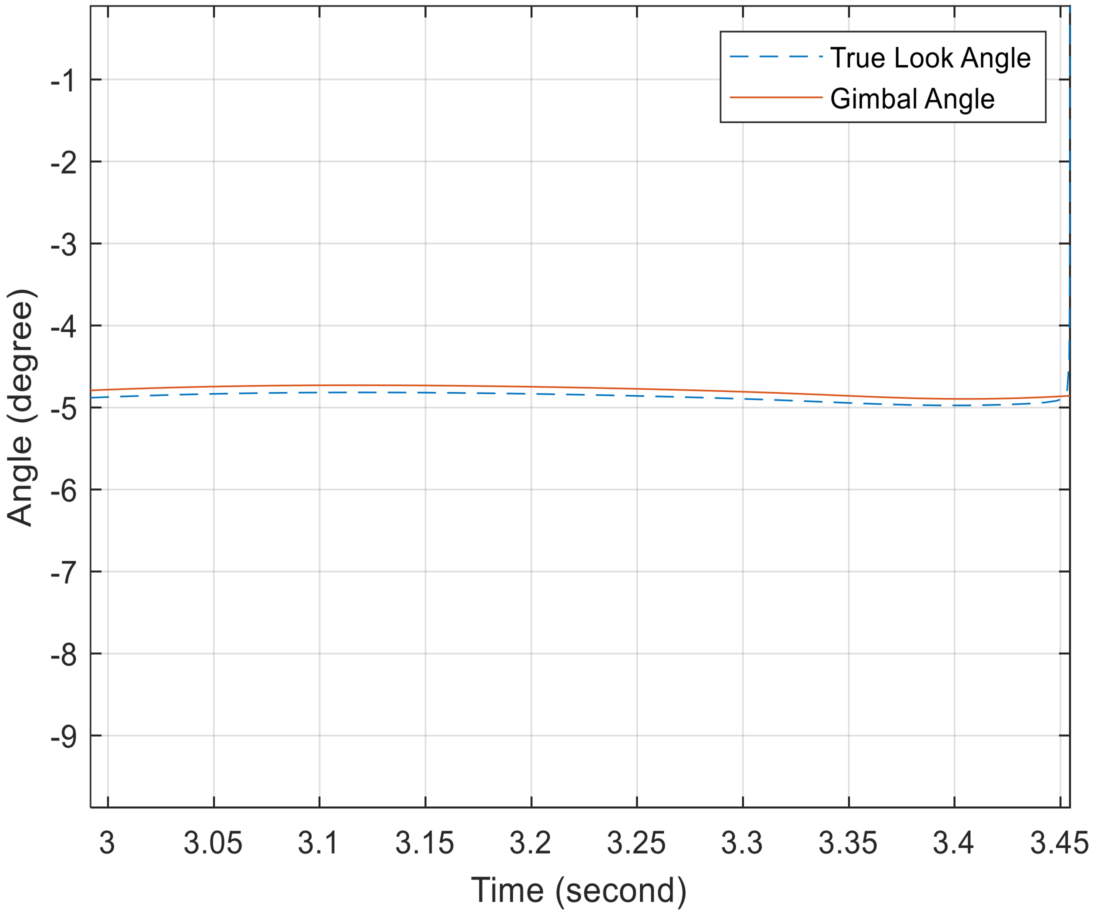

Figure 7.18. Vicinity of impact region for gimbal angle against look angle of the sliding mode fractional order PID integrated into autopilot system.

The previous figure demonstrates the vicinity of impact region for the FOPID system. As shown in the figure, there where no oscillation at the vicinity of impact region.

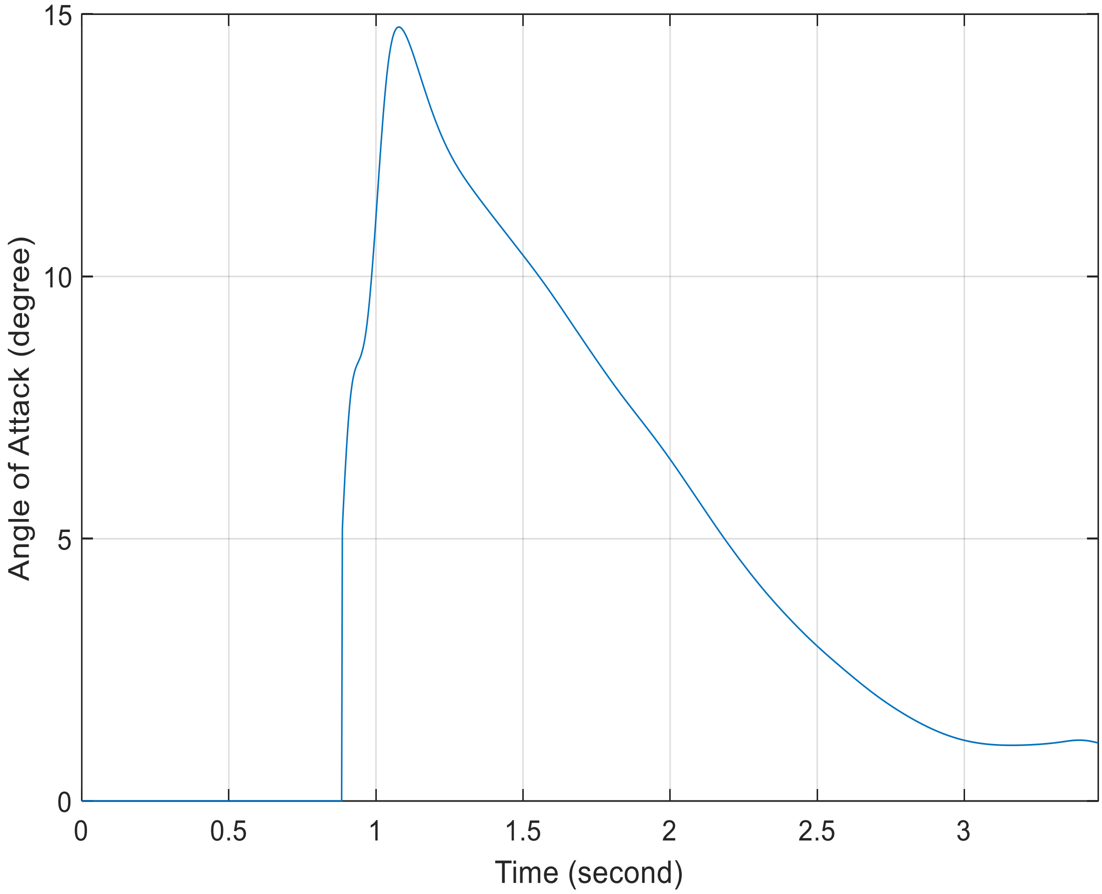

Figure 7.19. incidence angle of the missile for the sliding mode fractional order PID integrated into autopilot system.

The previous figure shows the behavior of Angle of Attack for the proposed FOPID. After the radar found the target at about the first second, the angle of attack changed suddenly to track the target, and then started to move smoothly until the missile impacted with the target.

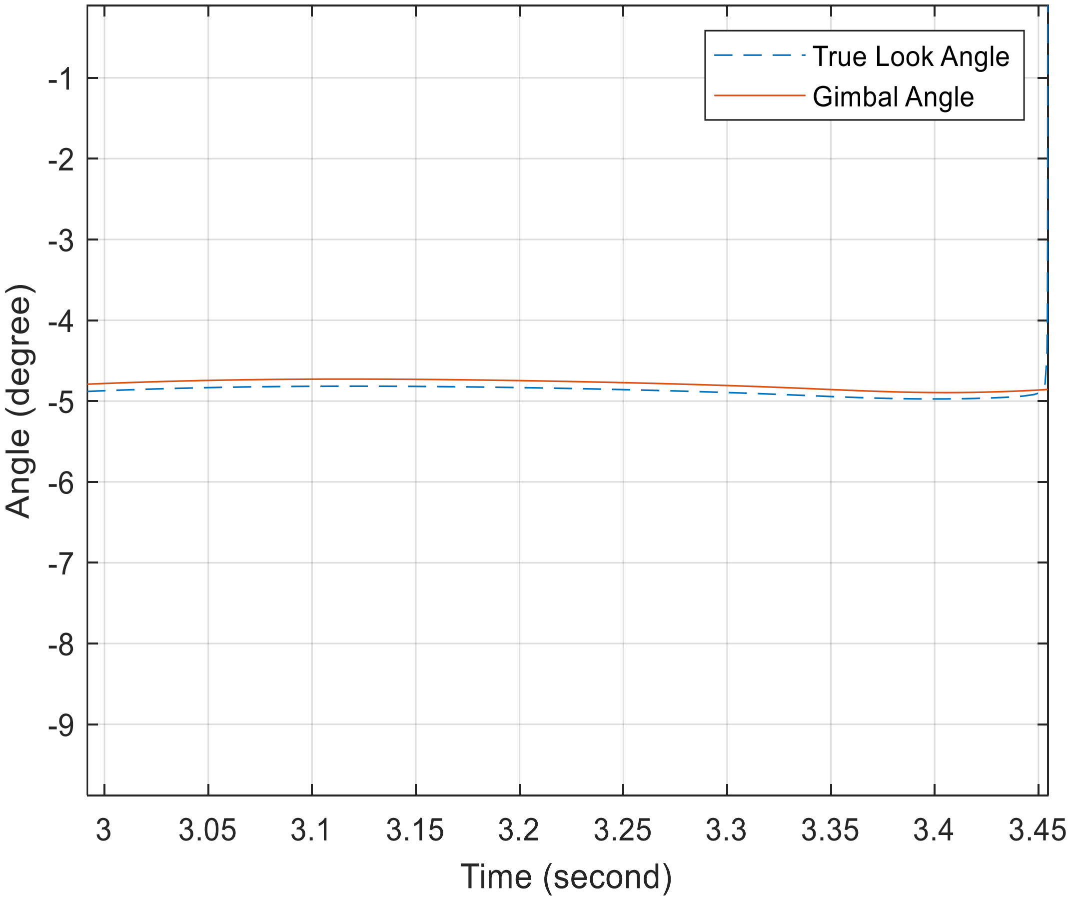

Figure 7.20. Vicinity of impact region for the angle of attack of the sliding mode fractional order PID integrated into autopilot system.

The previous figure shows the angle of attack at the vicinity of impact region. It’s proved by this figure that the missile didn’t show any oscillations near the time of impact.

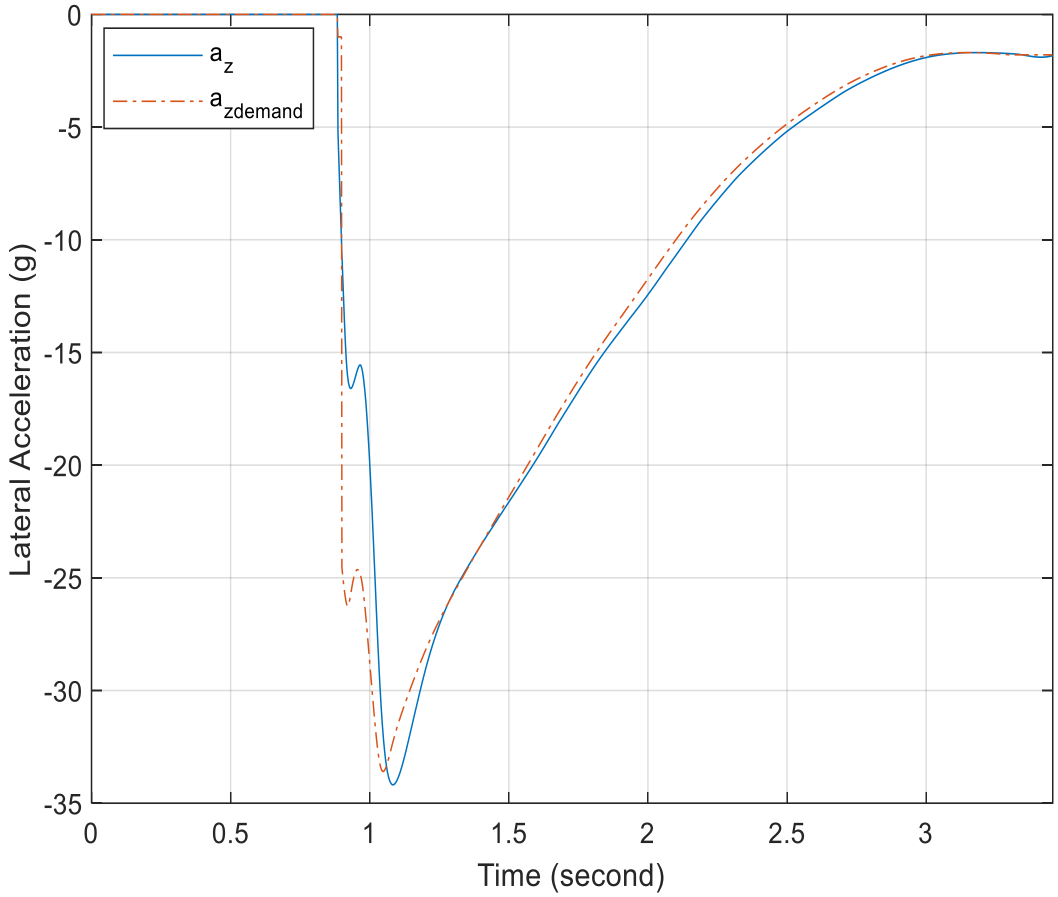

Figure 7.21. Lateral acceleration for the sliding mode fractional order PID integrated into autopilot system.

The previous figure shows the lateral acceleration using the sliding mode fractional order PID. The figure shows smooth behavior for the lateral acceleration during flight time and a good ability to track the demanded acceleration generated by the missile. The Next figure shows the lateral acceleration near the impact region which proves to have smooth behavior at the vicinity of impact.

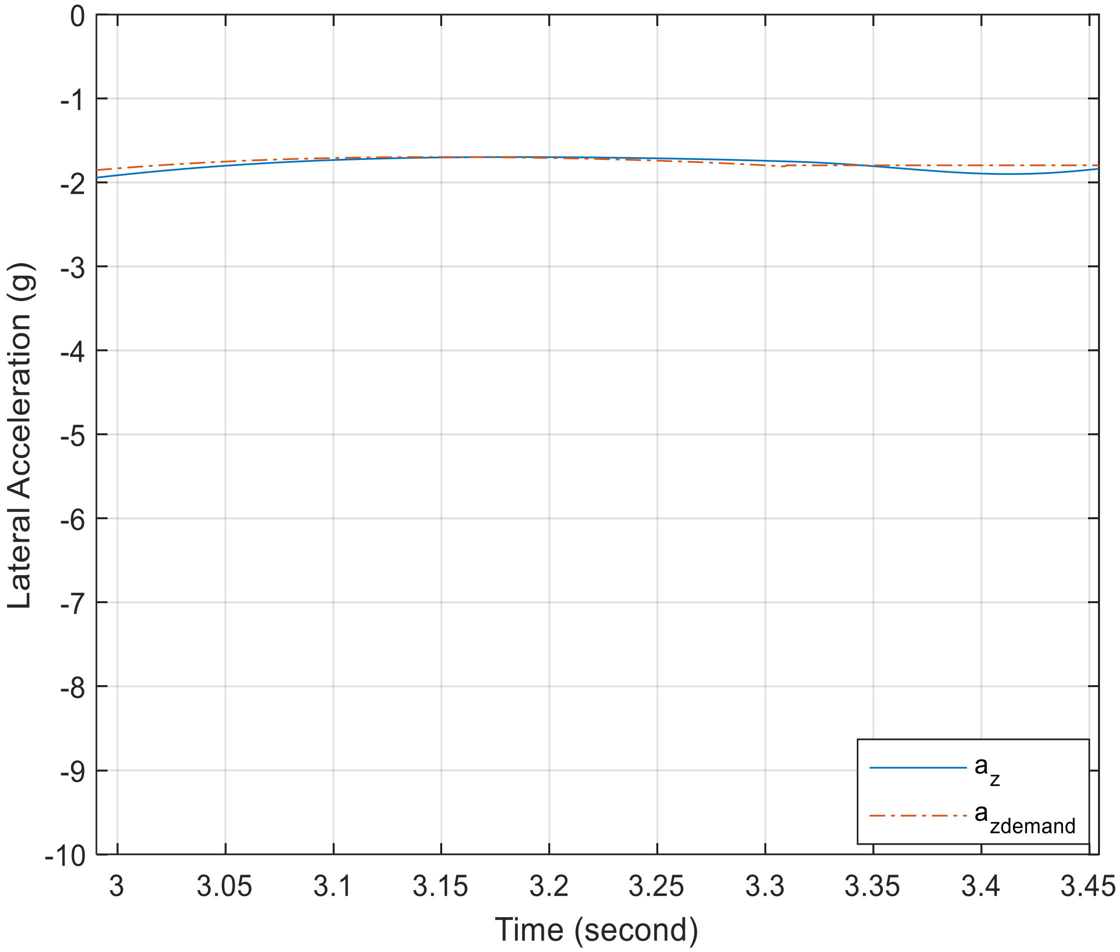

Figure 7.22. Vicinity of impact region for the lateral acceleration of the sliding mode fractional order PID integrated into autopilot system.

All of these previous figures prove the efficiency of the proposed sliding mode FOPID control system over the previous methods.

Table 7.1 shows the miss distance, H_2 and H_∞ performance metrics for the three controlling methods implemented to the autopilot system.

Table 7.1. Miss distance, H_2 and H_∞ of the three autopilot systems

Performance metric	**Conventional Three-loop Autopilot**	**Fractional Order PID Controller**	**Sliding Mode Factional Order PID**
Miss Distance	19.0782	3.1419	0.0549
H_2	2176.5	1801.1	1086.1
H_∞	265.2433	225.2670	136.6848

As presented in the table, the performance of the proposed sliding FOPID is outstanding compared to the conventional method in which the miss distance was 0.0549, which indicates a very high accuracy of the introduced controlling system for intercepting the target at the center. The 2-norm value H_2 of the implemented design is much less than of the conventional autopilot method, which indicates much more stability during the whole flight time for the implemented design. Also, the low value of the infinity norm H_∞ of the implemented design compared to the conventional one indicates that the highest error in the controller is much lower for the proposed sliding mode fractional order system.

7.3. Summary

By this chapter, a new autopilot structure based on sliding FOPID controller is proposed and employed to a nonlinear radar guided missile. The purpose of this autopilot structure is to direct a missile toward a target with low miss distance and high tracking performance. The adaptive sliding mode controlling system was optimized using genetic algorithm combined with mixed H_2/H_∞ optimization technique. Unlike the standard method, this method doesn’t include linearizing the system at multi operating points, which could achieve better tracking performance, but in the cost of possible sudden changes for short time intervals in the system behavior. The standard method that is used to overcome sudden changes problem is by interpolating the scheduled values, which might change the optimum values and degrade the controller performance, therefore mixed H_2/H_∞ is employed with genetic algorithm to guarantee smooth behavior of the system without any sudden changes. The superiority of the proposed control system is justified by the simulation results which showed smooth and stable behavior for the proposed sliding mode FOPID controller. Also, miss distance, H_2 and H_∞ values of the system showed better performance values achieved by the proposed autopilot system.

8. Neural FOPID Controller

8.1. Controller Design and Tuning

In this chapter, we are introducing a FOPID which can be applied to the navigation system of a high-speed aerial system or a missile. The proposed controller is applied and tested against the conventional PID. Figure 8.1 shows the standard PID controller added to the PN of a missile.

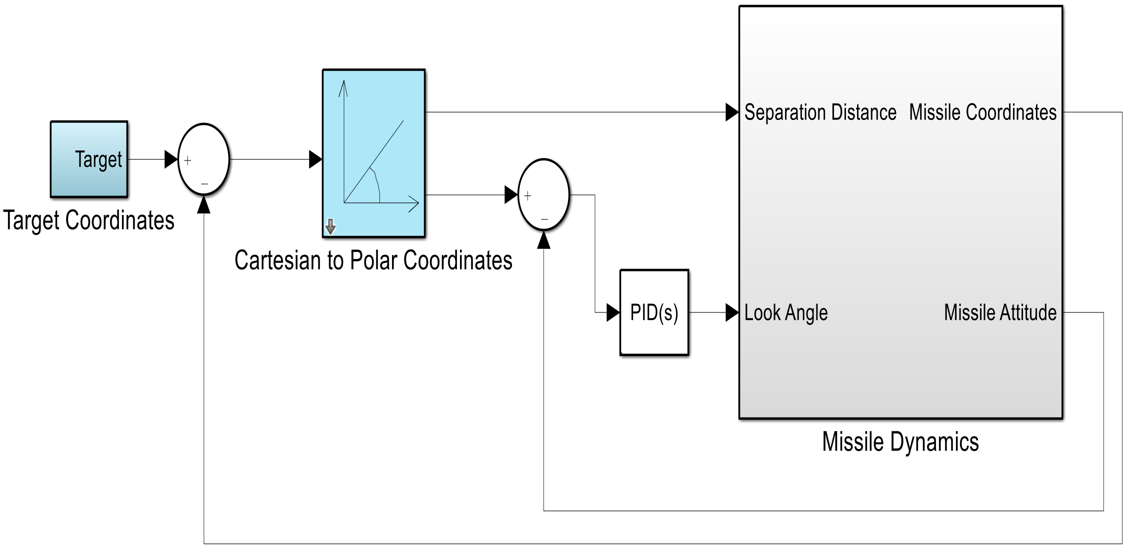

Figure 8.1. Standard PID controller added to the PN system.

The tuning procedure for this controller is accomplished by Ziegler–Nichols method. The tuning procedure is working to make the system linear at a specific point, and acquire a transfer function that is able to approximate the behavior of the missile, then the controller parameters of the controller could be acquired by ZN procedure. The parameters of the controller acquired by ZN method are shown in Table 8.1.

Table 8.1. The PID parameters acquired by ZN tuning procedure.

Parameter	**PID Controller**
K_i	1.6796
K_p	0.1075
K_d	0.0016

The introduced FOPID system is implemented in MATLAB software using a toolbox provided by (Tepljakov et al., 2011). This toolbox uses Oustaloup's method for acquiring an approximated value the fractional order operator (s^{γ}) as provided in these equations:

The other parameters of the FOPID that need to be tuned are (K_d, K_p, K_i, μ and λ) and the proposed FOPID is implemented into the PN guidance as presented in Figure 8.2.

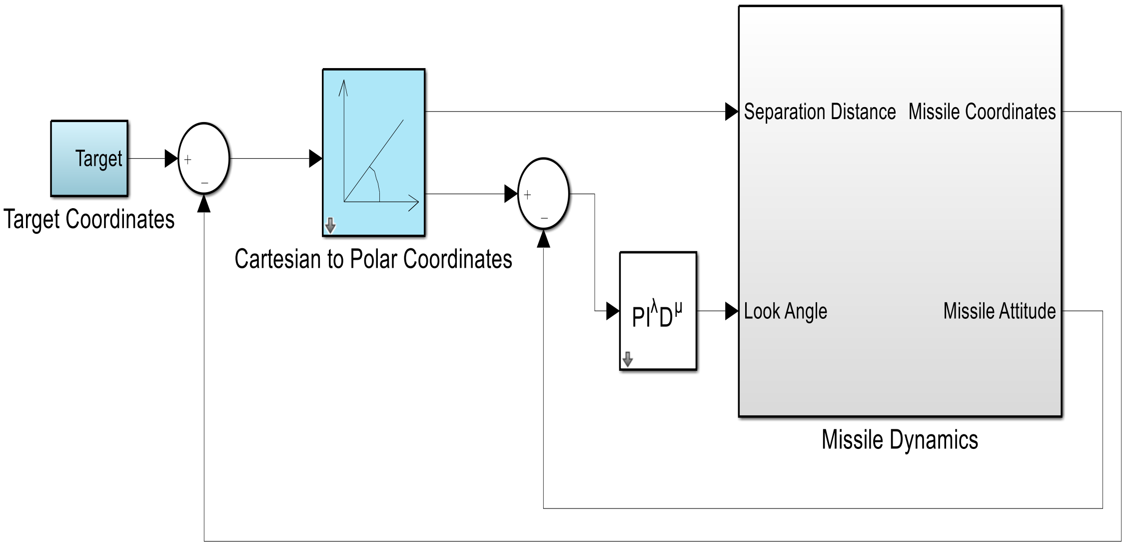

Figure 8.2. FOPID implemented with the PN.

The tuning procedure of the proposed fractional order PID is implemented by employing genetic algorithm that shows a fast convergence at the beginning of the simulation. In this simulation the genetic algorithm is designed to achieve a

0.1 miss distance value. The GA were able to converge to less than 0.1 miss distance value after the 7th generation, which has been done in few seconds.

After that, the genetic algorithm becomes slow and to achieve a more accurate results, the simulation takes much longer time for that. The parameters of the control system that obtained using GA are presented in Table 8.2.

Table 8.2. Tuned parameters after applying GA.

Parameter	**Value**
K_i	0.204
K_p	0.709
K_d	0.204
λ	0.416
μ	0.153

By adding these parameters to the fractional order PID, the miss distance that has been recorded was about 0.0168. This value is much better than 25.48 which achieved using the standard PID controller.

In the second stage of tuning, the GA tuning method is stopped and the proposed neural tuning begins to work in order to achieve more accurate parameters than the one achieved by the GA tuning process. The learning process of the proposed neural technique could help in reaching more accurate values much faster than GA near the optimal values. The learning procedure of the implemented neural network needs to obtain training samples that are the parameters of the FOPID existed near the values obtained by the GA tuning process as well as the corresponding miss distance achieved by the controller using these parameters. So, the inputs to the neural system are the parameters of the FOPID (K_p, K_i, K_d, μ and λ), while the output of this process is the value of miss distance.

The neural network now starts to learn how to find the miss distance value for each combination of the fractional order PID parameters as presented in Figure 8.3. The initial values of the biases and weights are obtained by Nguyen-Widrow strategy that is implemented in neural networks in order to accelerate the learning and employing all the available neurons. This strategy also includes a random process which produce different weights to the network in each time the learning process is applied, because of that, the final achieved miss distance in each simulation process has different values, but most of them converged to a good miss distance value. The final parameters extracting procedure is accomplished by providing an input to the neural network of a small miss distance that is approximately zero and so, the neural system is able to output the parameters of the FOPID that could achieve this miss distance value.

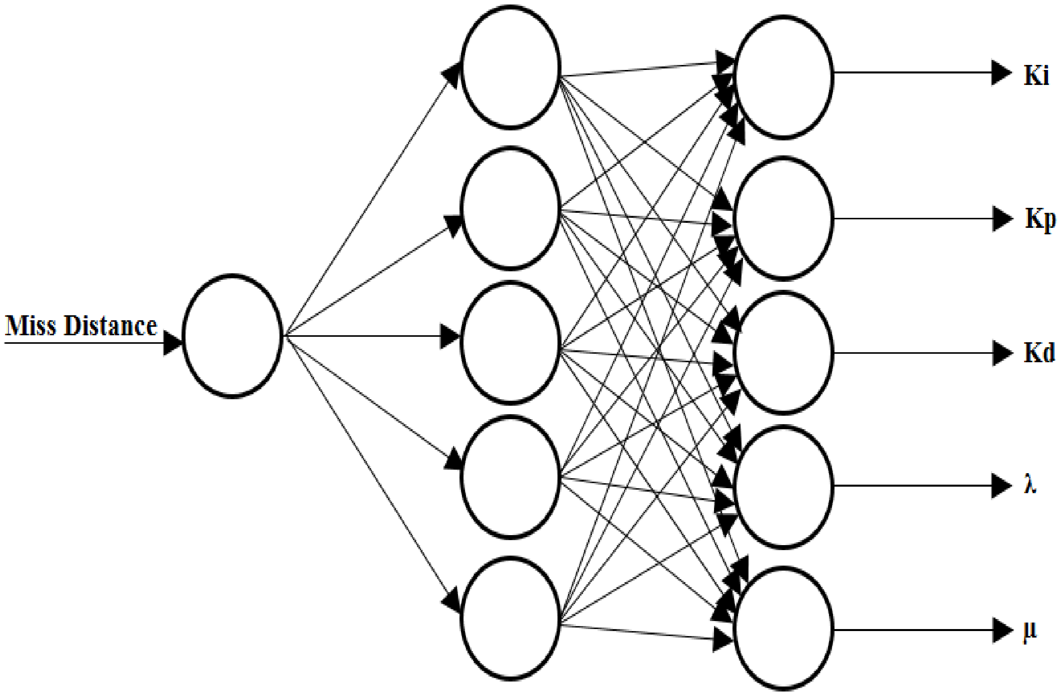

Figure 8.3. The proposed neural system for obtaining the fractional order PID.

The resulted parameters of the FOPID obtained by this stage presented in Table 8.3.

Table 8.3. The fractional order PID parameters obtained by the proposed neural tuning process.

Parameter	**Value**
K_i	0.011
K_p	0.936
K_d	0.041
λ	0.173
μ	0.058

By inserting these values into the fractional order PID, the observed value of miss distance was 0.0047. This is considered a much better value than the value obtained by GA technique and the conventional ZN tuning applied to the standard controller.

After neural networks tuning, more optimization can be achieved by implementing H_2/H_∞ tuning method. The second norm value for *f(t)*, or $\|f\|_2$ is yielded by integrating the squared root of $f(t)^2$ as follows:

$$\|f\|_2 = \left(\int_0^\infty f(t)^2 dt\right)^{1/2} \tag{37}$$

Where $t \geq 0$. The physical meaning of the second norm could be described as if *f(t)* is a signal. Then, $\|f\|_2^2$ value is related to the total energy. The H_∞ of *f(t)*, or $\|f\|_\infty$ is earned by obtaining the maximum absolute values of its components, as seen in the following equation:

$$\|f\|_\infty = \max_t |f(t)| \tag{38}$$

Where $t \geq 0$. The infinity norm is the highest amplification presented the output of the plant and it's employed for stabilizing the controlling system and achieving a guaranteed behavior over all the operating frequencies of the system (R. Toscano, 2013). By H_2/H_∞ optimization process the previous FOPID parameters obtained from the previous neural tuning is reused by the H_2/H_∞ process, and the simulation will try to find the parameters of the FOPID that will yield the lowest possible H_2 value with a guaranteed H_∞ value which is set to be less than one. By using H_2/H_∞ optimization, the results showed more improvement in the stability for the missile proved by the second and infinity norm values as shown in the conclusion section. The produced fractional order PID parameters acquired from H_2/H_∞ technique is shown in Table 8.4.

Table 8.4. The parameter of the FOPID yielded by the H_2/H_∞ method.

Parameter	**FOPID Controller**
K_i	0.0133
K_p	0.9434
K_d	0.0421
λ	0.1122
μ	0.0278

8.2. Performance Analysis

8.2.1. Missile Trajectory

Figure 8.4 shows the course of the target and the missile using ZN, GA and H_2/H_∞ neural technique. The figure shows that using ZN, the missile is oscillating during flight time and then misses the target as a consequence to that oscillation. GA tuning is having a better performance, where the course of the missile during flight is free of oscillations and the missile is able to collide accurately with the target. The proposed neural technique with H_2/H_∞ tuning, the missile is more stable with approximately linear course. Also, the path toward the target is shorter.

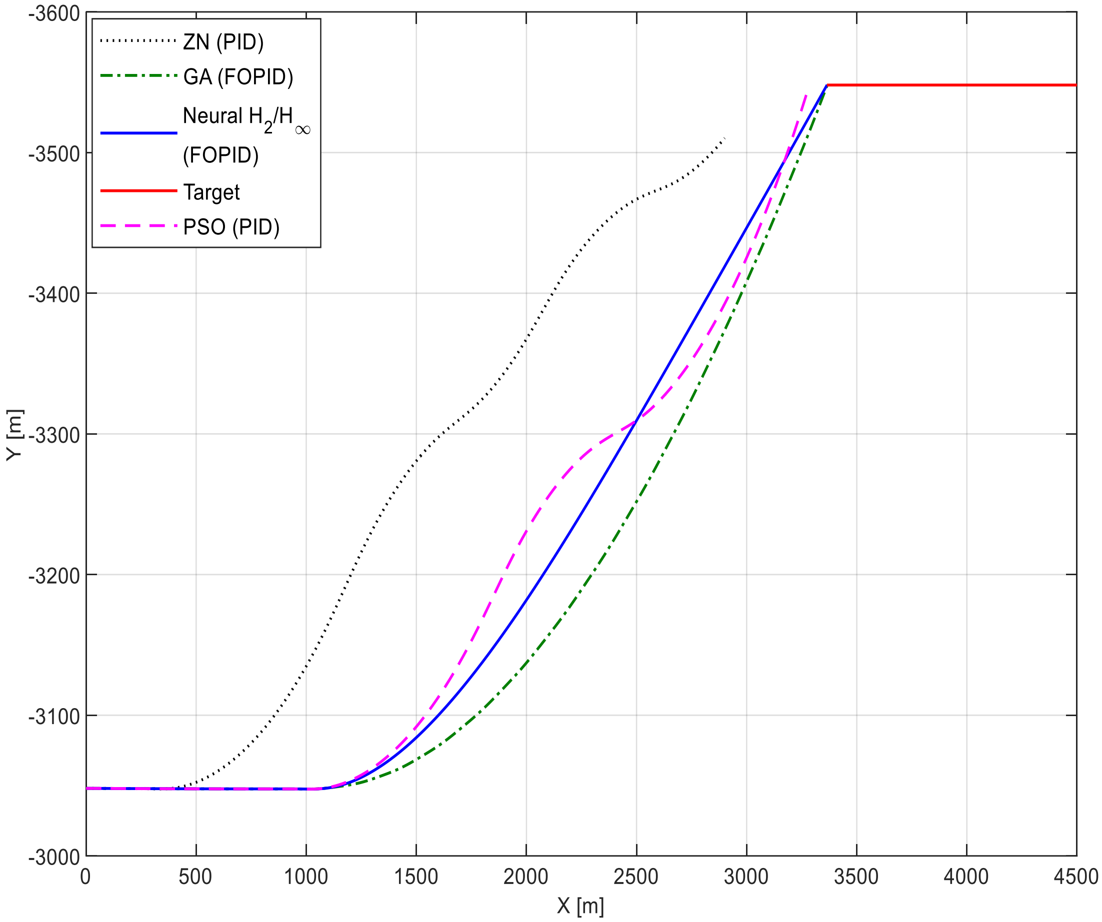

Figure 8.4. Target and missile navigation course using GA, ZN, and neural technique with H_2/H_∞ tuning.

8.2.2. The Incidence Angle

Figure 8.5 shows the effect of ZN tuning on incidence angle of the missile. As the figure shows, the incidence angle is changing its value between about 20 and -20 degrees which concludes to unstable behavior for the missile, and that will result in more drag force exerted on the missile, and due to that, the missile will consume more fuel during flight.

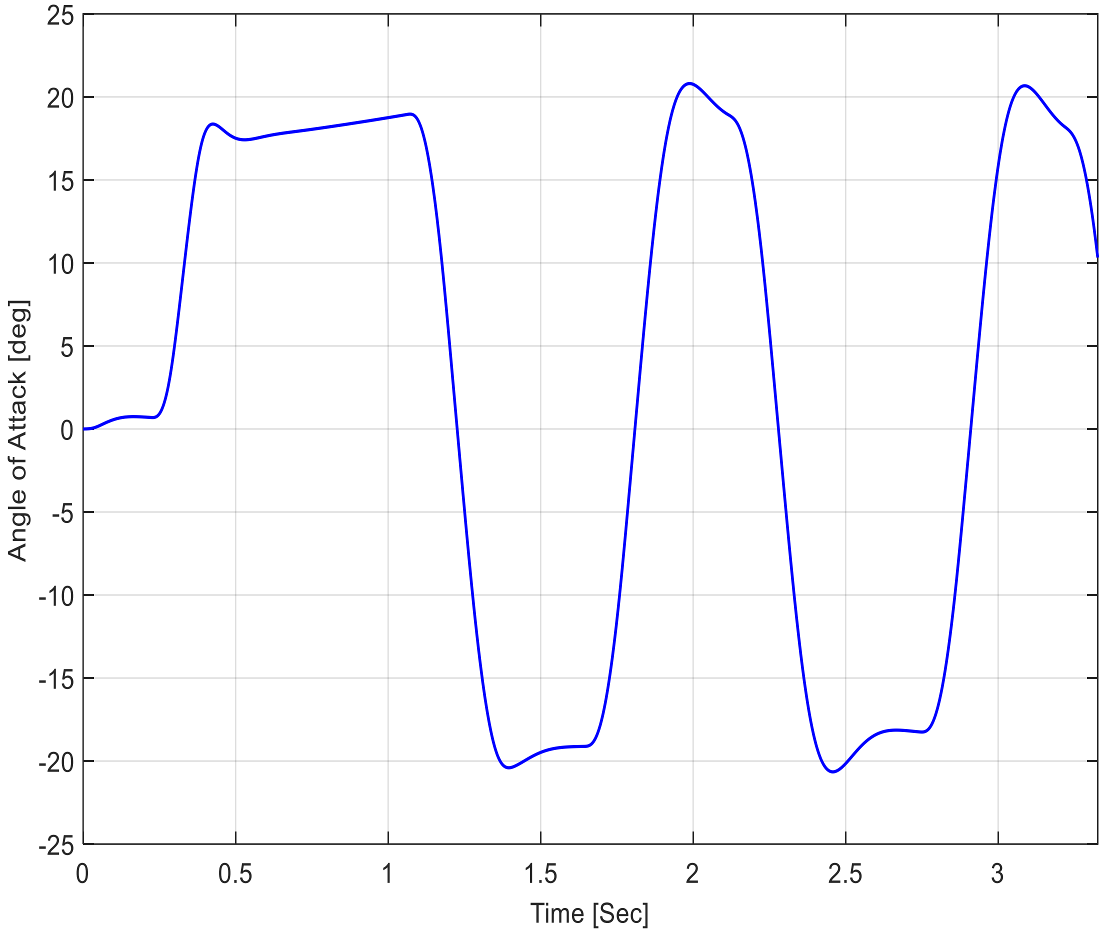

Figure 8.5. The effect of ZN tuning on the incidence angle of the missile.

Figure 8.6 demonstrates the behavior of the incidence angle using GA. By this tuning method the oscillation range decreased to values between 12.5 and 2.5 degrees, which is more efficient than ZN method, but the system still shows instability with a lot of oscillations during flight.

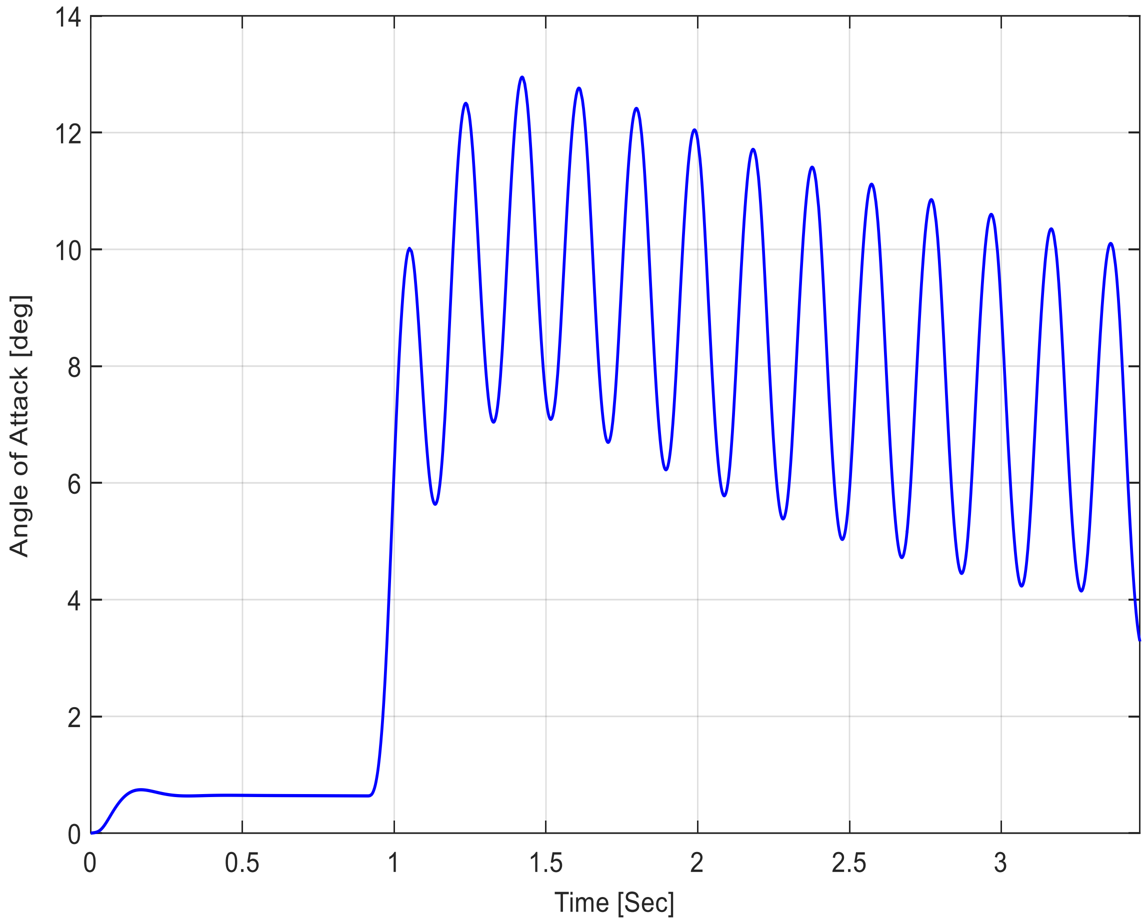

Figure 8.6. Incidence angle for missile using GA optimization for FOPID.

Figure 8.7 demonstrates the incidence angle behavior using the Neural-H_2/H_∞ tuning technique. it proved to result in more stability for the missile than GA and ZN. It is observed from the figure that the value of the angle approached its peak when the target is found, then it began to decrease without any oscillations until the missile collided with the target.

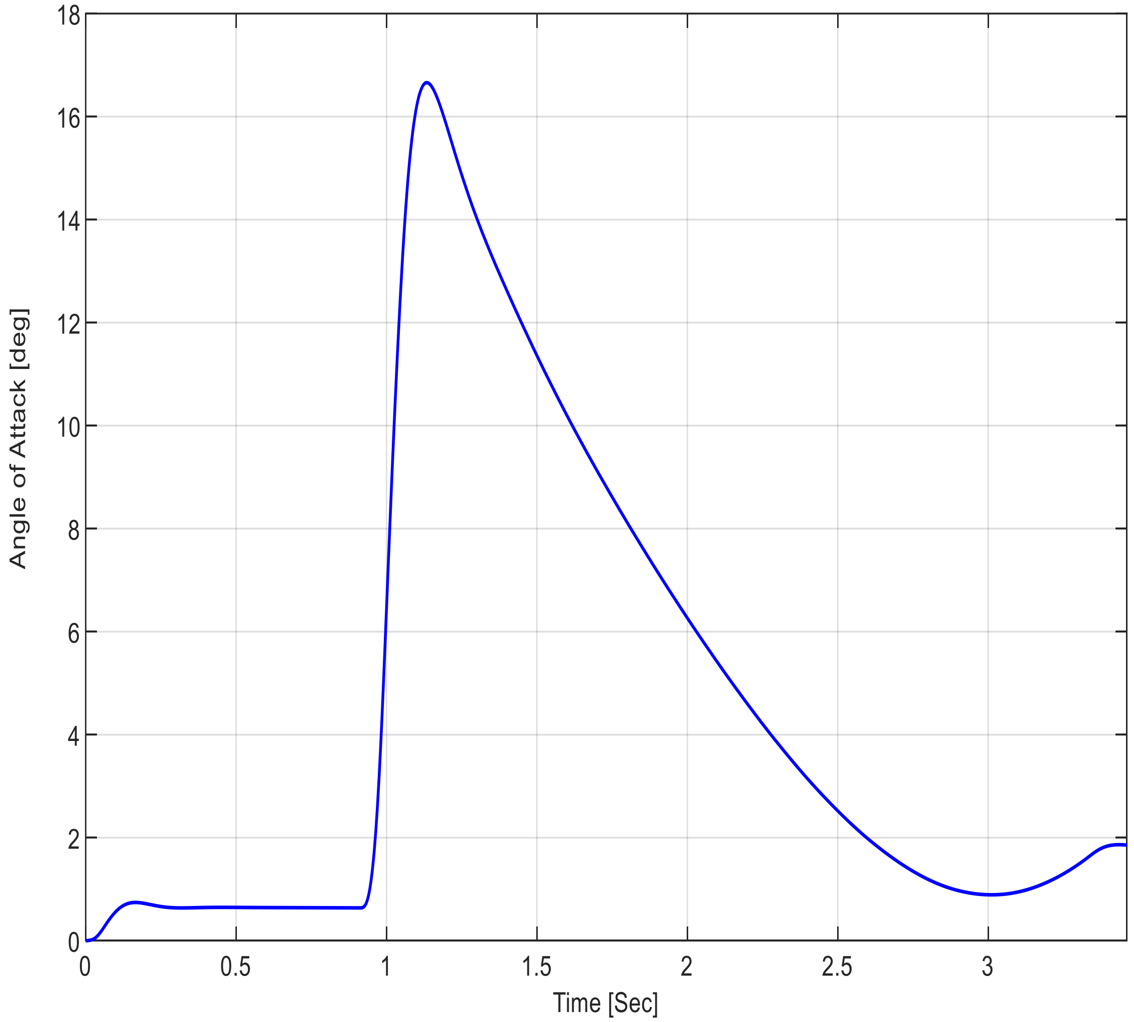

Figure 8.7. Incidence angle for the missile by employing the introduced H_2/H_∞ neural system for the FOPID.

8.2.3. Miss Distance

The introduced controller was tested in term of miss distance with the standard one. The value of miss distance achieved by ZN tuning was observed as 25.48. The optimization procedure of the proposed system is yielded by employing GA, which is faster than the neural network techniques at initial stages for acquiring better parameters. In this stage, the miss distance using the resulted parameters of the controller was 0.0168. After that, the next procedure is performed using neural technique. Near the optimal values, the neural training is faster and more optimized than GA. After this process, the observed miss distance was 0.0047.

Finally, more optimization is achieved by applying neural networks tuned by H_2/H_∞ method. The recorded miss distance value after the H_2/H_∞ process was 0.0262. Although the value has decreased using H_2/H_∞ based tuning process, but it's still considered very accurate, and the overall performance for the control process acquired by H_2/H_∞ tuning is more stable as demonstrated in the following section. These results demonstrated the effectiveness of the neural tuning over the conventional one that uses ZN tuning technique.

8.2.4. H_∞-Norm and H_2-Norm

The introduced FOPID is tuned and optimized using GA, neural networks and H_2/H_∞ tuning technique and then simulated against the standard PID that is optimized by ZN technique by calculating the second and infinity norms. The second norm achieved by the conventional controller is shown as 13.45. After applying genetic algorithm-based tuning, the second norm decreased to 6.81. Using Neural network technique, the second norm has reached 5.24. Finally, after implementing the proposed H_2/H_∞ tuning technique the second norm had a value of 4.18 which considered as 69% performance increment over the standard ZN tuning technique, and an increment of about 20% in the performance over the neural network-based optimization. The infinity-norm of the PID controller was observed as 0.4893, while using genetic algorithm it was recorded as 3.27. This proves that by GA, the measured efficiency of the H_∞ decreased. After employing the proposed neural network, the performance measured by the infinity-norm technique was 3.09, which is better than using genetic algorithm-based tuning, but still worse than using the conventional ZN tuning technique. After applying the proposed H_2/H_∞ technique the resulted H_∞ was recorded as 0.16, and that indicates a 66% more performance than the standard ZN technique, and about 95% more performance than the neural network alone. Thus, we can prove that the proposed H_2/H_∞ technique is able to stabilize the missile more efficiently, and the appeared problem with the H_∞ value after applying the neural networks disappeared by the proposed H_2/H_∞ technique. So, the Neural network supported by H_2/H_∞ was able to optimize the FOPID better than the standard PID tuned by ZN technique.

8.2.5. Radar Gimbal Angle vs Look Angle

The implemented controlling method has huge effect on the effectiveness of the aerial system or the radar guided missile. The used radar in the aerial system should be capable of tracking the target and aligning the true look angle of the radar system with the gimbal angle. While using the standard ZN optimization, the aerial system shows a lot of oscillations which increases the oscillations of the radar gimbals also as elaborated in Figure 8.8.

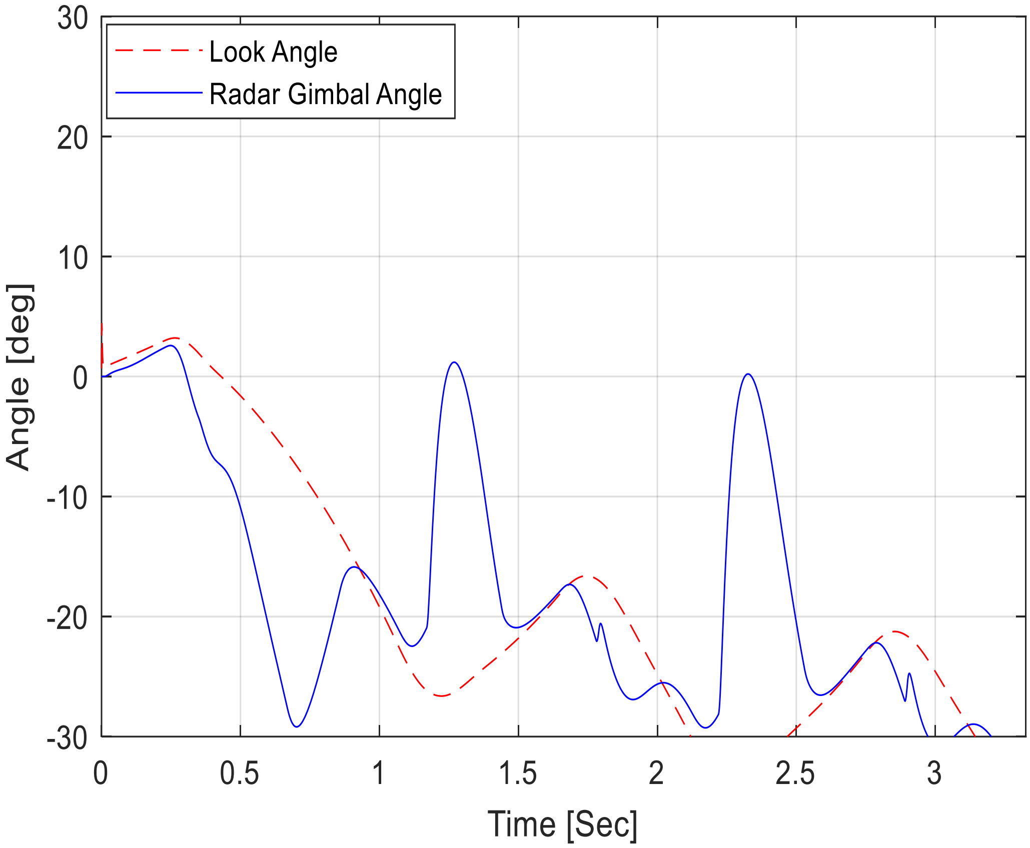

Figure 8.8. Gimbal angle against true look angle using ZN on the PID control system.

Figure 8.9 elaborates the behavior of the gimbal and look angles for the aerial system using genetic algorithm. So figure, the look angle shows a lot of oscillation because of the oscillation of the aerial system, but the capability of the radar system in following these oscillations and adjusting the gimbals in order to aligned it with the true look angle is relatively excellent.

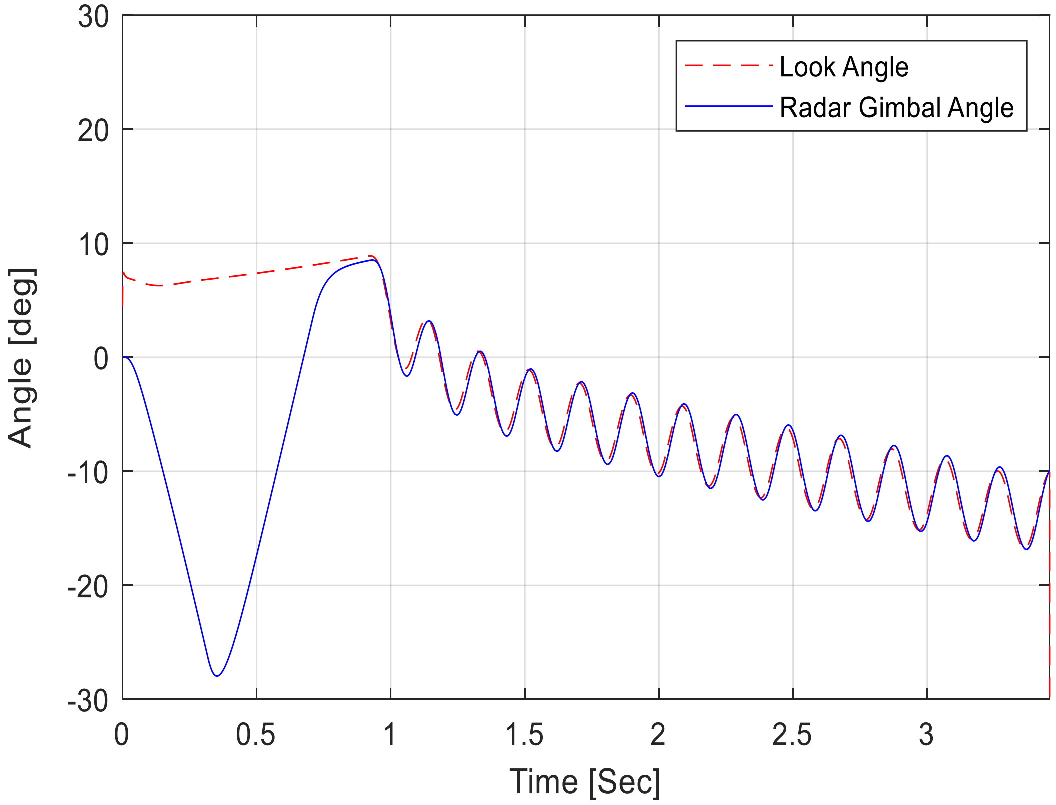

Figure 8.9. Gimbal angle against true look angle using GA applied on the FOPID system.

Figure 8.10 elaborates the behavior of the gimbal and look angles aerial system using the proposed H_2/H_∞ neural technique. It’s obvious that there is are no oscillations for the missile where the look angle is approximately linear during most of the flight time after the target is found by the radar system (near the 1st second). Also, the gimbal is capable of tracking the true look angle efficiently. This indicates the advantage of the H_2/H_∞ Neural network technique over the standard system tuned by ZN.

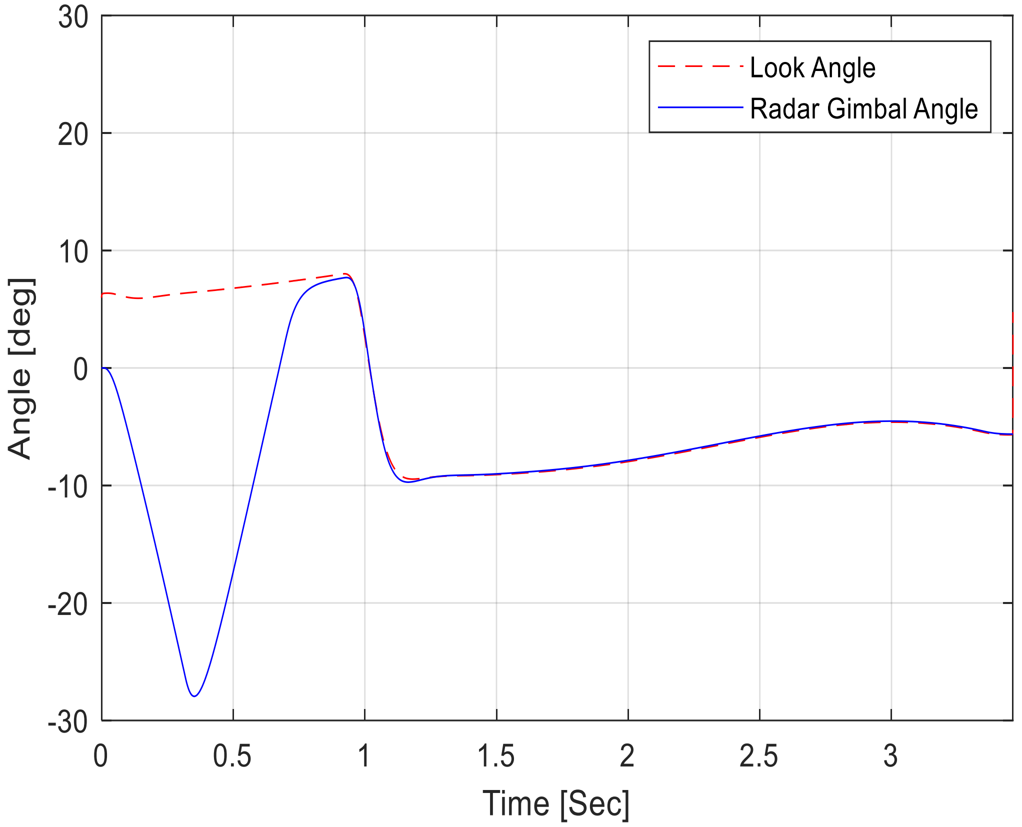

Figure 8.10. Radar gimbal angle vs look angle for H_2/H_∞ neural tuning.

9. Conclusion

In this dissertation, a novel neural-H_2/H_∞ based fractional order PID control system is introduced and implemented into a radar guided missile. The objective of this design is to guide the missile during flight and track a fast-moving target with an outstanding accuracy depicted by the miss distance and a good tracking ability during flight. There are the stages applied for tuning the aerial system. The first one employs GA for finding a near optimal parameters of the PID controller. The tuning process during this stage is fast at the beginning and slowing down when approaching near optimal parameters for the controller. The next stage makes use of the novel approached designed using the neural network method and applied to the FOPID. This method is able to achieve better efficiency and ability to acquire better fractional order PID parameters with higher speed near the optimal values compared to the GA. The last stage employs a mixed H_2/H_∞ tuning is applied in order to achieve higher tracking performance and more stable behavior for the aerial system. The introduced FOPID system is simulated and tested against the normal PID system that employs ZN for acquiring the PID parameters. The performance metrices that have been used for comparison includes miss distance, motion stability of the missile, incidence angle behavior during flight, second norm, infinity norm and the ability of the radar system to track the true look angle efficiently. The outcomes of the simulation proved that the novel proposed system was able to tune the FOPID and achieve an excellent hitting accuracy for the aerial system elaborated with an approximately zero miss distance. Also, the proposed system was able to achieve an outstanding stability compared with the normal PID system that has an oscillated motion during flight. The stability of the radar implemented on the top of the missile is expressed by the ability of the gimbal in following the target to have a good tracking performance in the introduced fractional order PID. Although the performance of infinity norm decreased when using neural and genetic techniques compared to ZN method, employment of the H_2/H_∞ technique after the neural optimization achieved a much better performance than the one achieved by the ZN implementation. This novel approach resulted in a performance increment of about 95% over the sole implementation of the neural network, and about 66% over ZN implementation. For the second norm also, the implementation of the mixed H_2/H_∞ method achieved 69% performance increment compared with the standard ZN implementation, and about 20% more than the value achieved by the implementation of the neural network alone. The angle of attack behavior during flight time shows better stability in the case of the proposed FOPID. Finally, the values of second and infinity norms (H_2 and H_∞) exerted by the introduced FOPID is more efficient than the standard PID system which demonstrates the ability of the fractional order PID system in stabilizing the missile efficiently while tracking process. This dissertation has resulted in publishing 7 peer reviewed papers, where 6 of them has been published in 6 different international prestigious conferences in different countries and one in a top-grade journal “IEEE Transactions on Industrial Electronics”.

REFERENCES

Babu, V. M., Das, K., & Kumar, S. (2017). Designing of self tuning PID controller for AR drone quadrotor. *2017 18th International Conference on Advanced Robotics (ICAR)*, 167–172. https://doi.org/10.1109/ICAR.2017.8023513

Bolandi, H., Rezaei, M., Mohsenipour, R., Nemati, H., & Smailzadeh, S. M. (2013). Attitude Control of a Quadrotor with Optimized PID Controller. *Intelligent Control and Automation*, *04*(03), 342–349. https://doi.org/10.4236/ica.2013.43040

Charles Stark Draper. (n.d.). Inertial guidance system | Britannica.com. Retrieved August 17, 2018, from https://www.britannica.com/technology/inertial-guidance-system

Cho, D., Kim, H. J., & Tahk, M.-J. (2016). Fast adaptive guidance against highly maneuvering targets. *IEEE Transactions on Aerospace and Electronic Systems*, *52*(2), 671–680. https://doi.org/10.1109/TAES.2015.140958

Davanipour, M., Javanmardi, H., & Goodarzi, N. (2018). Chaotic Self-Tuning PID Controller Based on Fuzzy Wavelet Neural Network Model. *Iranian Journal of Science and Technology, Transactions of Electrical Engineering*, *42*(3), 357–366. https://doi.org/10.1007/s40998-018-0069-1

David, S. A., Linares, J. L., & Pallone, E. M. J. A. (2011). Fractional order calculus: historical apologia, basic concepts and some applications. *Revista Brasileira de Ensino de Física*, *33*(4), 4302–4302. https://doi.org/10.1590/S1806-11172011000400002

Debnath, M. (2016a). A Backup System for the Beam Rider Guided Missile when the Guidance-beam is absent or the Radar-antenna of the System is destroyed. *International Journal of Research in Advent Technology*, *4*(9). Retrieved from www.ijrat.org

Debnath, M. (2016b). Protection of Cruise Missile from the Threat of Anti-Cruise Missile (ACM) by Using Small Air-to-Air Missile (AAM). *International*

Journal of Trend in Research and Development, *3*(5), 2394–9333. Retrieved from www.ijtrd.com

Edet, E., & Katebi, R. (2016). Design and tuning of fractional-order PID controllers for time-delayed processes. *2016 UKACC 11th International Conference on Control (CONTROL)*, 1–6. https://doi.org/10.1109/CONTROL.2016.7737589

Efe, M. Ö. (2011). Neural Network Assisted Computationally Simple PI$^\lambda$D$^\mu$ Control of a Quadrotor UAV. *IEEE Transactions on Industrial Informatics*, *7*(2), 354–361. https://doi.org/10.1109/TII.2011.2123906

El-Sousy, F. F. M. (2016). Intelligent mixed H2 /H∞ adaptive tracking control system design using self-organizing recurrent fuzzy-wavelet-neural-network for uncertain two-axis motion control system. *Applied Soft Computing*, *41*(C), 22–50. https://doi.org/10.1016/j.asoc.2015.12.009

El-Sousy, F. F. M., & Abuhasel, K. A. (2016). Self-Organizing Recurrent Fuzzy Wavelet Neural Network-Based Mixed H2/H∞Adaptive Tracking Control for Uncertain Two-Axis Motion Control System. *IEEE Transactions on Industry Applications*, *52*(6), 5139–5155. https://doi.org/10.1109/TIA.2016.2591901

Emam, M., & Fakharian, A. (2016). Attitude tracking of quadrotor UAV via mixed H2/H<inf>∞</inf> controller: An LMI based approach. *2016 24th Mediterranean Conference on Control and Automation (MED)*, 390–395. https://doi.org/10.1109/MED.2016.7535919

Erer, K. S., Tekin, R., & Özgören, M. K. (2016). Biased proportional navigation with exponentially decaying error for impact angle control and path following. *24th Mediterranean Conference on Control and Automation, MED 2016*, 238–243. https://doi.org/10.1109/MED.2016.7535911

Feng, J., Wang, D., Liu, T., & Cai, C. (2017). A study on the effect of radar seeker performance parameters on control and guide precision. *Proceedings of 2017 IEEE 2nd Advanced Information Technology, Electronic and Automation Control Conference, IAEAC 2017*, 315–319. https://doi.org/10.1109/IAEAC.2017.8054028

Gahinet, P., & Apkarian, P. (n.d.). *Automated Tuning of Gain-Scheduled Control Systems*. 1–6.

Golestani, M., Ahmadi, P., & Fakharian, A. (2016). Fractional order sliding mode guidance law: Improving performance and robustness. *2016 4th International Conference on Control, Instrumentation, and Automation (ICCIA)*, 469–474. https://doi.org/10.1109/ICCIAutom.2016.7483208

Gonzalez, E. A., & Petras, I. (2015). Advances in fractional calculus: Control and signal processing applications. *Proceedings of the 2015 16th International Carpathian Control Conference (ICCC)*, 147–152. https://doi.org/10.1109/CarpathianCC.2015.7145064

Guo, K. Y., Qu, Q. Y., Feng, A. X., & Sheng, X. Q. (2016). Miss Distance Estimation Based on Scattering Center Model Using Time-Frequency Analysis. *IEEE Antennas and Wireless Propagation Letters*. https://doi.org/10.1109/LAWP.2015.2490088

Guo, Z., Zhou, J., & Guo, J. (2017). Robust autopilot design for bank-to-turn missiles using adaptive dual-layer sliding mode control. *Optik*, *131*, 383–398. https://doi.org/10.1016/j.ijleo.2016.11.068

Hartzstein, C. (2016). Weighted filtering of monopulse signals. *2016 IEEE Radar Conference, RadarConf 2016*. https://doi.org/10.1109/RADAR.2016.7485229

Kim, B. (2016). *Proportional-Integral-Derivative Controller in Proportional Navigation Guidance* (Texas A&M University). Retrieved from http://oaktrust.library.tamu.edu/handle/1969.1/157866

Lee, J., Lee, Y., Kim, Y., Moon, G., & Jun, B. E. (2016). Design of an adaptive missile autopilot considering the boost phase using the SDRE method and neural networks. *Journal of the Franklin Institute*, *000*, 1–23. https://doi.org/10.1016/j.jfranklin.2016.12.004

Lin, J. M., & Lin, C. H. (2014). A novel intelligent neural guidance law design by using adjoint method. *Proceedings - International Conference on Machine Learning and Cybernetics*, *1*, 303–308. https://doi.org/10.1109/ICMLC.2014.7009133

Padhi, R., Sirisha, C. H. V, & Sarkar, A. K. (2014). Nonlinear autopilot design and guidance-in-loop validation for a tactical air-to-air flight vehicle. In *IFAC Proceedings Volumes (IFAC-PapersOnline)* (Vol. 3). https://doi.org/10.3182/20140313-3-IN-3024.00187

Palash Choudhari, Varun Karthikeyan, & Anoop Madhavan. (n.d.). Missile Technology 5 - Guidance - Full Afterburner. Retrieved August 15, 2018, from http://fullafterburner.weebly.com/next-gen-weapons/missile-technology-guidance

Pan, J., & Shen, T. (2016). Multiple-model weighted control for helicopter based on H2/H. *2016 Chinese Control and Decision Conference (CCDC)*, 1693–1698. https://doi.org/10.1109/CCDC.2016.7531255

Pradhan, R., Patra, P., & Pati, B. B. (2016). Comparative studies on design of fractional order proportional integral differential controller. *2016 International Conference on Advances in Computing, Communications and Informatics (ICACCI)*, 424–429. https://doi.org/10.1109/ICACCI.2016.7732082

Qilun, Z., Xiwang, D., Jian, C., Chen, B., Qingdong, L., & Zhang, R. (2016). Distributed cooperative guidance for multiple missiles. *2016 35th Chinese Control Conference (CCC)*, 5346–5351. https://doi.org/10.1109/ChiCC.2016.7554187

R. Toscano. (2013). Signal and System Norms. In *Structured Controllers for Uncertain Systems* (1st ed., pp. 25–44). London: Springer.

Ra, C., Kim, S., & Suk, J. (2017). Adaptive sliding mode autopilot design for skid-to-turn missile model with uncertainties. In *International Journal of Control, Automation and Systems* (Vol. 15). https://doi.org/10.1007/s12555-016-0497-5

Radhika, M. N., Parthasarathy, S. S., & Kumar, G. S. (2016). Estimation and guidance for manoeuvring targets. *2015 International Conference on Emerging Research in Electronics, Computer Science and Technology, ICERECT 2015*, 218–223. https://doi.org/10.1109/ERECT.2015.7499016

Raj, K. D. S., & Ganesh, I. S. S. (2015). Estimation of line-of-sight rate in a homing Missile Guidance loop using optimal filters. *2015 International Conference on Communications and Signal Processing (ICCSP)*, 0398–0402. https://doi.org/10.1109/ICCSP.2015.7322916

Seo, M. G., & Tahk, M. J. (2015). Observability analysis and enhancement of radome aberration estimation with line-of-sight angle-only measurement. *IEEE Transactions on Aerospace and Electronic Systems*, *51*(4), 3321–3331. https://doi.org/10.1109/TAES.2015.140531

Shah, P., & Agashe, S. (2016). Review of fractional PID controller. *Mechatronics*, *38*, 29–41. https://doi.org/10.1016/J.MECHATRONICS.2016.06.005

Solomon Raj, K. D., & Krishna, I. M. (2015). Kalman filter based target tracking for track while scan data processing. *2nd International Conference on Electronics and Communication Systems, ICECS 2015*, 878–883. https://doi.org/10.1109/ECS.2015.7125040

Su, W., Chen, L., & Li Kebo. (2016). Acceleration requirement analysis for true proportional navigation guidance and its modification. *2016 35th Chinese Control Conference (CCC)*, 5542–5546. https://doi.org/10.1109/ChiCC.2016.7554219

Sumardi, Sulila, M. S., & Riyadi, M. A. (2017). Particle swarm optimization (PSO)-based self tuning proportional, integral, derivative (PID) for bearing navigation control system on quadcopter. *2017 4th International Conference on Information Technology, Computer, and Electrical Engineering (ICITACEE)*, 181–186. https://doi.org/10.1109/ICITACEE.2017.8257699

Sun, H., Yu, J., & Zhang, S. (2016). The Control of Asymmetric Rolling Missiles Based on Improved Trajectory Linearization Control Method. *Journal of Aerospace Technology and Management*, *8*(3), 319–327. https://doi.org/10.5028/jatm.v8i3.617

Sun, J., & Liu, C. (2018). Disturbance observer-based robust missile autopilot design with full-state constraints via adaptive dynamic programming. *Journal of the Franklin Institute*, *355*(5), 2344–2368. https://doi.org/10.1016/j.jfranklin.2018.01.005

Tepljakov, A., Petlenkov, E., & Belikov, J. (2011). FOMCON: Fractional-order modeling and control toolbox for MATLAB. *Proceedings of the 18th International Conference Mixed Design of Integrated Circuits and Systems - MIXDES 2011*.

Tepljakov, A., Petlenkov, E., Gonzalez, E. A., & Petras, I. (2017). Design of a MATLAB-based teaching tool in introductory fractional-order systems and controls. *2017 IEEE Frontiers in Education Conference (FIE)*, 1–5. https://doi.org/10.1109/FIE.2017.8190681

Tian, S., Lin, D., Wang, J., & Li, B. (2017). Dynamic stability of rolling missiles with angle-of-attack feedback three-loop autopilot considering parasitic effect. *Aerospace Science and Technology*, *71*, 592–602. https://doi.org/10.1016/j.ast.2017.10.023

Tyan, F. (2015). Analysis of 3D PPN guidance laws for nonmaneuvering target. *IEEE Transactions on Aerospace and Electronic Systems*, *51*(4), 2932–2943. https://doi.org/10.1109/TAES.2015.140676

Viswanath, D., Krishnaswamy, S., & Deb, D. (2015). Homing missile guidance using LOS rate and relative range measurement. *2015 Annual IEEE India Conference (INDICON)*, 1–6. https://doi.org/10.1109/INDICON.2015.7443715

Wang, H., Lin, D. F., Wang, J., & Cheng, Z. X. (2010). Study on homing guidance systems based on different source errors. *2010 International Conference on Computer, Mechatronics, Control and Electronic Engineering, CMCE 2010*, *6*, 118–121. https://doi.org/10.1109/CMCE.2010.5609891

Yaghi, M., & Efe, M. O. (2017). Adaptive neural FOPID controller applied for missile guidance system. *Proceedings IECON 2017 - 43rd Annual Conference of the IEEE Industrial Electronics Society*, *2017-Janua*. https://doi.org/10.1109/IECON.2017.8216499

Yang, Y. (2018). A time-specified nonsingular terminal sliding mode control approach for trajectory tracking of robotic airships. *Nonlinear Dynamics*, *92*(3), 1359–1367. https://doi.org/10.1007/s11071-018-4131-3

Yanushevsky, R. (2008). *Modern missile guidance*. CRC Press.

Yueneng, Y., & Ye, Y. A. N. (2018). Backstepping sliding mode control for uncertain strict- feedback nonlinear systems using neural-network-based adaptive gain scheduling. *Journal of Systems Engineering and Electronics*, *29*(3), 580–586. https://doi.org/10.21629/JSEE.2018.03.15

Zhao, L., Shi, Z., & Zhu, Y. (2018). Acceleration autopilot for a guided spinning rocket via adaptive output feedback. *Aerospace Science and Technology*, *77*, 573–584. https://doi.org/10.1016/j.ast.2018.04.012

Zhe, D., Jiabin, C., Chunlei, S., & Hongye, C. (2017). Design of longitudinal control system for target missiles based on fuzzy adaptive PID control. *Proceedings of the 29th Chinese Control and Decision Conference, CCDC 2017*, 398–402. https://doi.org/10.1109/CCDC.2017.7978127

Zhou Weiwen, Liang Xiaogeng, & Jia Xiaohong. (2010). Finite-time stability analysis of proportional navigation guidance system. *2010 IEEE International Conference on Intelligent Computing and Intelligent Systems*, 108–112. https://doi.org/10.1109/ICICISYS.2010.5658711

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Name Surname:	Murad Yaghi
Student No:	N13143092
Department:	Computer Engineering
Program:	Computer Engineering
Status:	☐ Masters ☑ Ph.D. ☐ Integrated Ph.D.

ADVISOR APPROVAL

APPROVED.

Prof. Dr. Mehmet Önder Efe

(Title, Name Surname, Signature)

CURRICULUM VITAE

Name-Surname:	**Murad A. Yaghi**
Place of Birth:	**U.A.E**
Date of Birth:	**25/09/1985**
Email:	**murad.a.yaghi@gmail.com**

EDUCATION

Ph.D.	**Computer Engineering** Hacettepe University, Turkey Thesis: Fractional Order Feedback Control of Nonlinear Aerial Systems	Jan 2020
M.Sc.	**Computer Engineering / Embedded Systems** Yarmouk University, Jordan	Jan 2013
B.Sc.	**Electrical Engineering** Hashemite University, Jordan	Aug 2010

RESEARCH EXPERIENCE

Hacettepe University, Turkey Computer Engineering Department Autonomous Systems Lab Supervisor: Mehmet Önder Efe, Ph.D. Thesis Title: **Fractional Order Feedback Control of Nonlinear Aerial Systems**	Sep 2016- present
Hacettepe University, Turkey Computer Engineering Department Autonomous Systems Lab Supervisor: Mehmet Önder Efe, Ph.D. Project Title: **FPGA Based Obstacle Avoidance and Path Planning for UAV Systems using LIDAR Sensor**	Oct 2014- Sep 2015

Yarmouk University, Jordan — Jan 2012-Jan 2013
Computer Engineering Department
Supervisor: Amine Al-Qudah, Ph.D.
Project Title: **FPGA Based Controller for Static VAR Compensator**

Hashemite University, Jordan — Jan 2009-Jan 2010
Supervisor: Anas Al-Tarabsheh, Ph.D.
Project Title: **Parameters Extraction of Photovoltaic Cell**

TEACHING EXPERIENCE

Instructor (Online/Remote) — Sep 2018-Present
University of the People, USA
Computer Science Department

Instructor — Sep 2012-Present
Wadi Asseer Training College, Jordan
Electrical Department

Lecturer — Sep 2010-Sep 2012
Yaghi Cultural Academic Center, Jordan

PROFESSIONAL EXPERIENCE

Electrical and Control Engineer — Nov 2010-Aug 2012
Consolidated Jordanian Company for Steel Industry, Jordan