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Intelligent Missile Controller for Maneuverable Target

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Abstract:
Background: *A novel missile guidance law that works effectively for highly maneuverable targets is the major requirement of defense technique. To meet this requirement multi-controller architecture for guidance of missiles has been developed in this paper. A fussy logic-based system is designed to choose the proper control law for suitable range and closing velocity. The proportional navigational law, ON-OFF controller and fuzzy proportional navigational law are selected for the design of guidance scheme.*
Materials and Methods: *If the line-of-sight angles are not small, the large relative acceleration along line of site vector, or the target perform evasive maneuvers, then intercept performance of proportional navigation can be seriously degraded. Fuzzy logic system can use knowledge expressed in the form of linguistic rules without completely resorting to the precise plant models. Moreover, fuzzy logic can solve complex and practical problems using if-then rules.*
Results: *The fuzzy guidance law is based on the observation that the classical proportional navigation guidance law achieves target interception using only the line-of-sight rate measurements. This fact implies that it should be possible to guide the missile towards the target by applying a few fuzzy logics online-of-sight measurements.*
The advantage of including rate of change of LOS angle rate as another input-error signal is the earlier than proportional navigation guidance law.
Conclusion: *In the fuzzy logic controller, different phases of the missile target engagement and the respective needs of the control commands for the stages have been observed. These observations show that there are many laws which give excellent performance for different stages. Using this information multi controller architecture for guidance scheme has been proposed.*
Key Word: *Guidance; control; fuzzy logic; missile.*

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I. Introduction

Even a couple of decades ago the guidance and control laws worked effectively when the target was large and travelled at low speed and for such a target an acceptable missed distance can be obtained. However, these techniques[1] are not effective for new generation targets which are at high speed, small and highly maneuverable. Intercepting targets with such characteristics are a big challenge for today's guidance and controller designers.

Missiles and target dynamics are highly nonlinear in nature because the equation of motion is best described in an inertial system while the aerodynamics forces and moments are best represented in missile and target body axis system. Unmodeled dynamics and parametric perturbations are usually present in plant modelling. It is complex to design a nonlinear guidance design problem, so some approximations and simplifications have generally been required before the analytical gain can be derived in traditional approaches. Because of this one does not change in unpredictable ways. Therefore, it is difficult to ensure the optimality of the resulting design.

Proportional navigational guidance law[2,3] that produces the commanded missile acceleration which is the product of scalar gain, the relative closing velocity between missile and the line of sight (LOS) rate, has an effective guidance law for missile and target intercept for many years. However, there are many factors which reduce the efficiency of proportional guidance law. If the line-of-sight angles are not small, the large relative acceleration along line of site vector, or the target perform evasive maneuvers, then intercept performance of proportional navigation can be seriously degraded[2]. Fuzzy logic system can use knowledge expressed in the form of linguistic rules without completely resorting to the precise plant models[4]. Moreover, fuzzy logic can solve complex and practical problems using if-then rules. In recent years fuzzy logic controllers have been used in missile guidance wherever the system under consideration is not well-defined, uncertain, or model free[5] and researchers attempted to apply it on missile guidance designs.

In Ref.[5], a fuzzy guidance law with rules obtained based upon the conception of the existing 'classical' proportional navigation guidance (PNG) law was shown. Then, they propose membership functions parameters and optimized using particle swarm optimization (PSO) technique. In practice, PSO may look like a population based stochastic optimization technique. Based on that description[6,7], particle swarm optimization imitates human (or insects) social behavior. In that case individuals will interact with one another while learning from their own experience, and gradually the population members move into better regions of the problem space.

In Ref.[8] the simulation program has been utilized a proposed guidance algorithm based on artificial intelligent (AI) techniques. Fuzzy logic has been tolerated to propose homing guidance law based on PNG as in Ref.[5]. The setup has been integrated with a six-degree-of-freedom missile model.

II. Material And Methods

Missile Dynamic Model: In this research a fuzzy terminal guidance is designed by using the proportional and derivative-type (PD-type) fuzzy control technique. The proposed guidance configuration accelerates the tracking response and avoids overshooting the state response. This methodology is very close to Ref.[9].

Two-dimensional translation equations of missile motion are used to compute the trajectory of the guided vehicle. In this case the missile is modelled as a point mass, and the equations of motion as in Ref.[10].

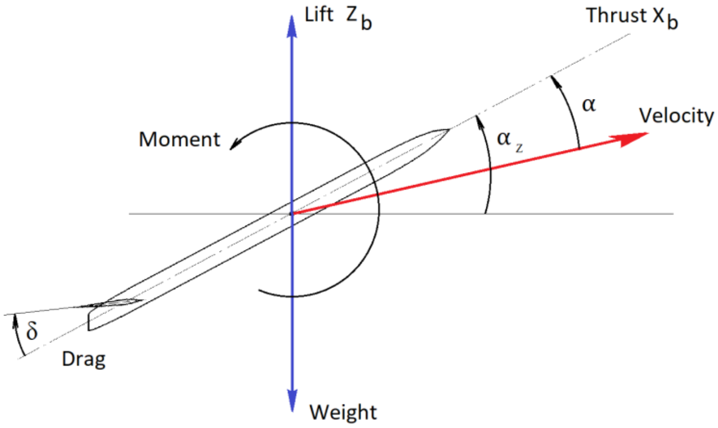

Fig. 1. Forces and variables around the missile airframe

From the analysis of the forces of aerodynamics around the missile shown in Fig. 1, we can get the following equations which describe the motion of the missile[3,11]:

$$\dot{U} = \frac{T+Fx}{m} - qW - gsin\emptyset, \tag{1}$$

$$\dot{W} = \frac{Fz}{m} + qU + gcos\emptyset, \tag{2}$$

$$\dot{q} = \frac{M}{I_{yy}}, \tag{3}$$

$$q = \dot{\emptyset}, \tag{4}$$

$$U_e = Ucos\Theta + Wsin\Theta, \tag{5}$$

$$W_e = -Usin\Theta + Wcos\Theta, \tag{6}$$

$$\dot{X}_e = U_e, \tag{7}$$

$$\dot{Z}_e = W_e, \tag{8}$$

where:

$$F_x = \bar{q} S_{ref} C_x(Mach, \alpha), \tag{9}$$

$$F_z = \bar{q} S_{ref} C_z(Mach, \alpha, \eta), \tag{10}$$

$$M = \bar{q} S_{ref} d_{ref} C_M(Mach, \alpha, \eta, q), \tag{11}$$

$$\bar{q} = \frac{1}{2}\rho V^2, \tag{12}$$

$$V = \sqrt{U^2 - W^2}, \tag{13}$$

$$\alpha = tan^{-1}(W, U). \tag{14}$$

Θ – attitude in radian;

q – body rotation rate in rad/sec;

m – missile mass in kg;

g – acceleration of gravity in m/sec^2;
I_{yy} – moment of inertia about y axis in $kg \cdot m^2$;
$\dot{W}$ – acceleration in the Z body axis in $m \cdot sec^2$;
$\dot{q}$ – the change in body rotation rate in rad/sec^2;
T – the thrust in the X body axis in N;
ρ - the air density in kg/m^3;
S_{ref} – the reference area in m^2;
C_x – the coefficient of aerodynamic force in X axis;
C_z - the coefficient of aerodynamic force in Z axis;
C_M - the coefficient of aerodynamic moment in Y axis;
d_{ref} – the reference length in m;
δ – the fin angle in radians;
F_x – the aerodynamic force in the X body axis in N;
F_z – the aerodynamic force in the Z body axis in N;
M – the aerodynamic moment in the Y body axis in $kg \cdot m$.

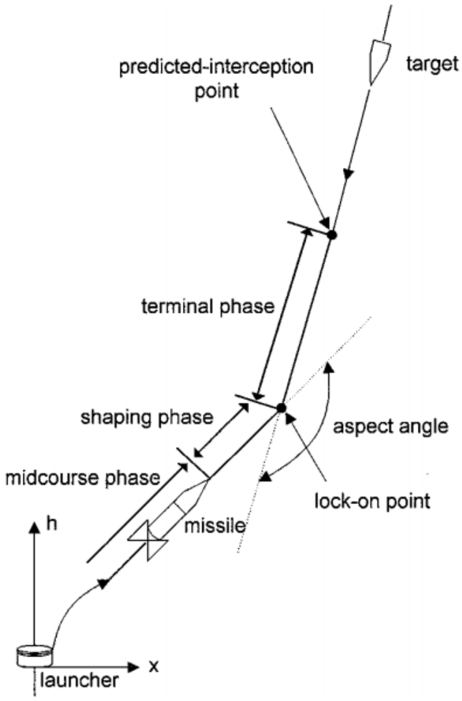

Fig. 2. Engagement scenario[9]

For the fuzzy terminal guidance law, it is natural to select the heading error angle σ and change of heading error angle $\dot{\sigma}$ as the variables like a PD-type controller, that is[10]:

$$\alpha_{ft} = f(\sigma, \dot{\sigma}). \quad (15)$$

The guidance law, used in this model is[10]:

$$a_n = N V_n \dot{\theta}, \quad (16)$$

where N is the proportional navigation gain and V_c is the closing to target velocity. If the mission objective is to engage an evasive target, the following fuzzy guidance law from Eq. (15) is transformed:

$$\alpha_{ft} = f(\dot{\theta}, \ddot{\theta}). \quad (17)$$

Because the control variable α has been determined, the lateral acceleration command to be fed into the plant can be obtained by substituting the control variable into this expression[3]:

$$a_n = \frac{1}{2} m \rho V^2 s C_{L\alpha} \alpha. \quad (18)$$

Multi Controller Architecture for Guidance: The interception of a high-speed target, an important guideline is that the missile and target both should be near head-on geometry while the interceptor entering the homing phase. The engagement scenario as in Ref.[9] is shown on Fig. 2.

The guidance scheme processes contain three phases: midcourse phase, shaping phase and terminal phase.

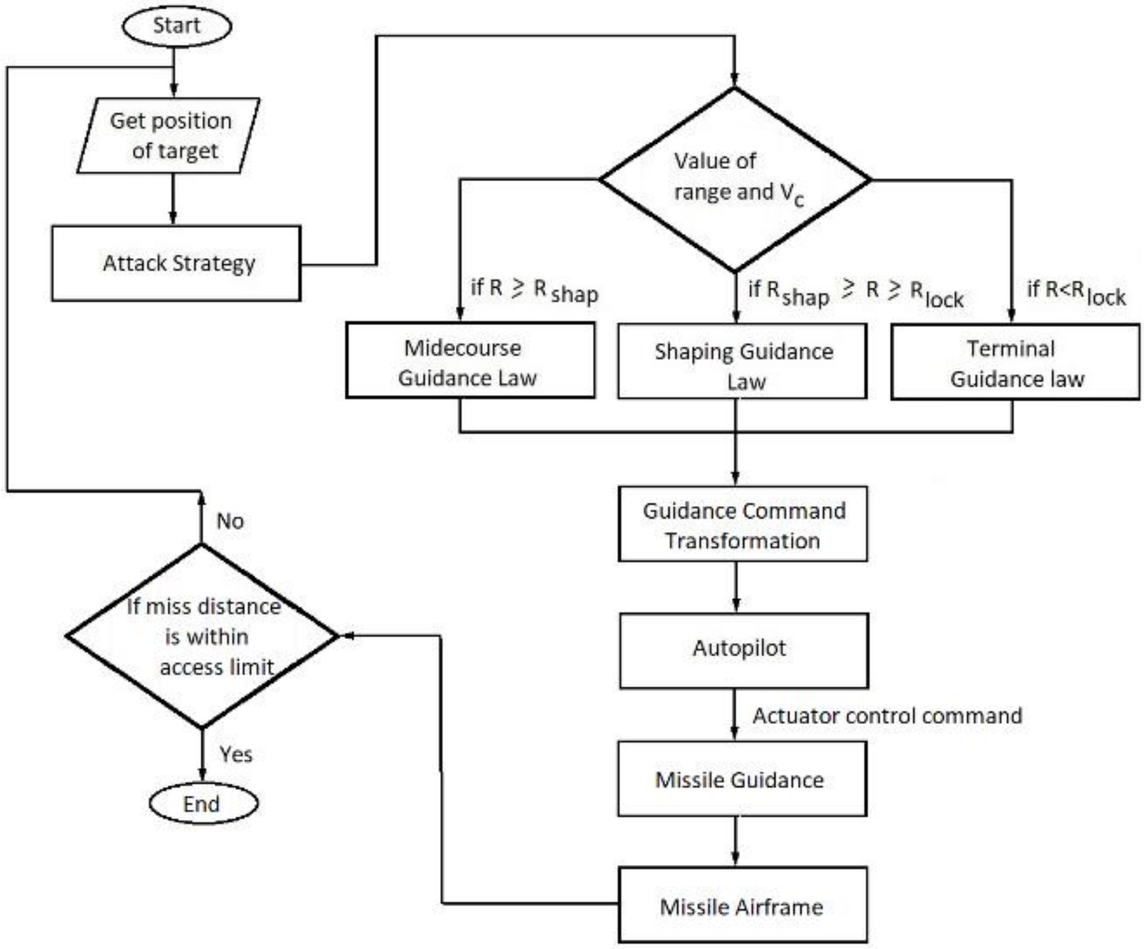

Fig. 3. Engagement strategy operational flow

When the target is far away, that means the distance between missile and target is very large, then Proportional Navigational Guidance Law generates moderate acceleration commands. This region is called the midcourse phase, which is generally up to 500 m. As the range becomes small the acceleration commands will become very large. Then the shaping phase starts. For small range conditions, which is also known as terminal stage, the guidance law should be used which uses bounded acceleration commands. The ON-OFF controller tracks targets using bounded acceleration, so this law is ideal for the terminal stage. According to engagement scenario (Fig. 2)[9], the operation flow of the engagement strategy was designed (Fig. 3).

For the shaping phase fuzzy proportional navigational law can be used.

Fuzzy Controller for the Selection of Law: Fuzzy logic inference controller is used for the selection of the law. The fuzzy logic uses the range and the rate of range to decide the output value of the parameters k_1, k_2 and k_3. The value of these parameters varies from 0 to 1 according to the conditions. The value can then act as a gain for the law, that means these parameters decide the role of a particular law for a particular range and rate.

For the transformation of the input parameters a triangular membership function is used. The range varies from 0 to 16,000 m. The values of the mapped variables are shown in Table 1.

Table no 1: Mapvariable from 0 to 16,000 m.

High, m	12500	14500	16000
Medium, m	500	6500	12500
Low, m	0	250	500

The range i.e., closing velocity varies from 330 m/s. The values of the mapped variables are shown in Table 2.

Table no 2: Mapvariable from 3300 to 500 m.

High, m	3300	2000	1000
Medium, m	1000	2100	3300
Low, m	500	750	1000

The output values are three scalar variables k_1, k_2 and k_3. The values of these parameters vary from 0 to 1. There are three parts of output High, Medium and Low. For smooth variation of the law's sigmoidal membership is used. All the three parameters are mapped similarly, the mapped parameters are mapped similarly, the mapped parameters are presented in Table 3.

Table no 3: Mapvariable from1to13.5m.

High, m	13.7	-1
Medium, m	2	0.55
Low, m	5	1.3

The fuzzy rules for the controller, which selects a particular controller for a particular range, are made and there are 18 rules governing the transformation of the mapping. The weight is adjusted as 1 for every rule. The rules are as follows[12]:
R1 If range is low then k1 is high
R2 If range is low then k2 is low
R3 If range is low then k3 is low
R4 If range is med then k1 is low
R5 If range is med then k2 is low
R6 If range is med then k3 is high
R7 If range is high then k1 is low
R8 If range is high then k2 is high
R9 If range is high then k3 is low
R10 If range is low then k1 is high
R11 If range is low then k2 is low
R12 If range is low then k3 is low
R13 If range is med then k1 is low
R14 If range is med then k2 is low
R15 If range is med then k3 is high
R16 If range is high then k1 is low
R17 If range is high then k2 is high
R18 If range is high then k3 is low
The fuzzy interface system is a Mamdani type, and the type of rule used is Verbose.

Proportional Navigation Guidance (PNG) Law: The first controller is the proportional navigation guidance law, which is based on the closing velocity and rate of LOS angle[9]. The mathematical formula for the acceleration commands given by this law can be started as

$$a_z = k_{SPNG} V_C \dot{\theta}. \qquad (19)$$

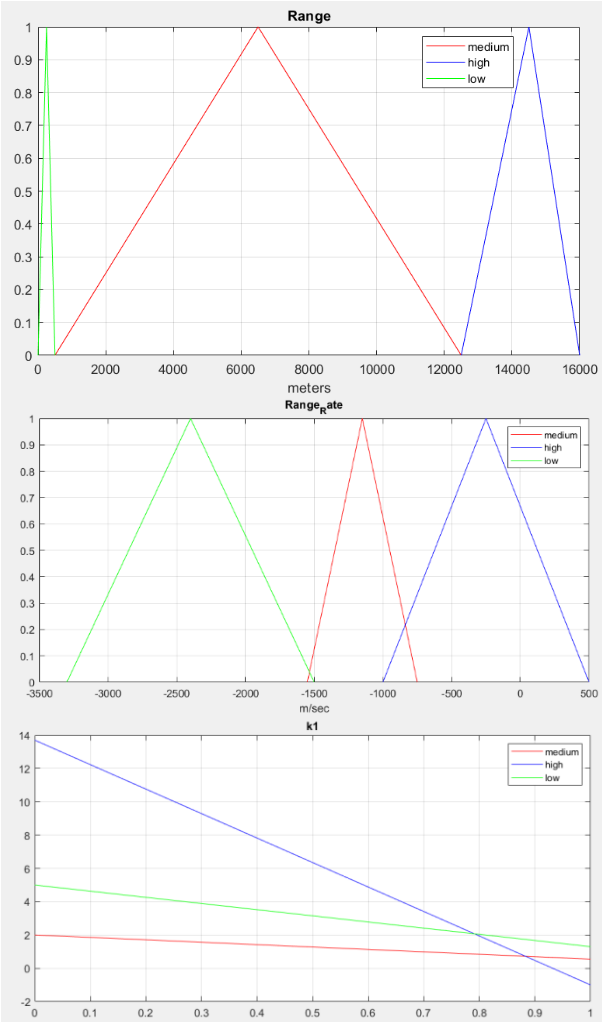

Fig. 4. Membership function used for the low selection.

The gain is an important factor in the performance of the PNG law[12]. Low gains cause sluggish response during the complete course and high gains oscillatory response during the terminal stage and sometimes in the first stage (Fig. 4). For various gains the response of the law was tested, and the best suited gain was found out.

III. Result

The input and out variables, also called the linguistic variables are LOS angle rate $\dot{\theta}$ and change of LOS angle rate $\ddot{\theta}$,and the output variable is acceleration α.

Each of the linguistic variables is assumed to take 5 linguistic sets defined as LN≡large negative, LP≡large positive, SN≡small negative, SP≡small positive, ZE≡zero. For these variables the corresponding membership functions are adopted in Fig. 5, where the physical domains are set to cover the operating range of all variables.

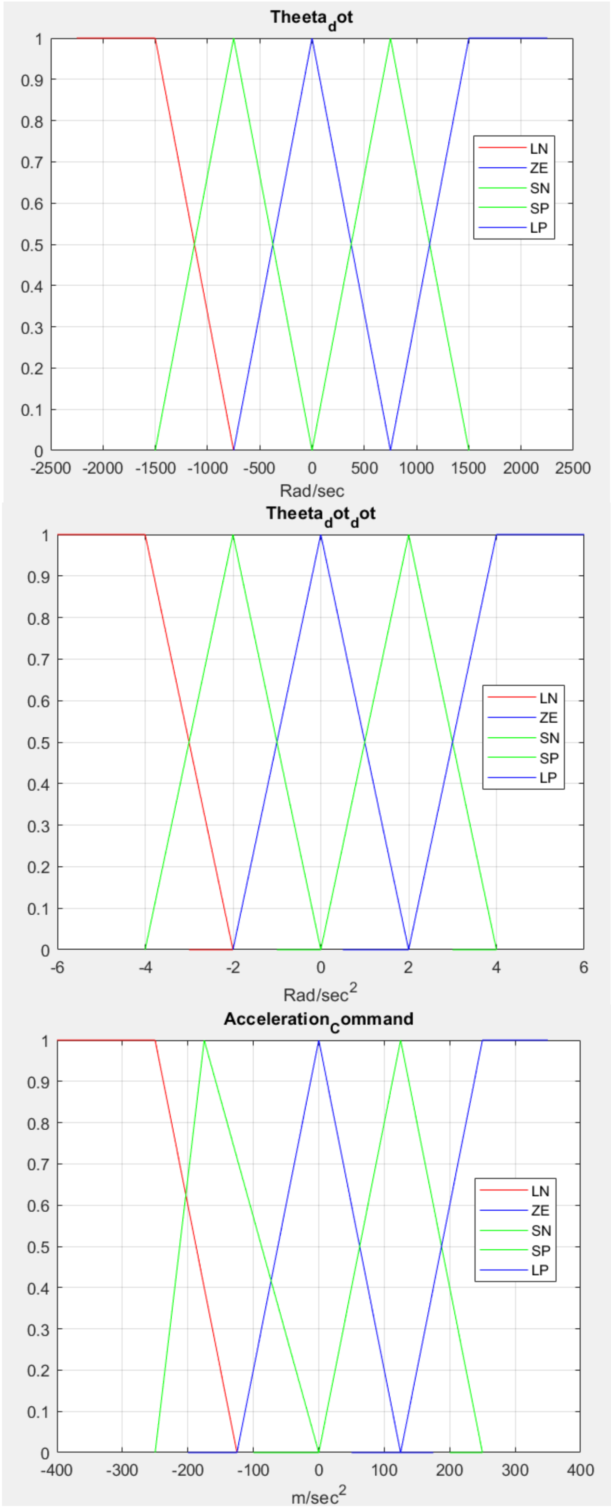

Fig. 5. Membership function used fuzzy logic based shaping guidance: a - angle rate$\dot{\Theta}$; b - change of LOS angle rate; c - acceleration α.

The fuzzy guidance law is based on the observation that the classical proportional navigation guidance law achieves target interception using only the line-of-sight rate measurements. This fact implies that it should be possible to guide the missile towards the target by applying a few fuzzy logics online-of-sight measurements. The proportional navigation guidance law and its derivatives have been used successfully in several missile programs[9]. In addition to the line-of-sight rate, the guidance commands can also be made functions of the instantaneous missile relative line-of-sight angle.

Table no 4: Suggestedrule table for the fuzzy logic based on shaping phase guidance.

	Acceleration $\ddot{\theta}$					
Normal command $\dot{\theta}$		LN	SN	ZE	SP	LP
	LN	LP	LP	LP	ZP	LP
	SN	LP	SP	SP	ZE	ZE
	ZE	LP	SP	ZE	SN	LN
	SP	ZE	ZE	SN	SN	LN
	LP	LN	LN	LN	LN	LN

The proposed fuzzy logic guidance scheme uses the LOS angle and change of LOS angle rate as the input linguistic variables, and the lateral acceleration command is used as output linguistic variable (Table 4). The advantage of including rate of change of LOS angle rate as another input-error signal is the earlier than proportional navigation guidance law.

ON-OFF controller is a kind of saturable controller, which means the output of these controllers is saturable in nature[12]. This controller takes the values of rate of LOS angle and then according to these parameters the required acceleration commands are generated. The controller used is a kind of relay with hysteresis. The controller has a limit for the value of input, where it should be switched off and it has a certain value of input where the controller should be switched on. It contains the values of outputs for the specified ON period and OFF period too[13].

IV. Discussion

Tall simulations are performed in MATLAB. The target is randomly moving. In the mathematical form the guidance commands generated can be stated as:

$$a_z = k_{SPNG} V_C \dot{\theta} + f_{ON-OFF}(\dot{\theta}) + f_{FUZZY}(\dot{\theta}, \ddot{\theta}). \quad (20)$$

As a result of simulation, we could get a graph, which shows the smooth tracking and stable missile operation in all three stages (Fig. 6).

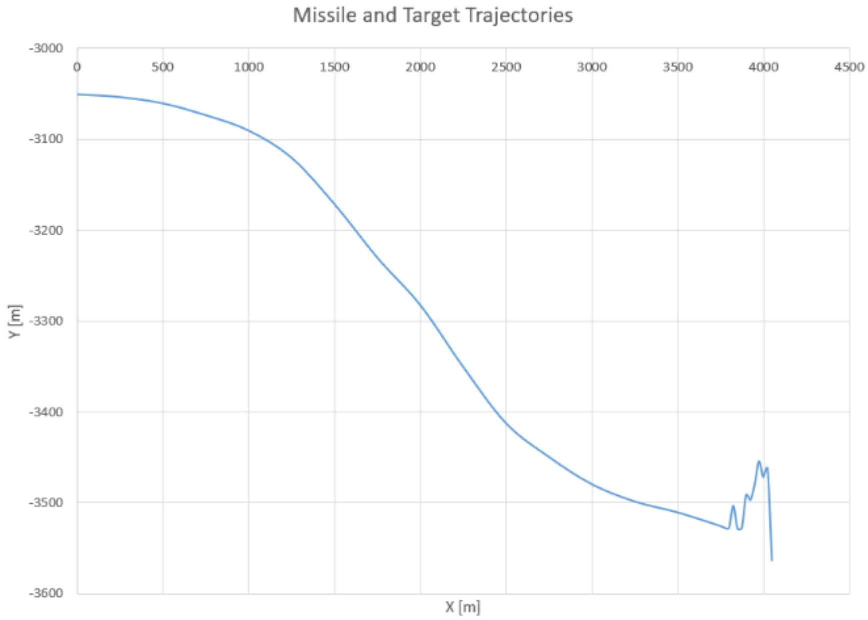

Fig. 6. Missile and target trajectory evolution.

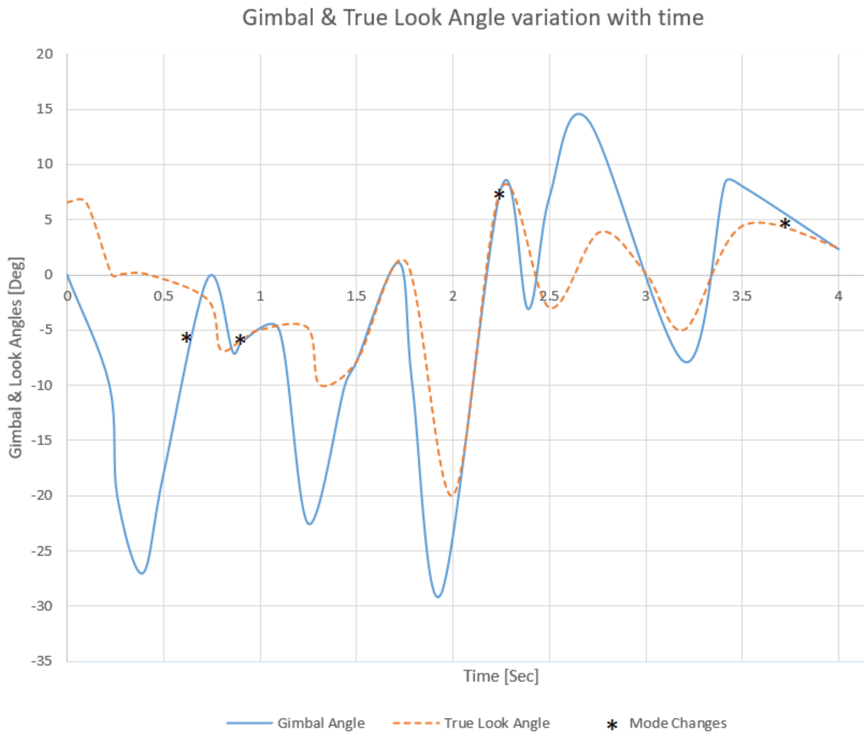

Fig. 7. Variation in Gimbal and Look Angle.

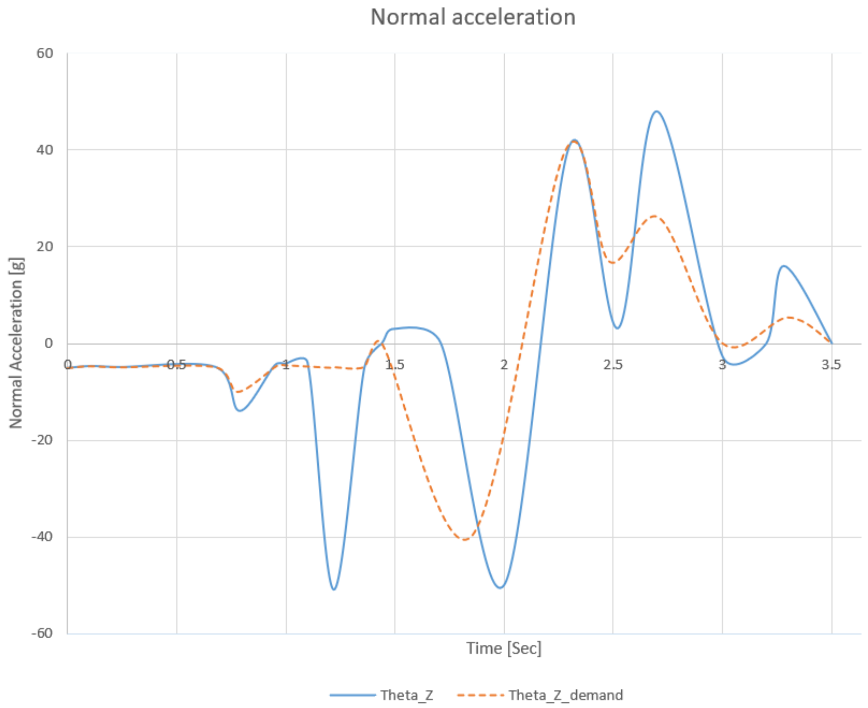

Fig. 8. Normal acceleration.

Fig. 6 shows the range to go history for the proposed multi controller architecture. The graph shows the smooth tracking and stable operation of the missile in all three stages.

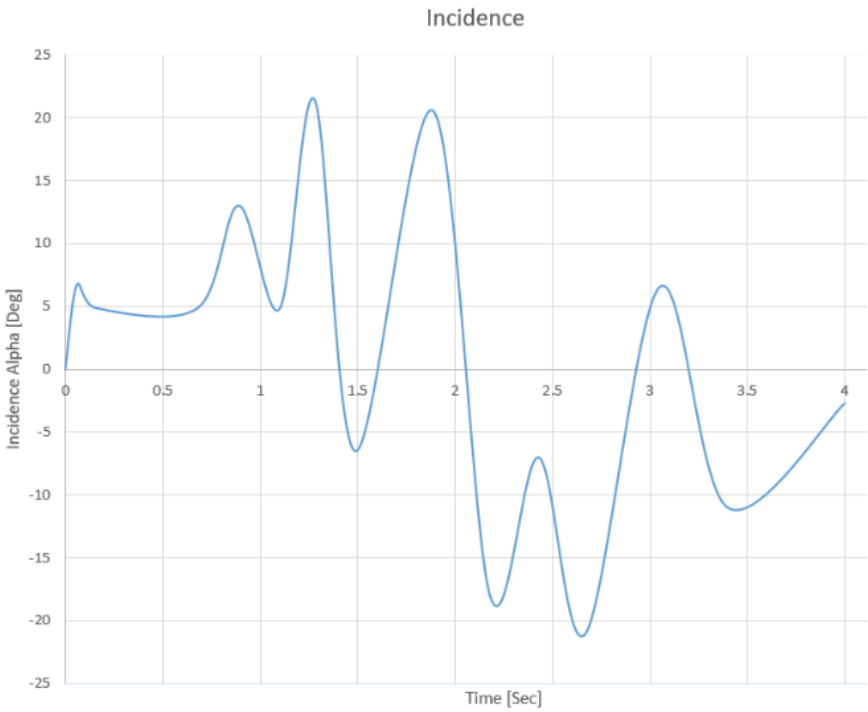

Fig. 9. Incidence angle.

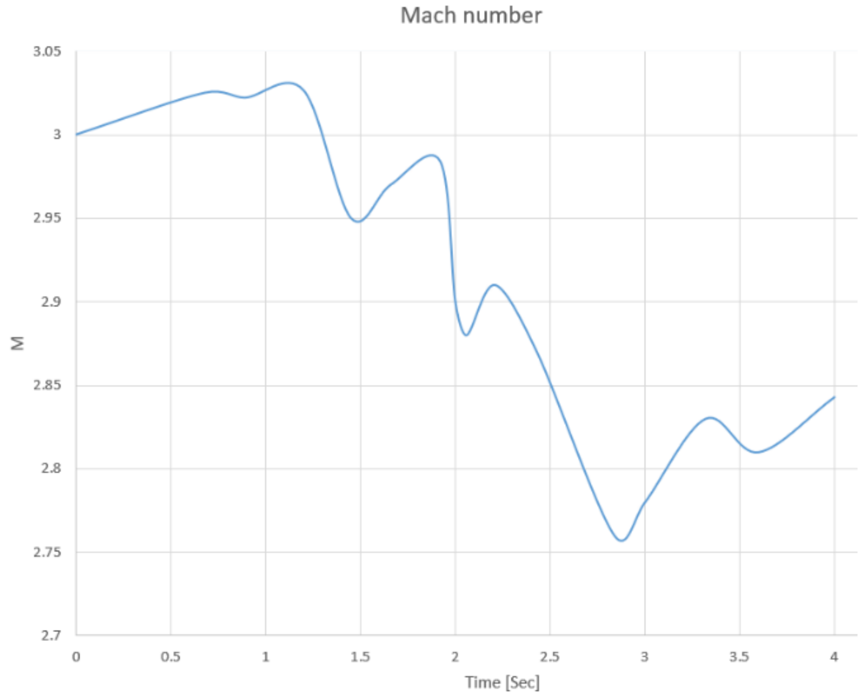

Fig. 10. Mach number.

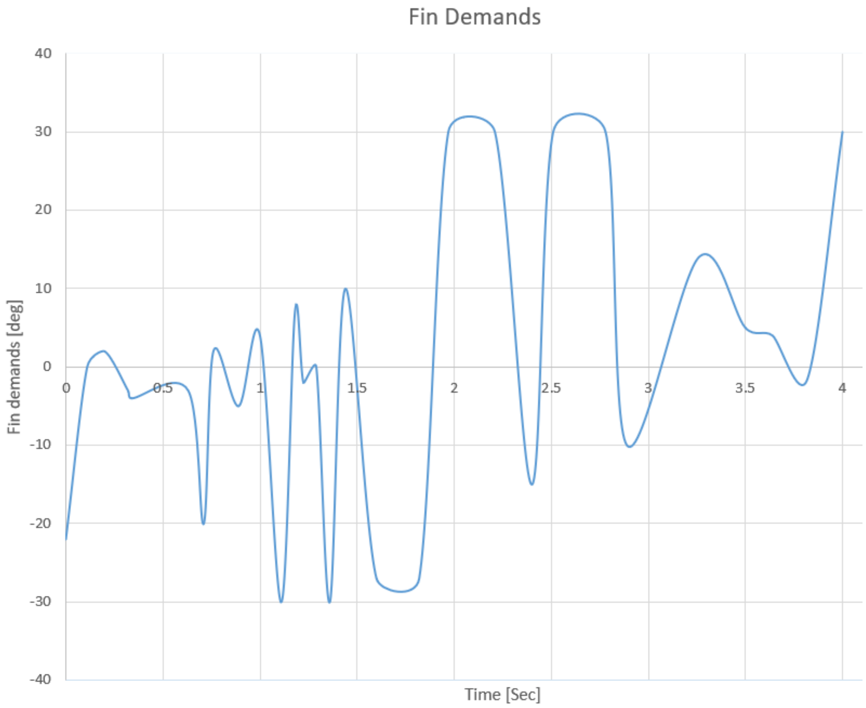

Fig. 11. Fin demands.

For the same target the missing distance obtain through proportional navigational law is 8.43 m, which is greater than acceptable range, so the miss distance performance of fuzzy controller is better that proportional navigational law.

V. Conclusion

In the fuzzy logic controller, different phases of the missile target engagement and the respective needs of the control commands for the stages have been observed. These observations show that there are many laws which give excellent performance for different stages. Using this information multi controller architecture for guidance scheme has been proposed. The three laws are chosen in the proposed architecture, they are the proportional navigation law, ON-OFF controller, and fuzzy proportional navigation law. The PNGL and FPNGL generate moderate control commands, while the ON-OFF controller generates the bounded control command. The final control command is the effective sum of the control commands from the three individual controllers. Extensive simulation shows satisfactory engagement performance of the proposed design.

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