Three-Dimensional Missile Guidance Laws Design Using Fuzzy Schemes

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Abstract: - This paper proposes three-dimensional fuzzy missile guidance laws based on line-of-sight, proportional navigation, and mixed strategy guidance. The results are promising and clearly demonstrate the potential of fuzzy guidance schemes against non-maneuvering and maneuvering targets. The miss distance and commanded acceleration profile are used in the performance evaluation of the proposed fuzzy guidance laws. A complete six-degrees-of-freedom flight simulation model for anti-aircraft command guided missile system is developed for verification.

Keywords: - Fuzzy Logic, Neural Network, Missile Guidance and control

NOMENCLATURE

Abbreviations

CoG = Center of Gravity
CLOS-STT = Command Line Of Sight Skid To Turn
FLOSCG = Fuzzy Line Of Sight Command Guidance
FPNCG = Fuzzy Proportional Navigation Command Guidance
FSG = Fuzzy Supervisory Guidance
LOS = Line-of-Sight
LATAX = Lateral Acceleration
MSG = Mixed Strategy Guidance
PN/APN = Proportional Navigation / Augmented PN
6DOF = Six-Degrees-of-Freedom

Symbols

I_{xx}, I_{yy}, I_{zz} = Moments of inertia about airframe axes.
P_{rox}, P_{roy}, P_{roz} = Products of inertia.
U, v, w, V_m = Velocity components along the missile's axes (X, Y, Z), and Total missile velocity, respectively.
p, q, r = Missile angular rates (roll, pitch, and yaw), respectively.
T_x = Engine thrust force (component in the missile longitudinal axis).
F_x, F_y, F_z = Aerodynamic forces.
M_x, M_y, M_z = Aerodynamic moments.
$c_{m\alpha}, c_{m\delta}, c_{mq}$ = Pitching moment derivatives.
$c_{n\beta}, c_{n\delta}, c_{mr}$ = Yawing moment derivatives.
$c_y^{\beta}, c_y^{\delta}$ = Side force derivatives.
$c_z^{\alpha}, c_z^{\delta}$ = Z-axis force derivatives.
α, β = Angle-of-Attack and sideslip angle.
ϕ, θ, ψ = Euler's angles (roll, pitch attitude, and heading angles), respectively.
c_x, c_y, c_z = Aerodynamic force coefficients that describe the missile airframe.
c_l, c_m, c_n = Aerodynamic moment coefficients that describe the missile airframe.
d, ℓ, m, s = Missile diameter, length, mass, and reference cross-sectional area ($\pi d^2 / 4$) respectively.
ρ, Q = Air density and atmospheric dynamic pressure ($1/2 \rho V_m^2$).
g = Acceleration due to gravity.
ε_m, β_m, ε_t, β_t = Missile and target LOS angles
r_m, r_t, r_{mt} = Missile, target slant ranges and relative distance respectively
x_r, y_r, z_r = Missile-Target relative distance
v_c , a_{tp}. a_{ty} = closing velocity, target acceleration in pitch and yaw respectively.

1 Introduction

The control hierarchy of a guided weapon consists of an outer guidance loop and an autopilot. As seen in Fig. 1, the guidance loop first measures the difference between the target and weapon trajectories and then produces guidance inputs to the autopilot, which controls the flight of the weapon through, for example, moving fins or other control surfaces and thrust vector control. The autopilot and its control elements are onboard the weapon and accepts guidance inputs through telemetry.

The aim of the guidance loop is to generate inputs so that the weapon will intercept the target in minimum time. This is a nonlinear time-varying control problem and while classical design methods have produced reliable systems, recently there have been numerous studies [1-10] into the application of intelligent control theory to guidance loop design. This is due in part to the inadequacy of classical techniques in dealing with highly maneuverable targets.

Common guidance laws in use are LOS guidance (either CLOS or beam-rider system) [11-14], LOS rate guidance [12], and other advanced guidance strategies, such as PN guidance [11-14], APN [13], and optimal guidance laws [13]. LOS guidance is designated as a three-point guidance system. A beam-riding missile generates its own commands internally whereas CLOS missile receives its commands from a remote station. In CLOS guidance strategy, the missile approaches the target along the line joining the control point and the target. The homing guidance system, which contrasts with the LOS guidance, is designated as a two-point guidance system and is implemented mostly as LOS rate guidance. PN guidance law issues acceleration commands, perpendicular to the instantaneous missile-target LOS, which are proportional to the LOS rate and closing velocity. Basically, this guidance law tries to nullify the LOS change, placing the missile and the target on a collision trajectory. Simply, APN is a PN guidance law with an extra term to account for the maneuvering target. Classical guidance laws different from these guidance laws were discussed in [12,13], where the performance of various guidance laws was extensively compared.

The main advantage of intelligent over classical control is that the former can provide robust systems when there are model and environmental uncertainties. Neural networks and fuzzy logic [15-17], by giving control laws based on input-output relationships, avoid the need for accurate knowledge of system dynamics, and are thus insensitive to their changes. Examples of application of intelligent control to missile autopilot design are in [1-6]. However, only a few [7-10] deal with the design of a guidance law.

Hopfield neural network architecture was developed to solve the optimal control problem for homing guided missile [7]. As an alternative approach, a fuzzy-logic-based closed loop optimal law for homing missile guidance was investigated [8]. Both of these studies are based on the well-known PN guidance method. It has been shown in [9] the superiority of two-fuzzy-logic based homing guidance schemes over the traditional PN or APN guidance methods. However, all the efforts listed above were limited to examining the single plane motion under certain parameter constraints for the homing guidance systems. Very recently, a three dimensional differential game missile guidance law using neural networks has been presented [10]. The results showed the great advantage of neural network based guidance law over the PN guidance law.

In this paper, fuzzy logic is used to design two pure guidance strategies for CLOS guided missile then a MSG [18] one. (1) Fuzzy logic based-LOS guidance law, (2) Fuzzy logic based APN command guidance laws, and (3) Fuzzy Supervisory controller based on MSG. These guidance algorithms are employed for guiding a missile to pursue and intercept a moving and very often accelerating target which is considered a highly nonlinear time-varying system.

The paper is organized as follows. In section 2, a 6-DOF-missile guidance and control model is presented. The nonlinear differential equations that describe the missile dynamics in the space are given to show the nonlinearities in the system kinematics and dynamics along with the environmental changes. In section 3 the investigations of designing missile guidance laws based on the fuzzy logic theory are presented. Evaluations of the three-dimensional missile-target engagement scenarios are given in section 4. Finally, this paper ends with the conclusions.

2 Missile Guidance and Control Model

The missile simulation that was used to generate all results in this paper is a 6-DOF nonlinear dynamic model of a guided missile system. The missile is aerodynamically controlled via two pairs of rear control fins. It has two identical control channels, each channel has lateral acceleration autopilot loop that control the missile lateral acceleration to be very close to the target at the end of engagement. The autopilot consists of a pneumatic fin servo, one accelerometer, one rate gyro, and the conditioning electronic circuits. In addition, a roll position control loop is utilized to keep the missile attitude fixed throughout the flight.

The equations for the missile’s CoG kinematical and dynamical motion, kinematical and dynamical rotation of the missile body around its CoG, and the on-board measuring and control devices are examined. Environmental parameter changes such as air density, velocity of sound as a function of altitude, and wind all effect the plant model. The motion of the missile in space is described by means of 6-differential equations. Referring to Fig. 2, the missile equations of motion are expressed in the body coordinate system as [14]:

$$\begin{aligned}
&T_x - F_x - mg\sin\theta = m\left(\dot{U} + qw - rv\right)\\
&F_y + mg\cos\theta\sin\varphi = m\left(\dot{v} - pw + rU\right)\\
&F_z + mg\cos\theta\cos\varphi = m\left(\dot{w} - qU + pv\right)\\
&M_x = I_{xx}\dot{p} + qr\left(I_{zz} - I_{yy}\right) + P_{rox}\\
&M_y = I_{yy}\dot{q} + pr\left(I_{xx} - I_{zz}\right) + P_{roy}\\
&M_z = I_{zz}\dot{r} + pq\left(I_{yy} - I_{xx}\right) + P_{roz}
\end{aligned} \tag{2.1}$$

The aerodynamic coefficients are computed at several operating points and a linear interpolation procedure computes their values at any intermediate point. The aerodynamic coefficients, considered to be one of the major uncertainties in the model dynamics, have in general nonlinear dependence on the Mach number and incidence angles. The aerodynamic forces and moments are given by:

$$F_{x,y,z} = c_{x,y,z}sQ\,,\ M_{x,y,z} = c_{l,m,n}sQ\,\ell \tag{2.2}$$

The aerodynamic force and moment coefficients that describe the missile airframe are given by:

$$\begin{aligned}
&c_x = c_{xo} + c_x^{\alpha}\alpha^2\,,\ c_y = c_y^{\beta}\beta + c_y^{\delta}\delta_r\,,\\
&c_z = c_z^{\alpha}\alpha + c_z^{\delta}\delta_e\,,\ c_l = c_{lp}\,p\,,\\
&c_m = c_{m\alpha}\alpha + c_{m\delta}\delta + c_{mq}\,q\,,\ c_n = c_{n\beta}\beta + c_{n\delta}\delta + c_{mr}\,r\,.
\end{aligned} \tag{2.3}$$

The aerodynamic force and moment coefficients that are presented previously are usually defined as a function of α, β, and other parameters. Therefore, it is desirable to show the relationship between the velocity components and these angles. These relations are defined as:

$\alpha=\tan^{-1}(W/U)$, $\beta=\tan(V/U)$, $\theta_T=\sqrt{V^2+W^2/U^2}$. (2.4)

where θ_T is the angle between the velocity vector and the missile longitudinal axis and it is referred to as the resultant angle of incidence. The orientation of these variables in the airframe coordinate system with all these conventions are shown in Fig. 2.

A simplified block diagram of the missile guidance loop and the location of the autopilot loop are shown in Fig. 1. In the autopilot loop, the difference between the desired and actual accelerations is sensed and used to drive the control surface actuator. A simplified block diagram of a typical autopilot composed of a control fin driver and measuring instruments is shown in Fig. 3. The control fin driver converts the input signal into mechanical deflections of the fins for the missile guidance. The accelerometer measures the missile's acceleration. This is modeled by the second order transfer function of the form:

$$Out.[volt]/Inp.[m/s^2]=-k_a/\tau_a^2 s^2+2\tau_a\zeta_a s+1 \quad (2.5)$$

In order to isolate the accelerometer pendulum from missile oscillations, it must be placed as near as possible to the missile's CoG. The damping gyro has two degrees of freedom and is utilized in the autopilot to damp the oscillations of the missile around its CoG. Its transfer function is:

$$Out.[volt]/Inp.[\deg/s]=k_g/\tau_g^2 s^2+2\tau_g\zeta_g s+1 \ .(2.6)$$

The STT steering policy requires that the roll autopilot performs attitude stabilization in the maneuver plane. A roll position controller is utilized to keep an adequate roll damping.

3 Fuzzy Logic Based Guidance laws

In general a fuzzy logic controller contains four main components; fuzzification, rule-base, inference mechanism, and defuzifiaction. The fuzzification interface simply modifies the inputs so that they can be interpreted and compared to the rules in the rule base. The rule base holds the knowledge in the form of a set of rules of how best to control the system. The inference mechanism or the decision making logic evaluates which control rules are relevant at the current time and then decides what is the input to the plant should be. The defuzzification interface converts the conclusions reached by the inference mechanism into the inputs to the plant to be controlled.

From the literature, beam-riding guidance can be significantly improved by taking the beam motion into account (CLOS). This is analogous to homing guidance in which PN performance is improved by tacking target maneuvering into account (APN). So a FLOSCG and FPNCG are presented in the next subsections with a suggested FSG scheme to cope with the problems for each individually.

3.1 Fuzzy-LOS Command Guidance

The CLOS guidance is classified as a three-point guidance law. In this guidance strategy, the missile maneuvers so as to be on LOS between the target tracker and the target. A guidance computer is utilized at the ground-based station and produces the acceleration commands, which are sent via radio link to the autopilot. The main objective of the CLOS guidance is to constrain the missile to lie as nearly as possible on the LOS. If the missile is always on the tracker-target LOS, then the missile will surely hit the target. Geometry of Missile-Target interception is shown in Fig. 4. The guidance strategy adopted in this section is given by:

$$\varepsilon_m=\varepsilon_t\ ,\ \beta_m=\beta_t \quad (3.1.1)$$

Thus, the method of control is proportional to the lateral displacement of the missile from the target LOS that is given by

$$EP=r_m(\varepsilon_t-\varepsilon_m),\ EY=r_m\,(\beta_m-\beta_t)\cos\varepsilon_m. \quad (3.1.2)$$

with the sign indicating the direction of missile movement that is required to nullify the error. The control signals depend not only on the error signal but also on its derivative with the aim of increasing the stability and improving the transients in the guidance system.

The FLOSCG scheme presented here based on the three-point guidance law is shown in Fig. 5. The fuzzy guidance law has four inputs and two outputs for generating the demanded acceleration to steer the missile in space. The inputs are the errors EP and EY along the pitch and yaw axes and the change in errors. This scheme uses 11 uniformly distributed triangular membership functions for each of its input universe of discourse and the minimum to represent the premise and implication. Whenever the input is high, the saturation of the left most and the right most membership functions are considered. For illustration, sample rules of the fuzzy scheme take the following form for pitch and yaw guidance:

If EP is I_1 and $\dot{E}_P$ is J_1 then A_{pc} is $R_p(1)$

If EY is M_1 and $\dot{E}_y$ is N_1 then A_{yc} is $R_y(1)$

Variables, I_i, J_i, M_i, N_i, $R_p(i)$, and $R_y(i)$, take the linguistic values expressed by linguistic sets such as LN and LP that are interpreted as large negative and large positive respectively.

Since the steering command signals must be crisp, the center of gravity defuzzification method [15] is used to calculate the crisp control action. Tuning via scaling universes of discourse is applied. A great effort has been made to choose the proper scaling gains (g_{pe}, g_{pc}, g_{ye}, g_{yc}, g_{pu}, g_{yu}) shown in Fig. 5. More emphasis should be put on finding out the optimum values.

3.2 Fuzzy-PN Command Guidance

One of the most widely used homing guidance laws for a few decades is PN guidance law. In this type of guidance system the missile seeker provides the information required for guidance process. However, a missile seeker is not required in command guidance. External missile/target trackers transmit and receive radar signals. i.e. we can assume that ε_m, β_m, r_m, ε_t, β_t, and r_t are available as well as target maneuvers. In order to implement PN in the command guidance system, λ and $\dot{\lambda}$ should be available from the measurement information [3]. The yaw and pitch components of the line of sight angle can be computed using missile and target position vectors in the inertial frame as:

$$\lambda_y = \tan^{-1}(y_r/x_r) \text{ and } \lambda_z = \tan^{-1}(z_r/x_r) \qquad (3.2.1)$$

The yaw and pitch components of LOS rates and the closing velocity can be computed as

$$\dot{\lambda}_y = (x_r \dot{y}_r - y_r \dot{x}_r)/(x_r^2 + y_r^2),$$
$$\dot{\lambda}_p = (x_r \dot{z}_r - z_r \dot{x}_r)/(x_r^2 + z_r^2) \qquad (3.2.2)$$
$$v_c = -\dot{r}_{mt} = -(x_r \dot{x}_r + y_r \dot{y}_r + z_r \dot{z}_r)/r_{mt}$$

The pitch and yaw acceleration commands are given by

$$A_{pc} = N\, v_c\, \dot{\lambda}_z + 0.5 a_{tp} N + \text{gravity bias.}$$
$$A_{yc} = N\, v_c\, \dot{\lambda}_y + 0.5 a_{ty} N \qquad (3.2.3)$$

The effective navigation ratio, N, is kept constant during the flight time. The magnitude of the missile demanded (pitch, yaw) acceleration (A_{pc}, A_{yc}) is restricted especially during the initial phase of guidance to not let the missile control surfaces reach saturation. It is a well-known fact that larger effective navigation ratio enables the missile to remove the initial heading error more rapidly, thus causing a much tighter trajectory. However, this results in larger missile acceleration at the beginning of flight and lower at the end [13]. Then, highly time varying navigation ratio can prevent the commands from reaching saturation in the beginning of flight and compensate for the target maneuverability.

A simple fuzzy rule structure is implemented to compute the proper N and provide it to the conventional PN/APN guidance law. These constitute in somehow what is called a hybrid fuzzy scheme. The proposed FPNCG scheme is shown in Fig. 6. The fuzzy rule base block has two inputs and one output for generating the time varying effective navigation gain. The inputs are the relative range between missile and target and the range rate. This simple fuzzy structure needs a less complicated rule base. . For illustration, a sample rule is given as:

If r_{mt} is Large and $\dot{r}_{mt}$ is large then N is small

The simulation results in section 4 showed that for the existing autopilot the FLOSCG and FPNCG are not working well individually. However this problem can be resolved in two ways. The first is to redesign the autopilot (the hardest choice) while the second is to combine the two based on MSG. In the next section the suggested solution is investigated.

3.3 Fuzzy Supervisory Guidance

Since aircrafts become smarter and smarter, no single guidance strategy seems to be adequate to have satisfactory performance. The MSG approach suggests to design two or more pure guidance strategies each has adequate performance against some of the set of all possible target behaviors [18].

A new missile guidance strategy which combines the proposed FLOSCG and FPNCG with certain weights depending on both the relative distance between the missile and the target and the closing velocity as well. The proposed fuzzy-supervisory guidance scheme is shown in Fig. 7. The fuzzy rule base block has two inputs and two outputs for tuning the weights (W1, W2). These weights are used to combine between the two proposed pure guidance strategies based on the relative distance between the missile and the target. The inputs are the relative range between missile and target and the range rate. This simple fuzzy structure also needs a less complicated rule base.

4 Simulation Results

In section 3.1 and 3.2, the design methodology of the fuzzy guidance laws to generate the steering commands are proposed. This section presents numerical simulation results for the FLOSCG and FPNCG to demonstrate the performance of the proposed guidance laws. Miss distance and commanded acceleration profile are used for the performance evaluation. Table 1 includes different target scenarios with non-maneuvering and maneuvering; approaching and receding targets with different speeds. The cost function is defined as

$$\text{LATAX} = \int_{t_o}^{t_f} \sqrt{A_{PC}^2 + A_{YC}^2}\, dt \qquad (4.1)$$

A three-dimensional missile-target engagement simulation was set up using the presented mathematical model in section 2. A complete 6-DOF-flight model for CLOS-STT missile system is developed. A computer code that solves the model is carried out with BORLANDC. Modular concept is considered in the code development. A simplified block diagram of the model is shown in Fig. 8.

The model is broken down into the following major parts: missile-target geometry, guidance, autopilot, airframe, and kinematics. In the missile-target geometry module, the missile position relative to the target is calculated. The guidance parameters, which are the deviation errors between the ideal and actual position of the missile measured by guidance radar, are then calculated. The guidance module receives the guidance parameters and generates the guidance steering command signals through different fuzzy guidance schemes. The guidance signals are supplied to the autopilot to steer the missile in space. For completeness, the actuator dynamics is considered. In general, each fin actuator has a finite bandwidth, for simplicity, the effectiveness of the fin deflection angles is modeled by a first order system with surface position saturation and rate saturation. In the airframe module various forces and moments are calculated. They involve aerodynamic, weight, thrust, and control forces and moments. The aerodynamics forces and moments are calculated in the velocity coordinate system. However the thrust and weight forces are computed in the board and reference coordinate systems respectively. Thus, the solution of the dynamical problem necessitates a reliable means for coordinate transformations between these systems. The transformations between these coordinate systems achieved by the Euler's angle method. Finally, the kinematics module solves the force and moment equations and produces the missile flight parameters, which are the instantaneous acceleration, velocity, and position data of the missile. The flight path variables are, then derived from the airframe module.

Table 1 shows that the missile succeeds in interception for all cases. It is clear the significant lower miss distance using FPNCG over the FLOSCG. Regarding the LATAX, FPNCG was superior in 8 cases (T2-T9) and inferior in only one case (T1).

Figures 9 through 11 show the missile-target engagement scenario (T3-Table1), control fin deflection as a result of the guidance commands, and histories of the resultant missile angle of attack and sideslip angle. In this case it is apparent from Fig. 9 that FPNCG scheme with the advantage of time varying navigation ratio results in much tighter trajectory than the FLOSCG scheme. However in the case of FLOSCG, the existing autopilot is able to track the error trajectory and achieve the demanded acceleration smoothly. On the other hand, as the relative distance between the missile and the target is large the proportional navigation can handle the heading error rapidly with a moderate acceleration commands. While the relative range becomes small (near the interception) the acceleration command becomes very large and rapid which leads to more challenge on the existing autopilot as shown in Fig.s 10 and 11.

The same principle criteria for performance evaluation have been used to evaluate the suggested FSG presented in section 3.3. The results are tabulated in Table 1 and shown in Fig.s 12 and 13. The miss distance is small enough for the missile to hit the target. The results are found to be encouraging and clearly demonstrate the potential of this fuzzy guidance scheme against non-maneuvering and maneuvering targets with different speeds.

5 Conclusion

Fuzzy approaches to CLOS-STT missile guidance have been presented. The obtained results show the superiority of the proposed FPNCG over FLOSCG. The results are for three-dimensional engagement. The FSG scheme has been suggested as a simpler solution. The use of combined guidance law (homing and command) allows achieving a great accuracy of fire even in case of rapid and/or maneuvering; approaching and/or receding targets. Fuzzy approach is promising in the realm of designing missile guidance laws.

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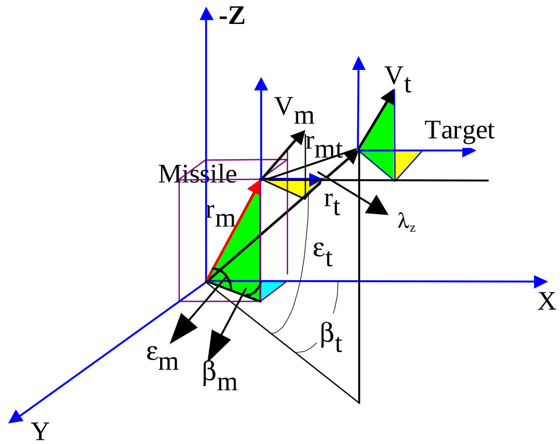

Fig. 4 Geometry of Missile-Target interception

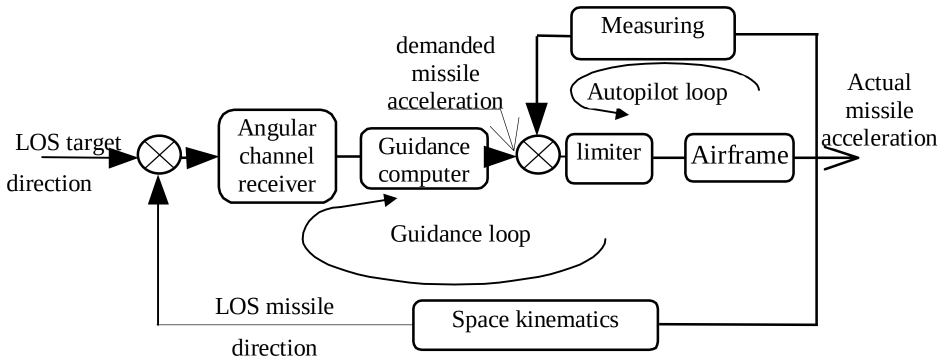

Fig. 1 Block diagram of the guidance-autopilot loop

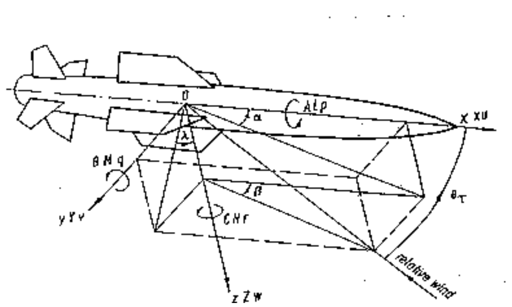

Fig. 2 Missile airframe reference axes

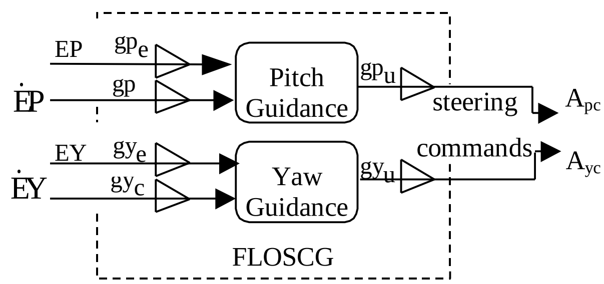

Fig. 5 FLOSCG scheme

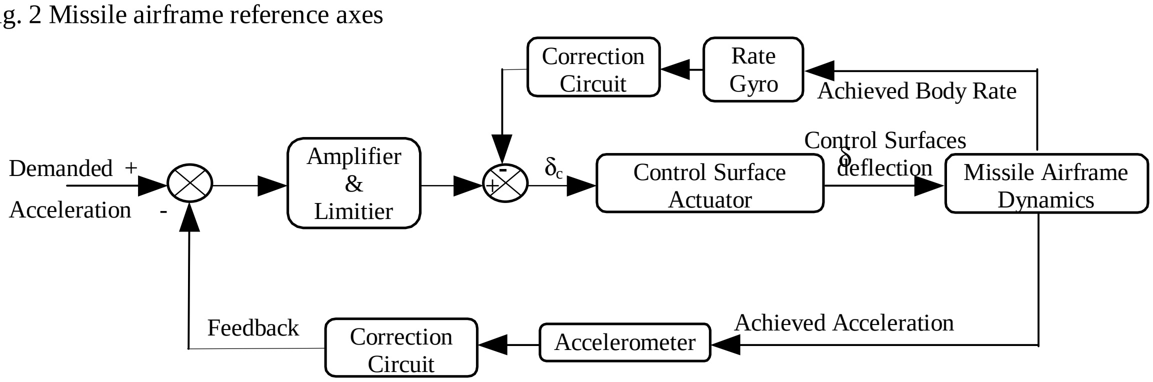

Fig. 3 Simplified block diagram of pitch autopilot.

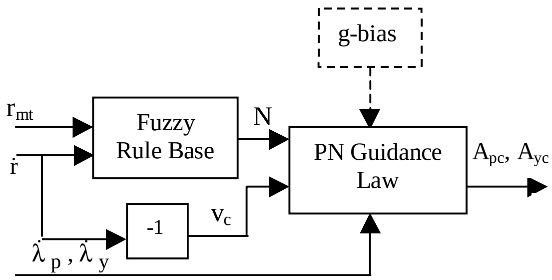

Fig. 6 FPNCG scheme

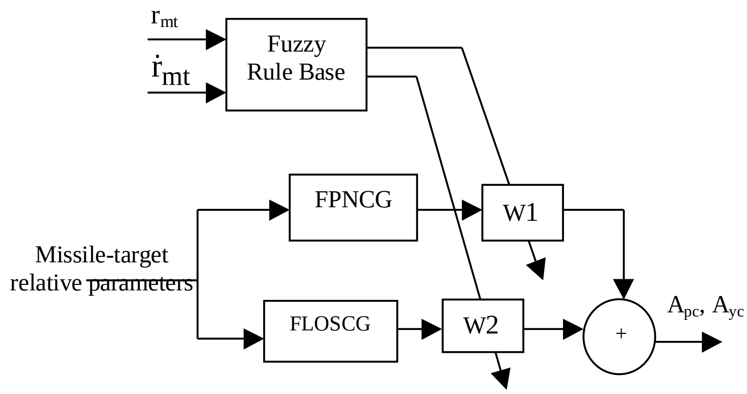

Fig. 7 Supervisory Fuzzy Guidance Scheme

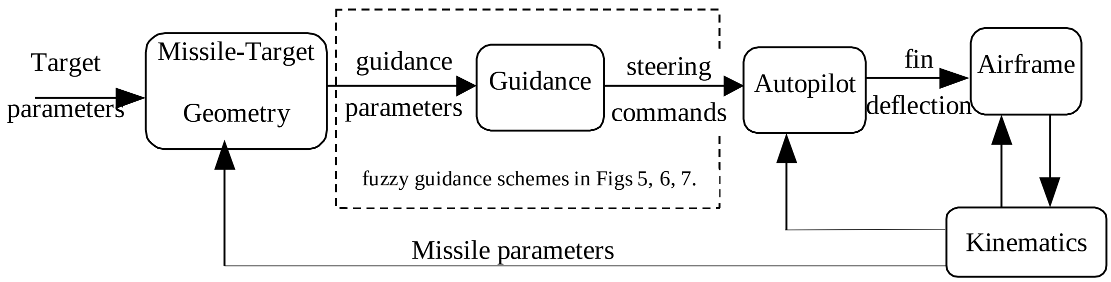

Fig. 8 Simplified block diagram of the main simulation model modules.

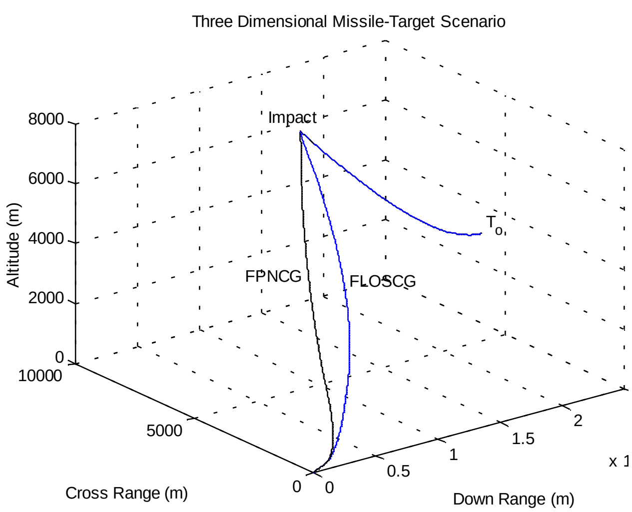

Fig. 9 Missile-target engagement scenario (T3-Table1)

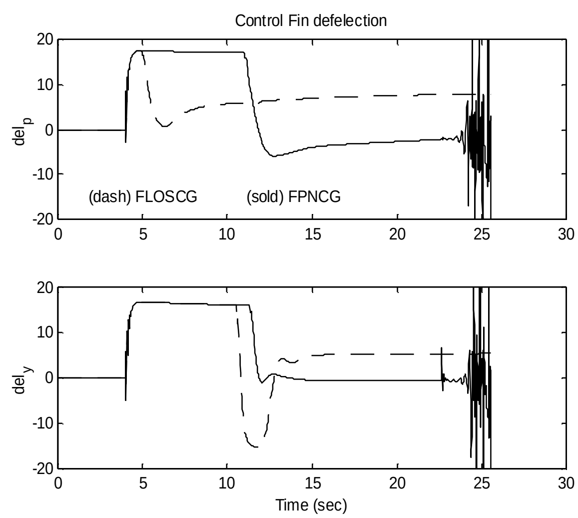

Fig. 10 Pitch and yaw control fin deflection

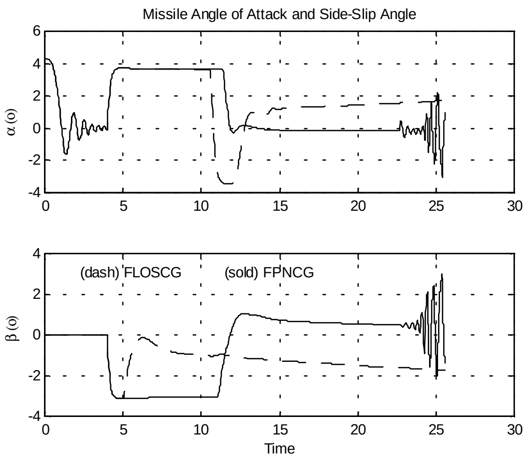

Fig. 11 Missile angle of attack and sideslip angle.

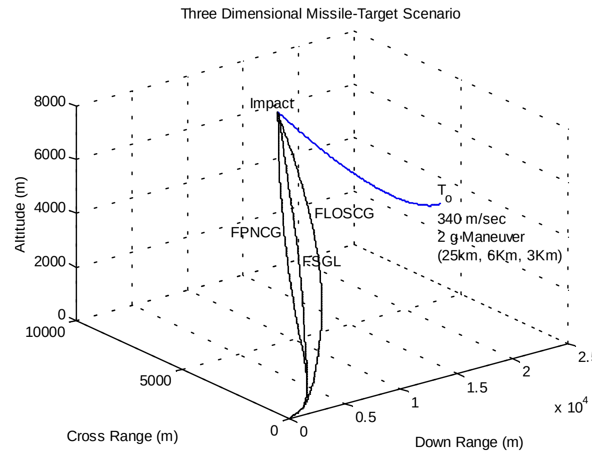

Fig. 12 Missile-target Engagement Scenario (T3)

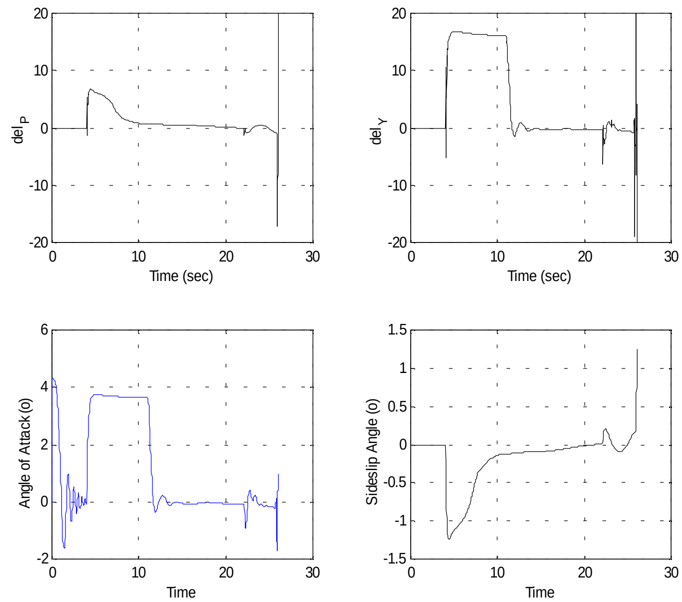

Fig. 13 Pitch and yaw control fin deflection and corresponding α and β in case of employing FSG.

TABLE 1

	Target Initial Parameters			Miss Distance [m]			LATAX		
	XT, YT, ZT [Km]	VT [m/sec]	AT [g]	FLOSCG	FPNCG	FSG	FLOSCG *e+004	FPNCG *e+004	FSG *e+004
T1			0	5.35	0.487	0.354	3.1755	4.6043	2.3478
T2	25, 6, 3	340	1	7.59	0.864	0.475	5.3086	5.0548	3.2331
T3	Approaching Target		2	9.56	1.429	1.128	8.4554	6.5736	4.7226
T4			0	6.78	0.680	0.708	3.6902	4.7420	2.3012
T5		430	1	9.86	1.064	1.125	5.7532	5.0165	3.3331
T6			2	12.45	1.641	1.847	8.8391	6.3892	4.7191
T7			0	3.45	0.513	0.255	4.4709	3.8431	3.0257
T8	5, 6, 3	330	1	6.23	1.105	0.985	5.6481	5.2074	2.9300
T9	Receding Target		2	8.52	1.378	1.012	7.6442	6.6642	4.6614