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Short Range Missile Autopilot Design using Fuzzy Control Technique

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Abstract: Anti-tank short range missiles can be categorized in the most widely used weapons in the recent ground battle field. Development of a trusted autopilot for these kinds of missiles is a very critical issue. Although classical control techniques can provide a good and stable solution, but with time, the uncertainties increase and hence the designed classical controller (CC) is no longer valid to cope with this kind of problems. This paper represents a lateral displacement controller design of a missile model. Classical control technique shows satisfactory results in missile maneuvering while it fails to intercept the target in case of thrust degradation (aging of the missile rocket motor) and uncertainties in aerodynamics. A new lateral autopilot design for a roll stabilized skid to turn (STT) missile using fuzzy control technique is adopted and introduced in this paper. In this new controller the parameters of fuzzy logic are designed to optimize the performance characteristics of the plant. The simulation results show that the fuzzy logic control shows better performance in case of thrust degradation and uncertainties in aerodynamics.

Keywords: Anti-tank missiles, Classical controller, Autopilot design, Fuzzy control.

The following table illustrating the symbols used throughout the paper;

Nomenclature

F	Total force acting upon the missile
m	Missile mass
V	Missile velocity
M	Total Acting moment upon the missile
H	Angular momentum
x, y, z	Missile linear displacement in the corresponding axes
ϑ, ψ, γ	Body pitch, yaw and roll angles
α, β	Missile angle of attack and angle of sideslip.
$\omega_{x1}, \omega_{y1}, \omega_{z1}$	Missile angular rates.
I_{xx}, I_{yy}, I_{zz}	Missile mass moment of inertial about x, y and z axes
δ_y	Rudder fin deflection
$m_{y1}^{\delta_y}, m_{y1}^{\beta}, m_{y1}^{\dot{\psi}}$	Aerodynamic moment coefficient due to fin deflection, sideslip and body rate respectively.
S	Reference area
q	Aerodynamic pressure

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l	Reference length
PB	Positive Big
PM	Positive Medium
PS	Positive Small
Z	Zero
NS	Negative Small
NM	Negative Medium
NB	Negative Big
σt	Target line of sight in yaw plane
σm	Missile line of sight in yaw plane
Δσ	Error angle between target and missile line of sights
δr	Rudder fin deflection
u	Control effort
Ψ_d	The demanded body angle in yaw plane
Ψ_a	The achieved body angle in yaw plane
Ψ_m	The measured body angle in yaw plane
ΔΨ	The error angle between the demanded and measured body angle in yaw plane

I. Introduction:

Guided missiles are able to seek out and navigate their way towards the target depending on the guidance method they adopt. The underlying missile system uses one of these methods that is called three-point guidance; where the missile, target and control station have to be in-line at any instant during the flight time as shown in figure(1). The missile is tracked by using an infrared tracker at the launcher side that tracks the radiations emitted from a thermal source mounted on the aft part of the missile. On other hand, the target is optically tracked by the operator, the error distance between the virtual target line of sight and the virtual missile line of sight is compensated in the control station and the steering commands are sent through wire to the on-board missile electronic to correct its trajectory. On-board; the commanded signal (angle in yaw plane) is compared with the actual angle carried out by the missile and the error angle is compensated again in the inner guidance loop which represents the autopilot to steer the missile.

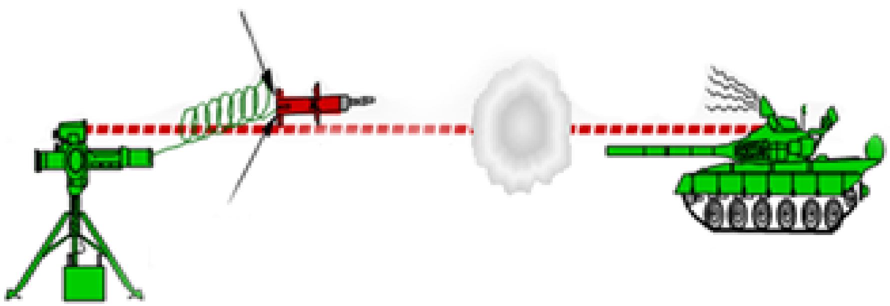


Figure 1 Three-point guidance

Some control schemes have been adopted to enhance the autopilot performance, including adaptive control[2], nonlinear control, H_∞ optimal control and gain scheduling[3]. The use of

fuzzy logic control is motivated by the need to deal with nonlinear flight control and performance robustness problems [1]. It is well known that fuzzy logic is much closer to human decision making than the traditional controller. Fuzzy control based on fuzzy logic provides a new design paradigm such that a controller can be designed for complex, ill-defined processes without knowledge of quantitative data regarding the input-output relations; the fuzzy logic controller is used to control the lateral displacement of a missile autopilot.
The rest of the paper is organized as follows: Problem formulation and equations of motion are explained in Section II. The controller approach is described in section III. Simulation results and discussion are brought in section IV and finally a brief discussion is introduced in section V.

II. Problem Statement

The mathematical model of the underlying system representing the kinematic and dynamic equations governing the spatial missile motion is very useful for designing the proposed controller [4]. This model is a roll stabilized (γ=0) 5 degree-of-freedom (DOF) model in parametric format with nonlinear behavior, therefore this study looks at the reduced problem of a controller for the uncoupled lateral motion. Although the conventional classical control technique has a better performance in missile maneuvering but in case of missile aging and uncertainties in missile aerodynamic calculations this classical controller is unable to guide the missile till interception. Figure (1) shows the main missile guidance outer loop and the autopilot inner loop that consists of servos, control surface, the airframe, and feedback instrument plus control electronics.

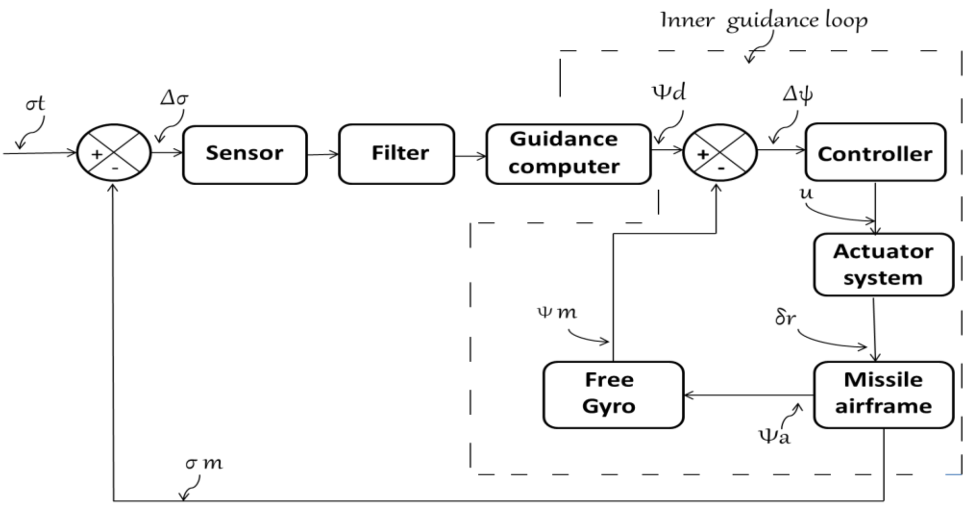


Figure 2 guidance loops

The missile autopilots are usually designed using linear models of nonlinear equations of aerodynamic forces and moments. The objective of this paper is to develop a robust design of lateral autopilot displacement for a nonlinear missile model. The set of nonlinear equations describing the missile motion are as follows:

$$\sum F = \frac{d(mV)}{dt} \qquad \sum M = \frac{d(H)}{dt} \tag{1}$$

$$\dot{x} = V_{x1}\cos\psi\cos\vartheta - (\cos\psi\sin\vartheta\cos\gamma - \sin\psi\sin\gamma)V_{y1} + (\cos\psi\sin\vartheta\sin\gamma + \sin\psi\cos\gamma)V_{z1}$$
$$\dot{y} = V_{x1}\sin\vartheta - \cos\vartheta\cos\gamma V_{y1} - \cos\vartheta\sin\gamma V_{z1} \qquad (2)$$
$$\dot{z} = -V_{x1}\sin\psi\cos\vartheta + (\sin\psi\sin\vartheta\cos\gamma + \cos\psi\sin\gamma)V_{y1} - (\sin\psi\sin\vartheta\sin\gamma - \cos\psi\cos\gamma)V_{z1}$$

The aerodynamic force and moments coefficients are mainly function of angle of attack α and side slip angle β. Thus it is necessary to show the dependence of theses angles upon the velocity components as follows:[5]

$$\alpha = \arctan(\frac{-V_{y1}}{V_{x1}})$$
$$\beta = \arcsin(\frac{-V_{z1}}{V}) \qquad (3)$$

$$\dot{\psi} = (\omega_{y1}\cos\gamma - \omega_{z1}\sin\gamma)\cos ec\vartheta$$
$$\dot{\vartheta} = \omega_{y1}\sin\gamma + \omega_{z1}\cos\gamma \qquad (4)$$
$$\dot{\gamma} = \omega_{x1} - (\omega_{y1}\cos\gamma - \omega_{z1}\sin\gamma)\tan\vartheta$$

$$\dot{\omega}_{x1} = \frac{M_{x1} - (I_{zz} - I_{yy})\omega_{z1}\omega_{y1}}{I_{xx}}$$
$$\dot{\omega}_{y1} = \frac{M_{y1} - (I_{xx} - I_{zz})\omega_{z1}\omega_{x1}}{I_{yy}} \qquad (5)$$
$$\dot{\omega}_{z1} = \frac{M_{z1} - (I_{yy} - I_{xx})\omega_{x1}\omega_{y1}}{I_{zz}}$$

The previous equations are used in the upcoming sections to develop the missile airframe transfer function.

Autopilot configuration:

The missile control system consisting of servos, control surfaces or thrust vector elements, the airframe and a feedback element plus control electronics is usually called an autopilot. The underlying model uses a free gyroscope or simply gyro as a feedback element that senses the angular displacement in the lateral direction.
Equations from (1.2) to (1.5) are linearized and hence the airframe transfer function in yaw plane is calculated to be follows:

$$\frac{\psi}{\delta_y} = \frac{(-M_{y1}^{\delta_y})*s + (M_{y1}^{\delta_y}*n_\beta - M_{y1}^{\beta}*n_{\delta_y})}{-s^3 + (n_\beta + M_{y1}^{\dot{\psi}})*s^2 - (n_\beta*M_{y1}^{\dot{\psi}} + M_{y1}^{\beta})*s} \qquad (6)$$

Where:

$$M_{y1}^{\delta_y} = \frac{m_{y1}^{\delta_y} * S * q * l}{I_{yy}},$$
$$M_{y1}^{\beta} = \frac{m_{y1}^{\beta} * S * q * l}{I_{yy}}, \quad (7)$$
$$M_{y1}^{\dot{\psi}} = \frac{m_{y1}^{\dot{\psi}} * S * q * l}{I_{yy}}$$

The transfer function of position gyro is modeled to be a the second order system, with natural frequency and damping ratio equal to (60 rad/sec, 0.5) respectively[6]. So the transfer function of free gyroscope is as follows:

$$\frac{\psi_{out}}{\psi_{act}} = \frac{1}{s^2 + 60 * s + 3600} \quad (8)$$

And the actuator can be modeled as a single lag filter with 5 millisecond time constant as follows [6]:

$$\frac{\delta_a}{\delta_c} = \frac{1}{0.005 * s + 1} \quad (9)$$

III. Autopilot design using fuzzy logic controller (FLC)

Due to the missile aging and the uncertainties in missile aerodynamic calculations, the conventional classical controller is unable to hit the target. Hence it is a necessary to develop a controller to deal with these uncertainties and the ageing of each missile. Fuzzy logic controller (FLC) is considered to be the advanced control technique to deal with these sources of uncertainties depending on the available information about the system. The block diagram illustrating the inner guidance loop is shown in figure (3) where the demanded body angle in yaw plane (ψ) is subtracted from the actual ψ performed by the missile and measured by the on-board free gyro, the error ($e = \Delta\psi$) and rate of change of error ($\dot{e}$) are introduced to the fuzzy logic controller.

The fuzzy logic control process system has three main processes:

- The fuzzification process.

  Is the process of mapping inputs to the fuzzy logic control into fuzzy set membership values in the various input universes of discourse. Decisions need to be made regarding

  i. Number of inputs
  ii. Size of universes of discourse
  iii. Number and shape of fuzzy sets

Fuzzy rulebase: the fuzzy rulebase consists of a set of antecedent-consequent linguistic rule of the form:

IF e is PS AND $\dot{e}$ is NS THEN u is PS

This style of fuzzy conditional statement is called "Mamdani" type rule[1]. The rule base is constructed using a priori knowledge from either from one or all of the following sources:

i. Physical laws that govern the planet dynamics.
ii. Data from existing controller.
iii. Imprecise heuristic knowledge obtained from experienced experts.

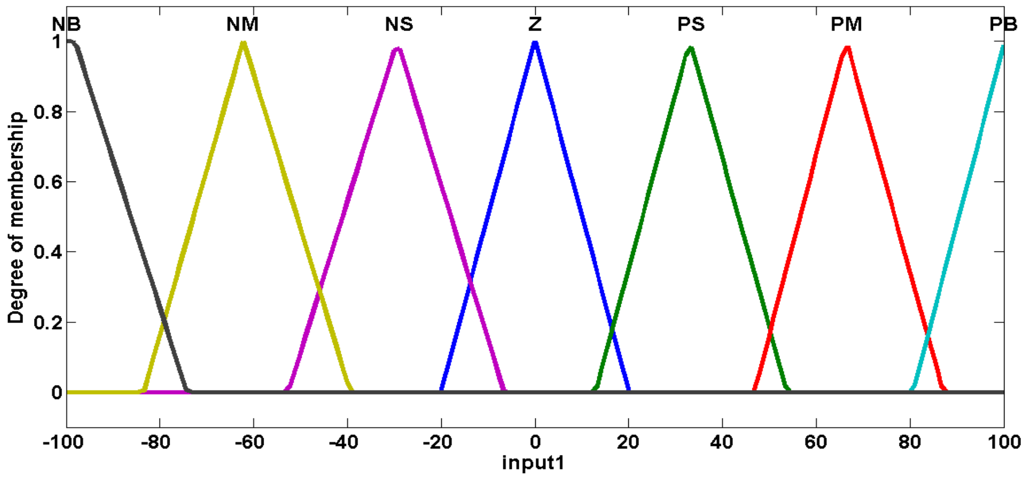
- Fuzzy inference:

  Fuzzy inference is the process of mapping membership values from input windows through the rulebase to the output window.
- Defuzzification process:

  It is the procedure for mapping a set of inferred fuzzy control signals contained within a fuzzy output window to a crisp signal. The center of area method is most well-known defuzzification technique, such that:

$$u = \text{Sum of first moment of area/ sum of areas}$$

In this design seven triangular sets will be used for e, $\dot{e}$ and control effort (u). Each set is given a linguistic label to identify it, such as Positive Big (PB), Positive Medium (PM), Positive Small (PS), Zero (Z), Negative Small (NS), Negative Medium (NM) and Negative Big (NB). The seven fuzzy sets for e, $\dot{e}$ and control effort (u) and the fuzzy rule base are shown in figure (4) and table (2) respectively.



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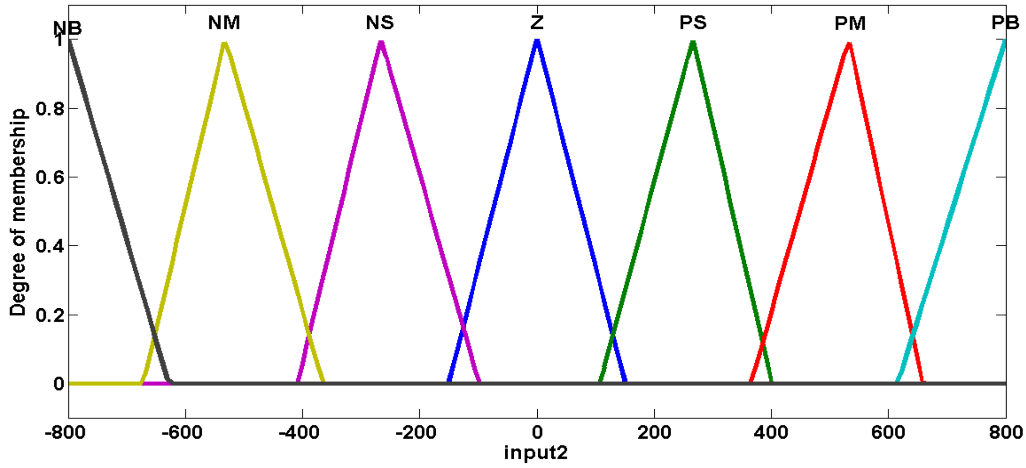

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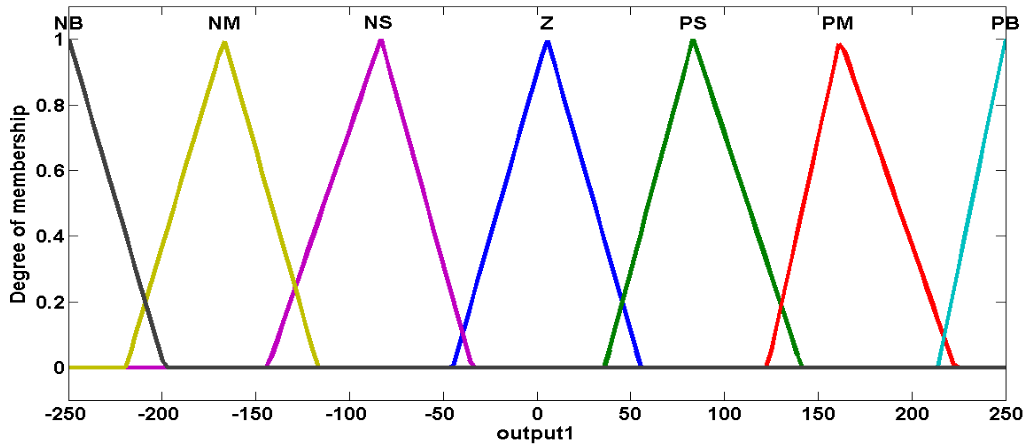


(c)

Figure 3 Membership function for (a) error, (b) error dot and (c) control signal

Table 1 Tabular structure of a linguistic fuzzy rulebase

e / $\dot{e}$	NB	NM	NS	Z	PS	PM	PB
NB	NB	NB	NB	NB	NB	NB	NB
NM	NM	NM	NM	NM	NM	NM	NM
NS	NS	NS	NS	NS	NS	NS	NS
Z	Z	Z	Z	Z	Z	Z	Z
PS	PS	PS	PS	PS	PS	PS	PS
PM	PM	PM	PM	PM	PM	PM	PM
PB	PB	PB	PB	PB	PB	PB	PB

IV. Simulation results

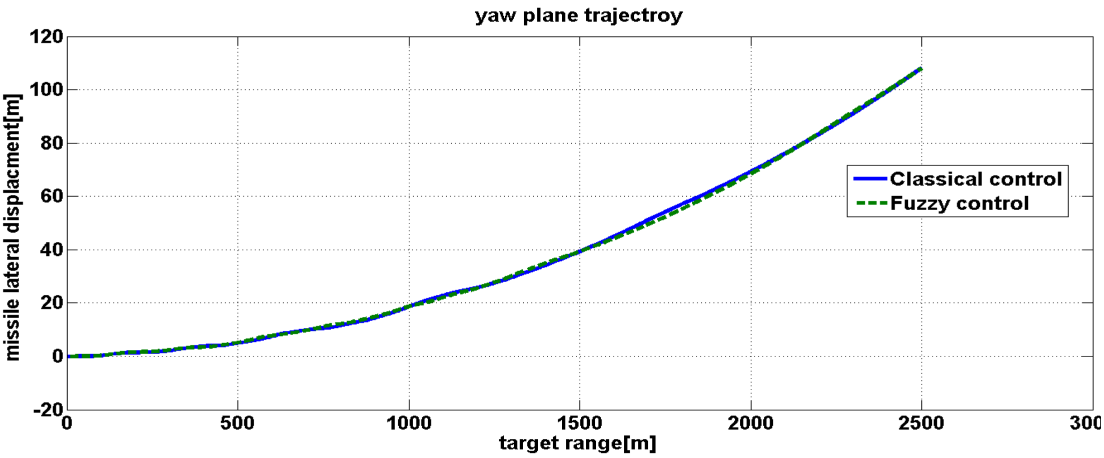
In this section the behavior of the developed fuzzy logic controller is evaluated throughout two main categories; i) different target scenarios ii) uncertainties in thrust (missile aging) and in aerodynamic calculations.

i. <u>*Different Velocities*</u>:

At different target velocities at opposite directions, the developed FLC is evaluated. Some of these scenarios are tabulated below. The simulation results show that the FLC has the same performance as the classical controller. Figures (5, 6) show the yaw trajectory and control effort between FLC and classical controller at different target speeds. At different missile velocities the FLC shows the same performance of the CC but with less control effort.

Table 2 miss distance at different target speeds using different controllers

Controller / Target speed	Fuzzy logic controller	Classical controller
13 m/sec	0.0124 m	0.0645 m
-8m/sec	0.26m	0.24 m



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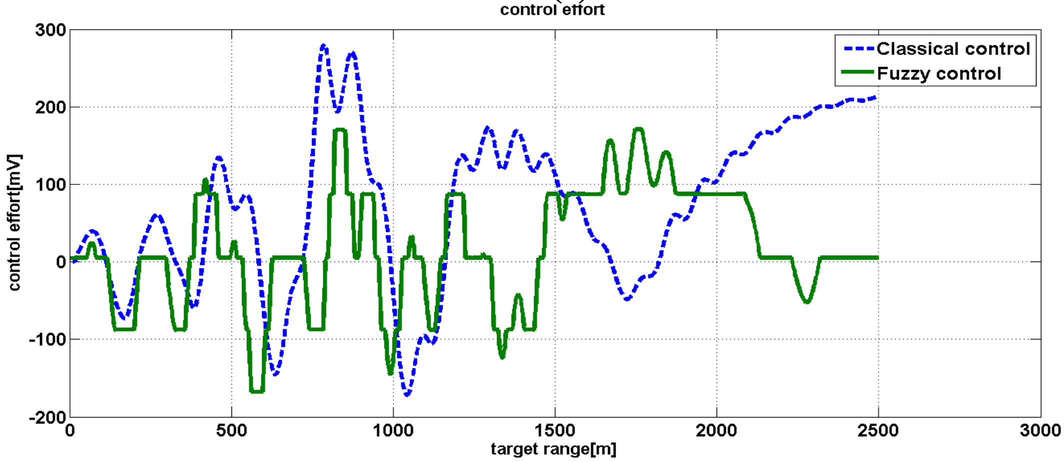
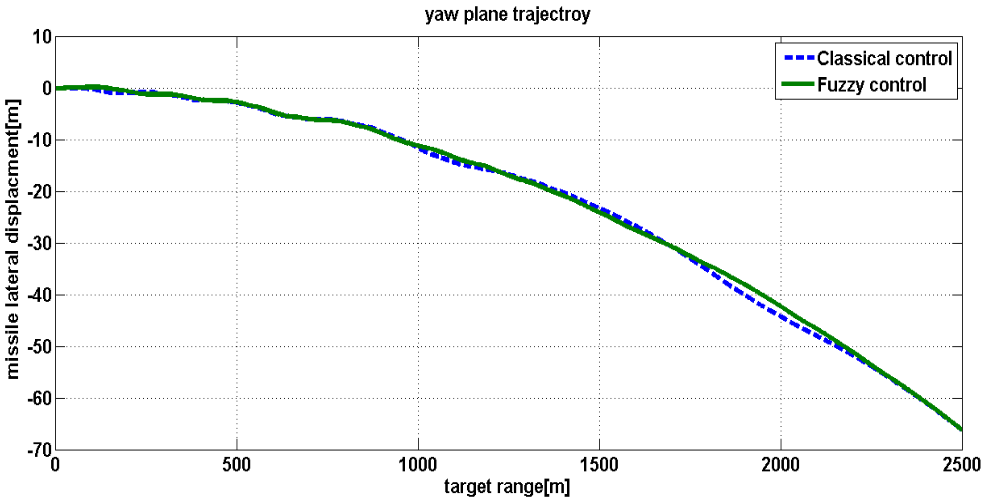


(b)

Figure 4 Compeission between FLC and CC in (a) yaw trajectory (top view) and (b) control effort for target velocity =13m/sec



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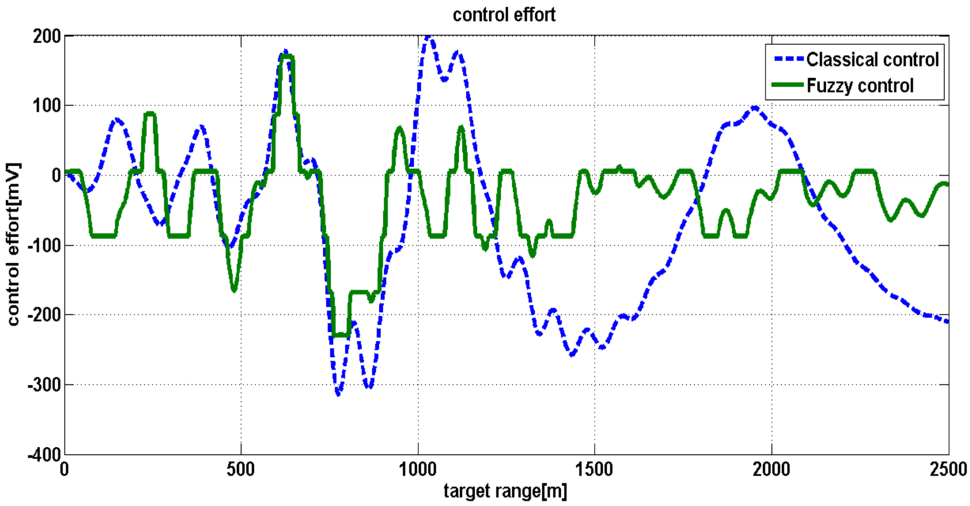


(b)

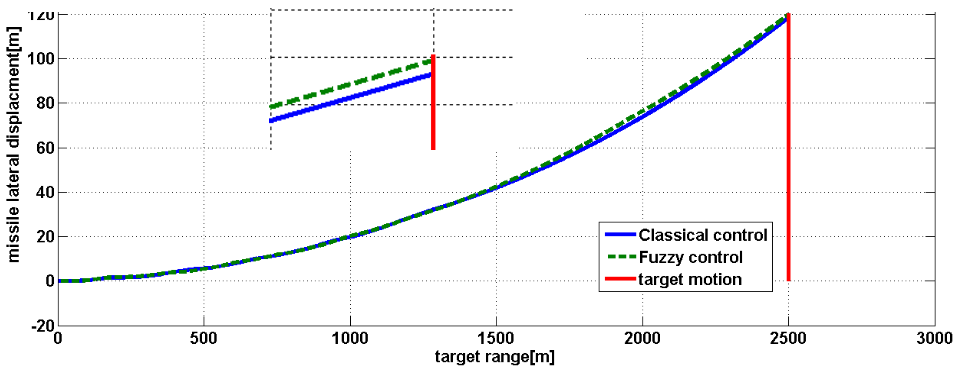
Figure 5 Compression between FLC and CC in (a) yaw trajectory and (b) control effort for target velocity =-8m/sec

ii. *Thrust degradation*

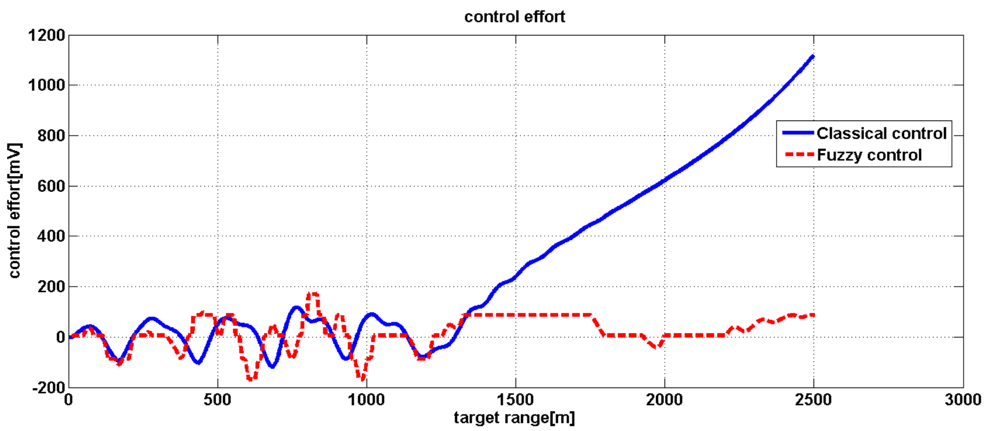
Due to the missile aging the missile thrust efficiency is affected and therefore affects the missile behavior. Here the missile thrust is reduced by 10% and 20%. The simulation results show that the classical controller has failed to hit the target while the FLC can deal with this kind of uncertainty. on other hand, the control effort resulted from using FLC is less than that of CC. Table (4) shows the miss distance in the two cases in the scenario of thrust degradations. Figures (7, 8) show the yaw plane trajectory and control effort for both FLC and CC.

Table 3 miss distance at different thrust degradation using different controllers

Thrust degradation \ Controller	Fuzzy logic controller	Classical controller
10% off	1.78 m	1.78 m
20% off	0.6 m	9m



(a)



(b)

Figure 6 Compression between FLC and CC in (a) yaw trajectory and (b) control effort for thrust decreased by 10%

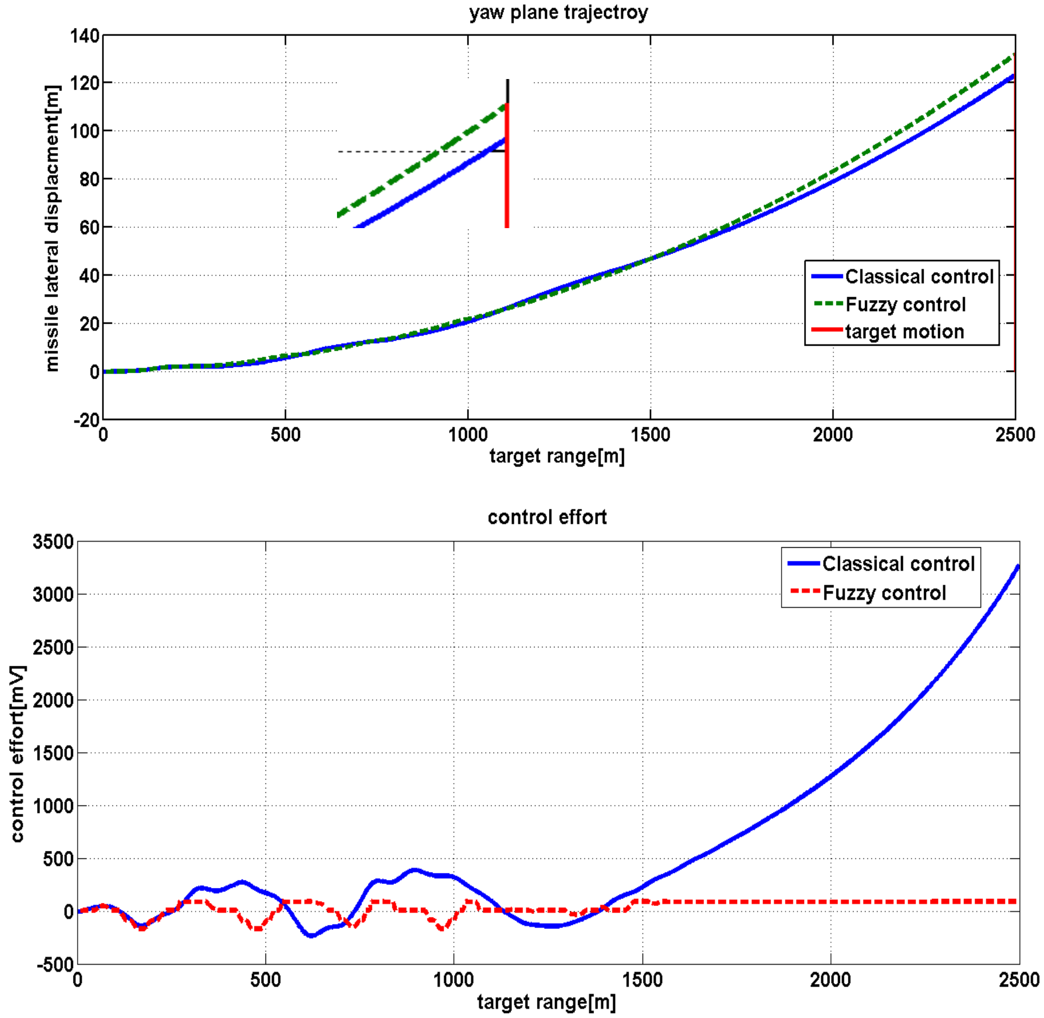


Figure 7 Compression between FLC and CC in (a) yaw trajectory and (b) control effort for thrust decreased by 20%

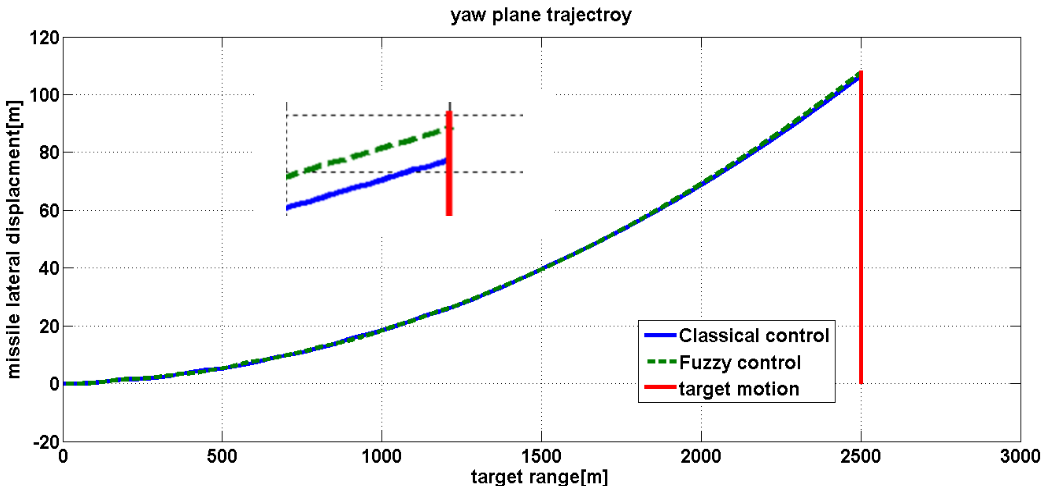
From the above simulations; the CC fails to deal with thrust degradations which is the result of missile aging while the FLC has a better performance to certain limit and less control effort than that of the CC.

iii. *Uncertainty in aerodynamic calculation*

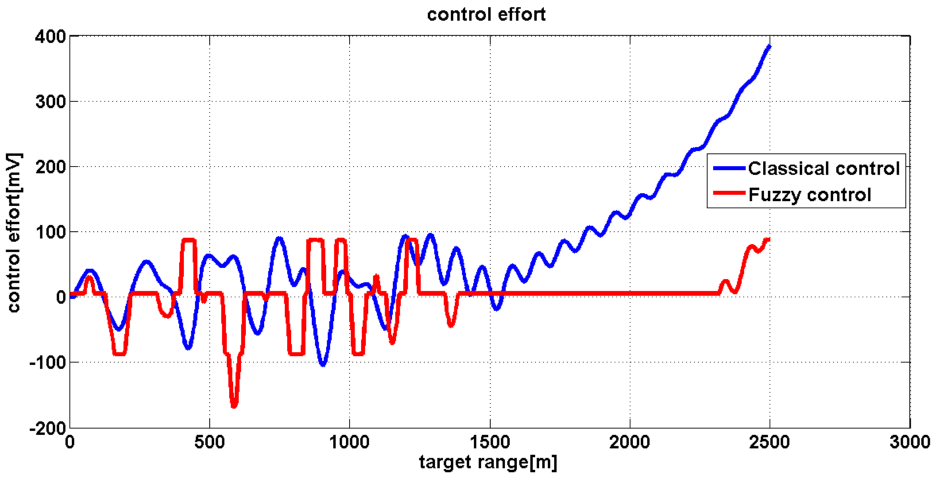
Another source of uncertainties is the aerodynamic calculations. From the simulation results; the FLC is capable of hitting the target up to (30%) uncertain in calculations while CC fails at (20%) uncertain and the FLC control effort is less than that of CC as shown i n table (5) and figures (8,9).

Table 4 Miss distance at uncertainties in aerodynamic calculations using different controllers

Controller / uncertainty	Fuzzy logic controller	Classical controller
30%	0.5 m	1.6 m
40%	4.2 m	3.2m

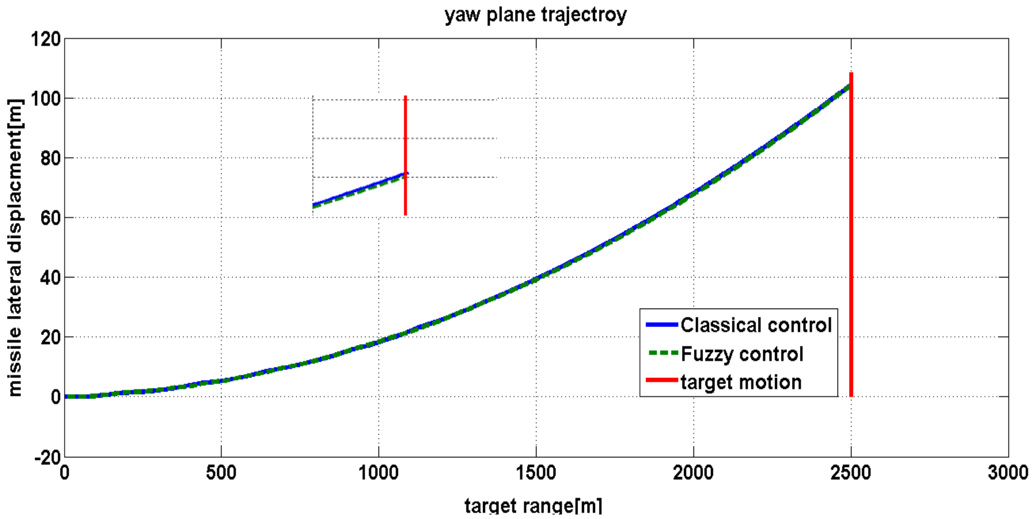


(a)



(b)

Figure 8 Compression between FLC and CC in (a) yaw trajectory and (b) control effort for aerodynamic uncertainty by 30%



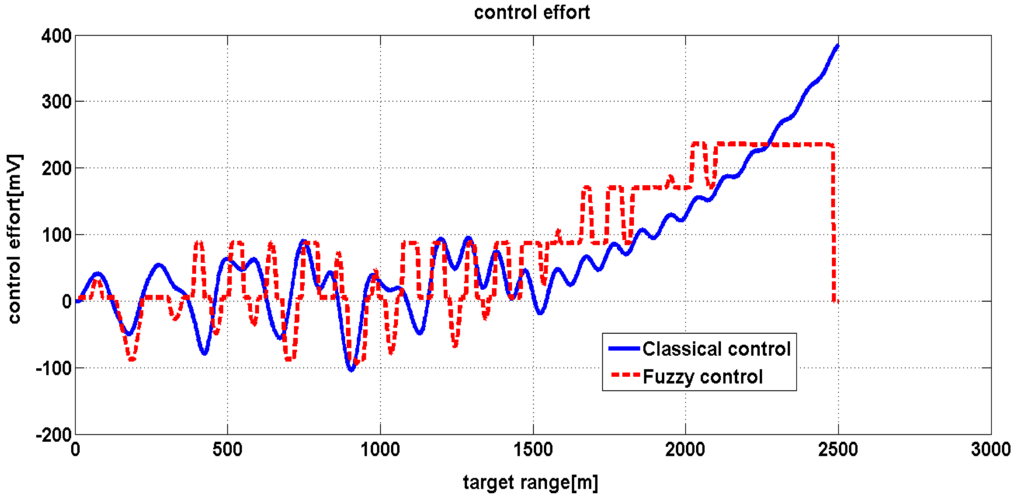


Figure 9 Compression between FLC and CC in (a) yaw trajectory and (b) control effort for aerodynamic uncertainty by 40%

From the above simulations; the CC fails to deal with missile aerodynamic uncertainties while the FLC has a better performance to certain limit and less control effort than that of the CC. The FLC has the ability to deal with aerodynamic uncertainties till certain limit (30%) and fails to deal with such uncertainties above this value.

V. Summary and conclusion

Anti-tank guided missile systems are considered to be one of the most important weapons in the recent battle field as they can intercept with tanks and other fortifications counting on the adopted guidance method. The underlying missile system is one of these systems; it is a wire guided optically tracked missile that applies three-point guidance method to hit hostile targets. Due to the missile aging the missile thrust is badly affected and the conventional classical controller is too idle to deal with such thrust degradation and other kind of uncertainties and therefore the missile tactical specifications are also badly affected and hence the need to design another controller that has the ability to deal with these kind of uncertainties and improve the missile tactical specifications emerged. This advanced controller is fuzzy logic controller; it has a magnificent ability to deal with non-linear systems and uncertainties associated with imprecision and vagueness and lack of information. In this paper a fuzzy logic controller is adopted and applied to the inner loop of the underlying missile system. The simulation results shows that the FLC has the same performance of the CC in case of missile maneuvering in lateral direction and good performance in case thrust degradation and uncertainties in missile aerodynamic calculations and these are cases that failed with the CC design.

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