Tuning of Composite Fuzzy Logic Guidance Law Using Genetic Algorithms

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ABSTRACT

The application of Fuzzy Logic (FL) for the development of guidance laws for homing missile is presented. Fuzzy logic has been used to develop a Composite Fuzzy Guidance (CFG) law. The objective of this proposed guidance law is to combine desirable features of PN and APN homing guidance laws to enhance the interception of targets performing uncertain maneuvers without reaching the missile to saturation limit.

During this work, it became apparent that the fuzzy controller of the CFG law can be further tuned to enhance its performance. Genetic Algorithms (GAs) which are inspired by natural genetics are one of the algorithms that can be used to tune the parameters of fuzzy controllers due to the promising results that they introduced in the field of optimization.

This paper introduces the integration of GAs and FL with a main emphasis on tuning the membership function parameters of fuzzy logic controller of the proposed CFG law using Genetic Algorithms (GAs) with the view to improve its performance. The simulation has been performed using Borland C++ programming language (version 5.02) along with the Matlab programming package (version 7.0) that has been used for plotting the results of simulations.

Keywords: Guidance Law, Fuzzy Logic Control, Genetic Algorithms (GAs)

تنغيم طريقة توجيه مزيج المنطق الغامض بإستخدام الخوارزميات الجينية

الخلاصة

يتناول هذا البحث تطبيق المنطق الغامض لتطوير طرق التوجيه للصواريخ الموجهة ذاتيا والخروج بطريقة توجيه مزيج المنطق الغامض (CFG). إن الهدف من طريقة التوجيه المقترحة هو مزج الخصائص المطلوبة لطريقتي التوجيه الملاحة التناسبية (PN) و الملاحة التناسبية الموسعة (APN) للتحسين من ملاقاة الأهداف ذات المناورة العالية من دون وصول الصاروخ إلى حد الإشباع.

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لقد اصبح واضحا من هذا البحث أيضا، بأنه من الممكن تنغيم المسيطر الغامض لطريقة توجيه مزيج المنطق الغامض للتحسين من خصائصها. إن الخوارزميات الجينية (Genetic Algorithms GAs) المستوحاة من البناء الجيني للإنسان هي واحدة من الخوارزميات التي من الممكن ان تستخدم لتنغيم قيم المسيطرات الغامضة بسبب نتائجها الموعودة بمجال التحسين.

يقدم هذا البحث تكامل الخوارزميات الجينية مع المنطق الغامض بالتأكيد الأساسي على تنغيم قيم الدوال العضوية للمسيطر المنطقي الغامض لطريقة مزيج المنطق الغامض بإستخدام الخوارزميات الجينية للتحسين من خصائصها.

إن المحاكاة قد أنجزت بأستخدام لغة البرمجة (Borland C++ version 5.02) بالأضافة الى لغة البرمجة (Matlab version 7.6.0.324) التي أستخدمت لغرض رسم نتائج المحاكاة.

INTRODUCTION

The focus of the present paper is on the development of a blended guidance law for homing missiles using fuzzy logic capable of blending large uncertainties in the missile model. The fuzzy logic scheme combines the two guidance laws (PN&APN) to obtain a "**composite guidance law**". The objective of the composite guidance law is to combine desirable features of the two guidance laws to enhance the interception of targets performing uncertain maneuvers. Fuzzy logic guidance law development employs triangular, membership functions. Mamdani-style inference is employed in Fuzzy Inference System (FIS) [1,2].

The creation of the Knowledge Base (KB) in FIS is the most important part in the implementation of fuzzy logic guidance law. Usually extracting the expert experience from human process operators is the most used method to perform this task. However, when using FL to design a composite guidance law, it is difficult even for an expert, to provide "good" definition for the membership functions i.e., he may not be capable of expressing his knowledge in terms of fuzzy rules [3-5].

The integration of FL and GAs is bi-directional. First possible combination is the use of FL based techniques for improving GA behavior and modeling GA components. The other, is the application of GA in various optimization and search problems involving FSs [6].

The present paper will introduce the combination dealing with the application of GA for solving optimization and search problems related with FSs. This is related directly to the main object of this study but, first, the composite fuzzy guidance (CFG) law must be explained. As can help to understand where and how GAs are inserted within CFG law.

In this paper, a composite fuzzy logic guidance scheme will be discussed. This fuzzy guidance scheme uses fuzzy logic to combine two well-known guidance laws (PN, APN) to obtain enhanced homing performance. Fuzzy logic plays more of a supervisory role in this guidance law. This guidance law is then evaluated using a step-maneuvering target.

A COMPOSITE FUZZY GUIDANCE (CFG) LAW

The CFG law is based on the notion that each of the guidance laws that reported in the reference [7] has a region of operation where they are superior to other guidance laws. Hence, if a fuzzy inference system (FIS) could be set up that selects the appropriate guidance law based on the interception conditions, such a guidance scheme can be expected to incorporate the best features of all the guidance laws. Towards this end, two guidance laws are chosen for inclusion in the composite guidance law. These are the classical proportional navigation (PN) and the augmented proportional navigation (APN).

The justification for selection any one of the guidance laws from this set is based on the following heuristic analysis.

- When the target is far away, PNG law yields moderate acceleration commands [8]. However,
- As the range becomes small, the acceleration commands will become very large. Thus, under small range conditions, alternate guidance laws that use bounded acceleration commands must be found. Since the APNG law intercepts target using bounded acceleration at small range conditions, this guidance law is ideal for use under small range conditions.

Similar arguments can also be developed for guidance law selection under different range rate conditions.

The fuzzy logic guidance law can be further tuned to enhance performance. For this purpose a GAs will be used.

The FIS scheme is next set up to implement this heuristic reasoning. Figure (1) shows the composite fuzzy guidance (CFG) scheme.

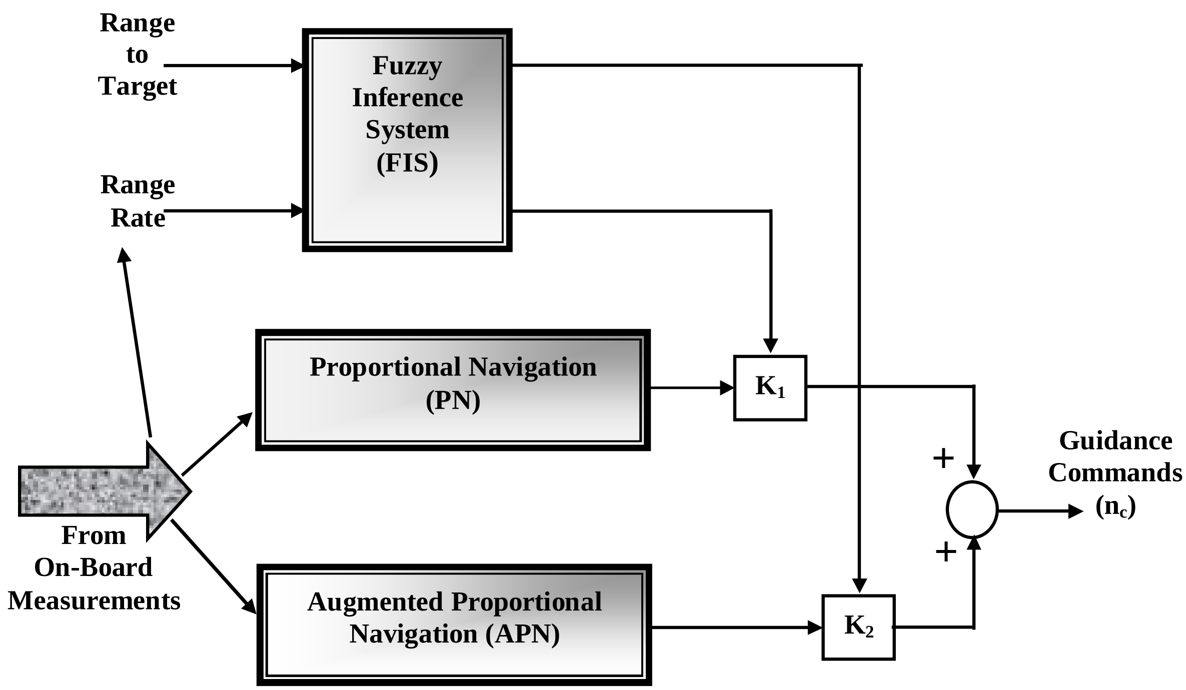


Figure (1): Composite Fuzzy Guidance Law [1].

one based on the measured range (R_{TM}) and range rate ($\dot{R}_{TM}$). Zero value indicates inactive guidance logic, while a value between zero and one indicates the relative importance of the particular guidance law.

Three triangular membership functions are used for each of the inputs (**R_{TM}, $\dot{R}_{TM}$**) of the fuzzy inference system (FIS) and two triangular membership functions are used for each of the outputs (**K_1, K_2**) of the FIS.

Twelve fuzzy inference rules are used in the composite fuzzy inference system. These rules are listed below.

1. If (***Range*** is High) then (***K_1*** is High)
2. If (***Range*** is High) then (***K_2*** is Low)
3. If (***Range*** is Medium) then (***K_2*** is High)
4. If (***Range*** is Medium) then (***K_1*** is Low)
5. If (***Range*** is Low) then (***K_1*** is Low)
6. If (***Range*** is Low) then (***K_2*** is High)
7. If (***Range-Rate*** is Low) then (***K_1*** is High)
8. If (***Range-Rate*** is Low) then (***K_2*** is Low)
9. If (***Range-Rate*** is Medium) then (***K_1*** is Low)
10. If (***Range-Rate*** is Medium) then (***K_2*** is High)
11. If (***Range-Rate*** is High) then (***K_1*** is Low)

12. If (***Range-Rate*** is High) then (***K_2*** is High)

The composite guidance law will be evaluated later for the point-mass missile simulation, together with the step maneuver target model. The composite guidance law uses PNG law during the first few seconds. Toward the end, it uses a combination of the guidance laws to achieve target interception.

Design of GA-Composite Fuzzy Guidance (CFG) Law

The task of designing GA-CFG law is essentially of tuning membership functions (MFs) for fuzzifier and defuzzifier of the FIS part of CFG scheme, assuming the existence of a Knowledge Base (KB) of the FLC that is to be tuned.
A FIS is set up with two inputs and two outputs.
The inputs to this inference system are the relative range separation between missile and target ($\mathbf{R_{TM}}$) and rate of this separation or range rate $(\dot{\mathbf{R}}_{TM})$. The outputs are the switching or scaling parameters ($\mathbf{K_1}$& $\mathbf{K_2}$), zero output value indicates an inactive guidance law, while a value between zero and one indicates the relative importance of the particular guidance law.
Figure (2) shows the proposed GA-CFG scheme.

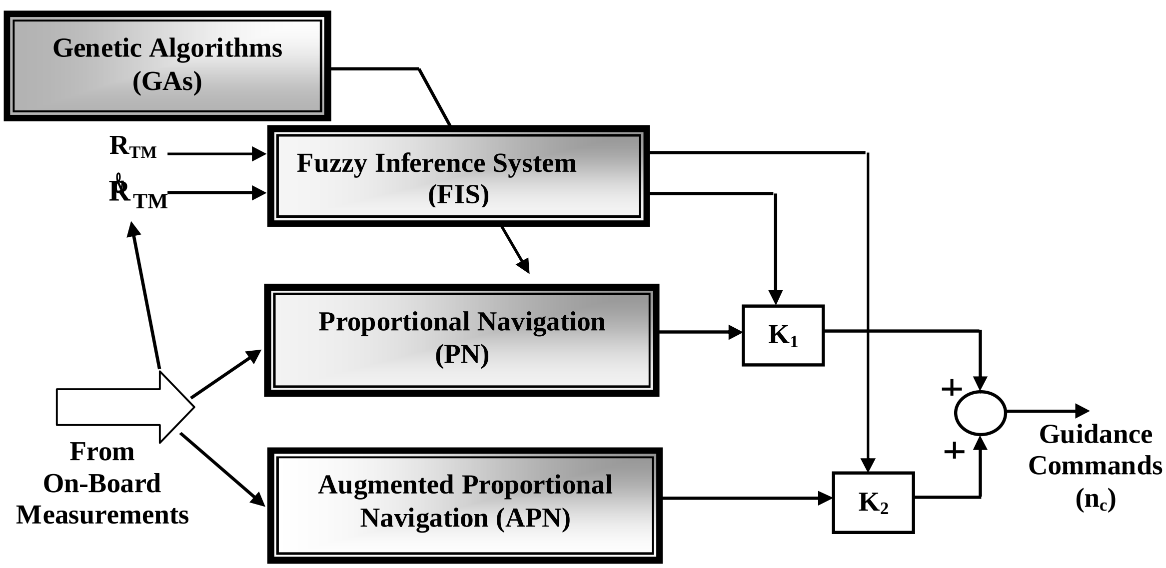


Figure (2): GA-Composite Fuzzy Guidance Scheme.

Three triangular membership functions are used for each of the inputs of the FIS to convert the range ($\mathbf{R_{TM}}$) and range rate $(\dot{\mathbf{R}}_{\mathbf{TM}})$ into linguistic variables.

Each of the outputs of the FIS uses two triangular membership functions. Twelve rules are used in this FIS. These rules are listed in previous section.

Initial setting for a triangular-shaped MFs are defined and distributed on the appropriate universe of discourse as shown in figures (3-a), (3-b), and (3-c).

The universe of discourse boundaries for $\mathbf{R_{TM}}$ are [0, R_{max}], where R_{max} is the maximum separation between missile (M) and target (T), and the universe of discourse boundaries for $\dot{\mathbf{R}}_{\mathbf{TM}}$ are [cc1, cc2], where cc1 is the minimum range rate

$$cc1=-(V_M+V_T) \qquad \dots (1)$$

and cc2 is the maximum range rate

$$cc1=-(V_M-V_T) \qquad \dots (2)$$

V_M and V_T are missile and target velocities respectively.

These boundaries are taken from the range rate equation [7]

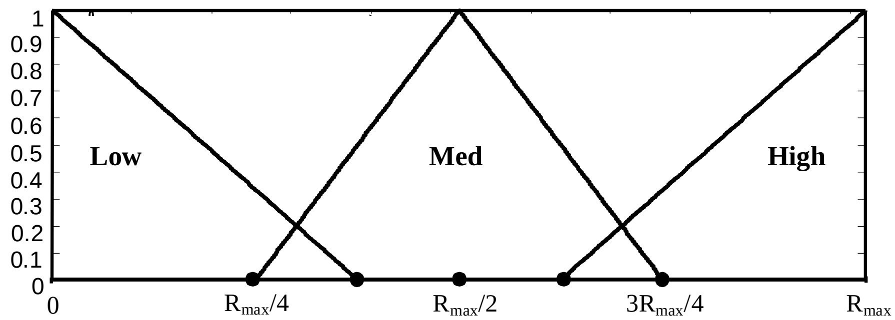


Figure (3-a): Membership function distribution for "Range".

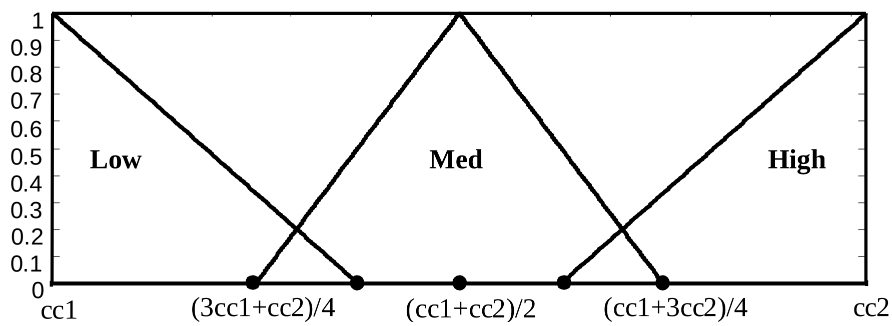


Figure (3-b): Membership function distribution for "Range Rate".

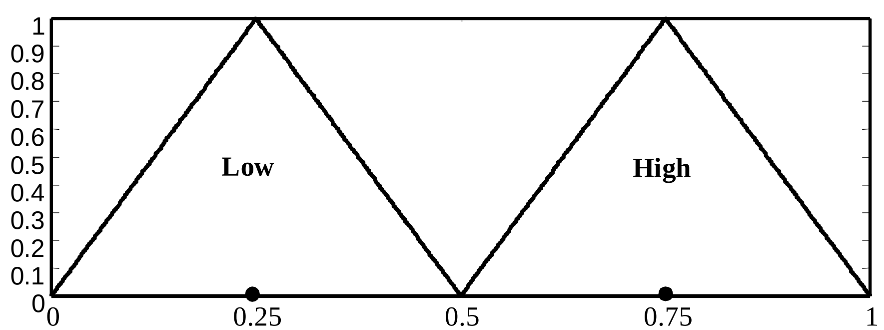


Figure (3-c): Membership function distribution for "K_1" and "K_2".

The values of R_{max}, V_M and V_T are taken from the initial conditions of the example used in the simulation. Flow chart shown in figure (4) explains the basic programming chart used to implement the Composite Fuzzy Guidance (CFG) law.

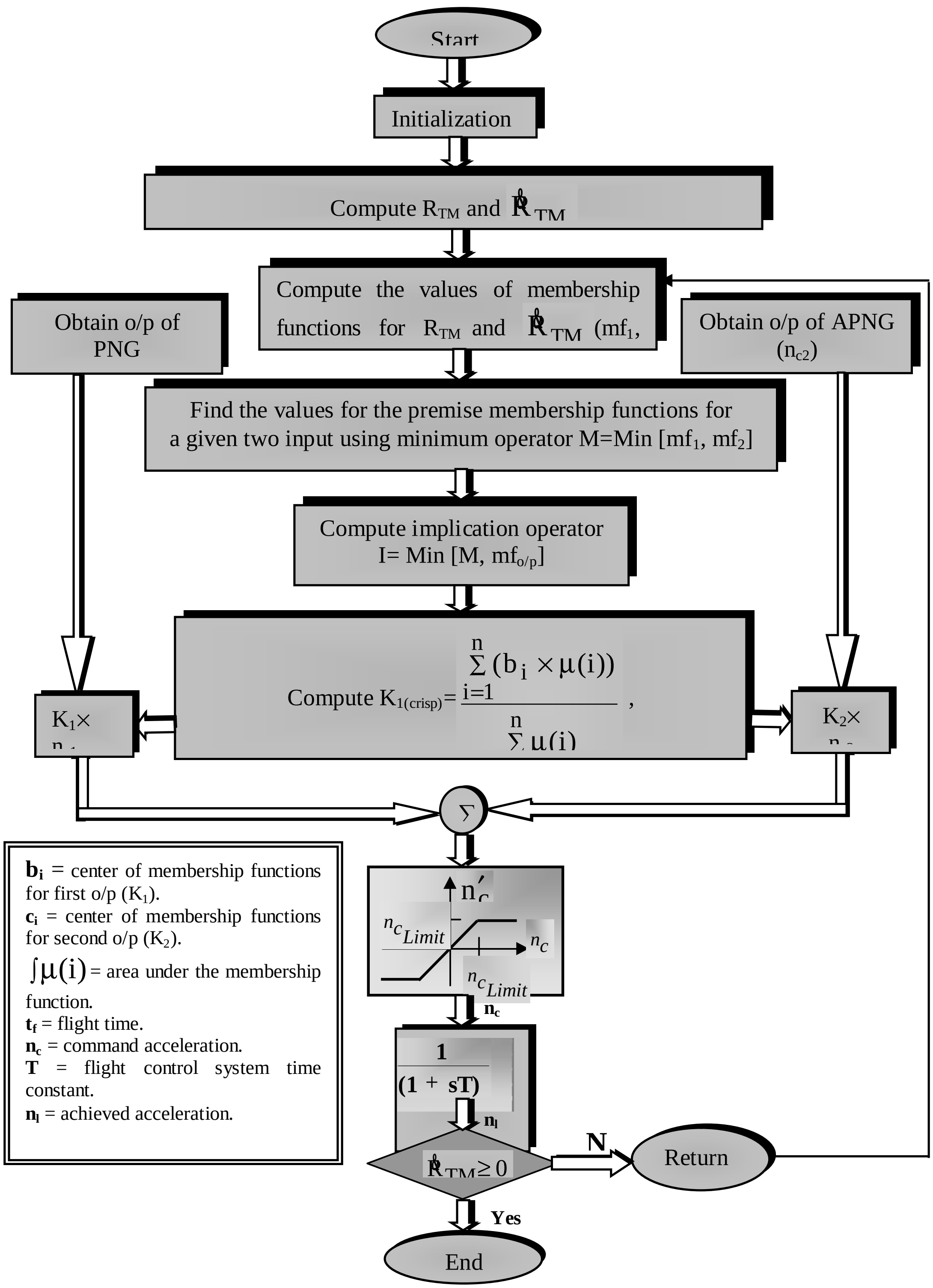


Figure (4): Flow Chart of CFG-Law

MF Definition in GA (Chromosome Representation)

Each chromosome forming the genetic population will encode a complete DB definition that will be combined with the existing RB in order to evaluate the individual adaptation. Each chromosome C_r will contain the definition of ten membership functions (three for each input and two membership functions for each output). The DB is encoded into a fixed length real coded chromosome C_r built by joining the partial representations of each one of fuzzy partitions as shown:

$$\mathbf{C_r = C_{r1}\ C_{r2}\ C_{r3}\ C_{r4}} \quad \ldots(3)$$

Where C_{r1} and C_{r2} code the fuzzy partition of range ($\mathbf{R_{TM}}$) and range rate $(\dot{\mathbf{R}}_{\mathbf{TM}})$ respectively as shown:

$$\mathbf{C_{r1} = (c_{11}, a_{12}, b_{12}, c_{12}, a_{13}) \qquad C_{r2} = (c_{21}, a_{22}, b_{22}, c_{22}, a_{23})} \quad \ldots(4)$$

But C_{r3} and C_{r4} codes the fuzzy partition of first and second output variable (K_1) and (K_2) respectively as shown:

$$\mathbf{C_{r3} = (b_{31}, b_{32}) \qquad C_{r4} = (b_{41}, b_{42})} \quad \ldots(5)$$

In this work, the aim is to minimize integral of the square of the lateral acceleration command with respect to time (J)

$$J = \int_0^{t_f} n_c^2 .dt \quad \ldots(6)$$

GA is a maximization routine and so to minimize J using GA, the chosen fitness function is defined as

$$\text{fitness} = \frac{1}{J + \varepsilon} \quad \ldots(7)$$

Where ε is a small positive number.

The ***GA operators*** used for tuning process are set as follows:

Type of selection is a Roulette wheel selection.
Type of crossover is a Multi point crossover (2 point).
Type of mutation is a uniform mutation.
Elitist strategy operator is used.

The ***GA parameters*** used for tuning the GA-CFG are set as follows:

Population size (pop_size) = 200.
Chromosome-length or string-size = 14.
Probability of crossover (pcross) = 0.95.
Probability of mutation (pmut) = 0.01.
Maximum number of generations = 1000, as a termination condition.

Problem Formulation

In this paper, an example is chosen to evaluate the performance of PN, APN and the CFG laws in terms of missile trajectory and acceleration history, thereby obtaining a comparison between these guidance methods in terms of Miss Distance (MD) and energy expenditure (J).

In this example used in the simulation, the following assumptions are maked in order to formulate the guidance problem. These assumptions are:

(1) The missile-target engagement is a two-dimensional motion.

(2) The missile and target are considered as constant velocity mass points.

(3) The time lag in the missile guidance system is taken into consideration as lag time (T) = 0.5 second. The transfer function of the flight control system has been converted into a discrete model using bilinear (Tustin) transformation with sampling time (Ts=0.001second).

(4) The lateral acceleration limit of the missile is taken into consideration to explain its effect on the MD of each guidance law, which has been simulated.

The two-dimensional engagement model used in the simulation is represented by differential equations described in reference [7].

SIMULATION CONDITIONS

In this example (scenario), the following data, which is taken from reference [9], are considered to evaluate the performance of the PN, APN and the proposed CFG laws, where

$$n_{c_{PNG}} = -N'\dot{R}\dot{\lambda} \qquad \ldots(8)$$

$$n_{c_{APNG}} = -N'\dot{R}\dot{\lambda} + \frac{N'}{2} n_T \qquad \ldots(9)$$

The navigation constant N' is set to 3, furthermore, the target executes a 9g maneuver (n_T) in the initial direction of 120 degrees away from the reference line (i.e., $\beta_0 = 60^\circ$), with a constant velocity (V_T) of 400 m/s. The initial relative range (R_{TM}) is 3 km. In this engagement scenario, the missile has a constant velocity (V_M) of 600 m/s and is fired in a direction 35.27 degrees away from the reference line (i.e., $O_{M0} = 35.27^\circ$). The missile saturation limit used in the simulation is 15g.

These initial conditions used for simulate this example is rewritten below:

$V_T = 400$ m/s, $V_M = 600$ m/s

$X_{M0} = 0$ m, $Y_{M0} = 0$ m

$X_{T0} = 3$ km, $Y_{T0} = 0$ m

$O_{M0} = 35.27^\circ$

$\beta_0 = 60^\circ$

SIMULATION RESULTS

The simulation results obtained using (PN, APN and GA-CF) guidance laws are listed in table (1), taken into consideration the saturation limit (15g).

These results are shown in Figure (5). Where Figure (5-a) shows the missile-target trajectory corresponding to the three guidance laws for the saturation limit (15g). Remaining Figure (5-b) shows the time history of the missile lateral acceleration corresponding to the three guidance laws for the saturation limit (15g).

The simulation results listed in table (1) show that the proposed guidance law gives the best performance in terms of the miss distance (MD) among the three schemes. Where it may be observed, that in the case of low missile acceleration limit (15g), the proposed guidance law is successful in bring the missile within 0.804 m of the target i.e., MD = 0.804 m, at which point, the simulation was terminated. In addition, it may be observed that the proposed guidance law requires far less energy cost (J) than the other two schemes (PN and APN). Where the proposed guidance law requires energy cost (J) of 17408 m^2/s^3, but PN and APN guidance laws require 49136 m^2/s^3 and 40987 m^2/s^3 respectively. The energy cost as explained previously is determined by integrating the square of the missile lateral acceleration with respect to time.

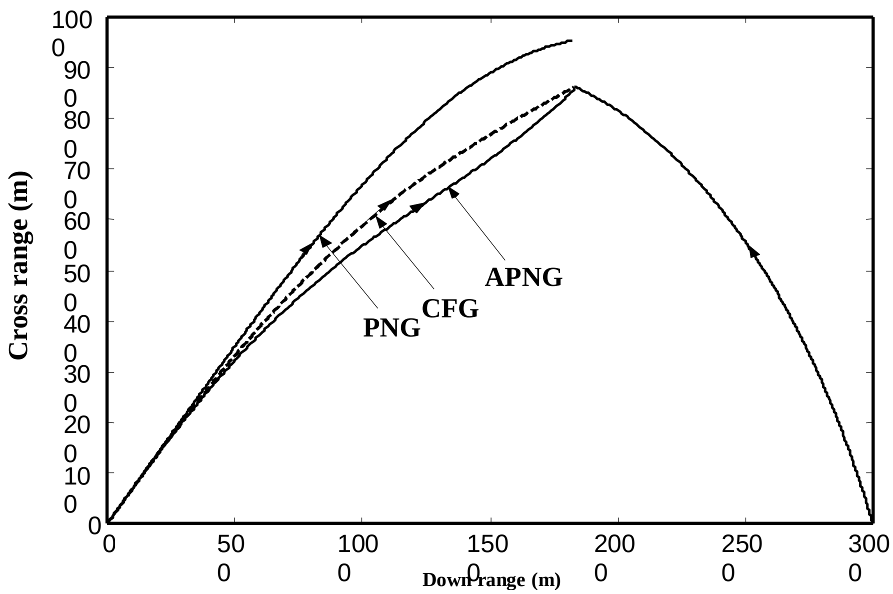
It is not surprise that the performance of the PN is inferior to that of both APN and CF guidance laws. Since the LOS rate ($\dot{\lambda}$) is smaller at long range, the PN drives the missile heading slightly towards a collision course at the beginning of the engagement and then saturates at the final phase of the engagement. Figure (5-b) demonstrates this fact. This is because the PN responds to the change rate of LOS (λ) only, and is unaware of the existence of target maneuver. Hence, it induces large miss distances as shown in table (1). This also indicates that the PN can not intercept the target with highly evasive maneuver.

In contrast, the APN, with an extra term to account for target maneuver, enables the missile to maneuver in a more efficient manner as shown in Figure (5-a).

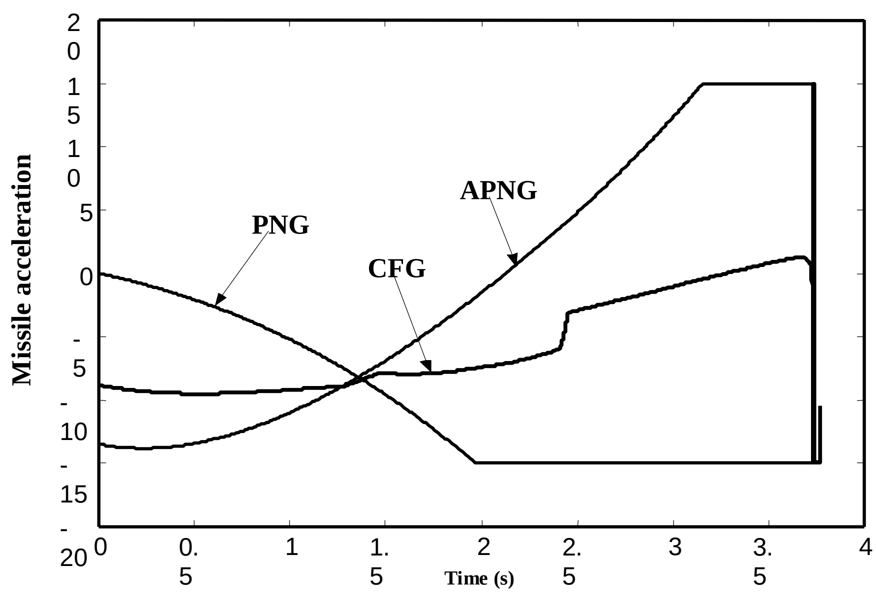
At the early phase of the engagement, the APN commands the missile heading quickly towards the collision course and then the missile lateral acceleration command is decreasing until the hit. Accordingly, it yields less Miss Distances (MD) and control energy expenditure (J) as compared with PN. Where in the case of the acceleration limit of 15g, the miss distances of APN and PN are 2.21 m and 89.51 m respectively.

Table (1): Results of the example.

Acceleration Limits (g)	MD (PNG) (m)	J (PNG) (m^2/sec^3)	MD (APNG) (m)	J (APNG) (m^2/sec^3)	MD (CFG) (m)	J (CFG) (m^2/sec^3)
15	89.51	49136	2.21	40987	0.804	17408



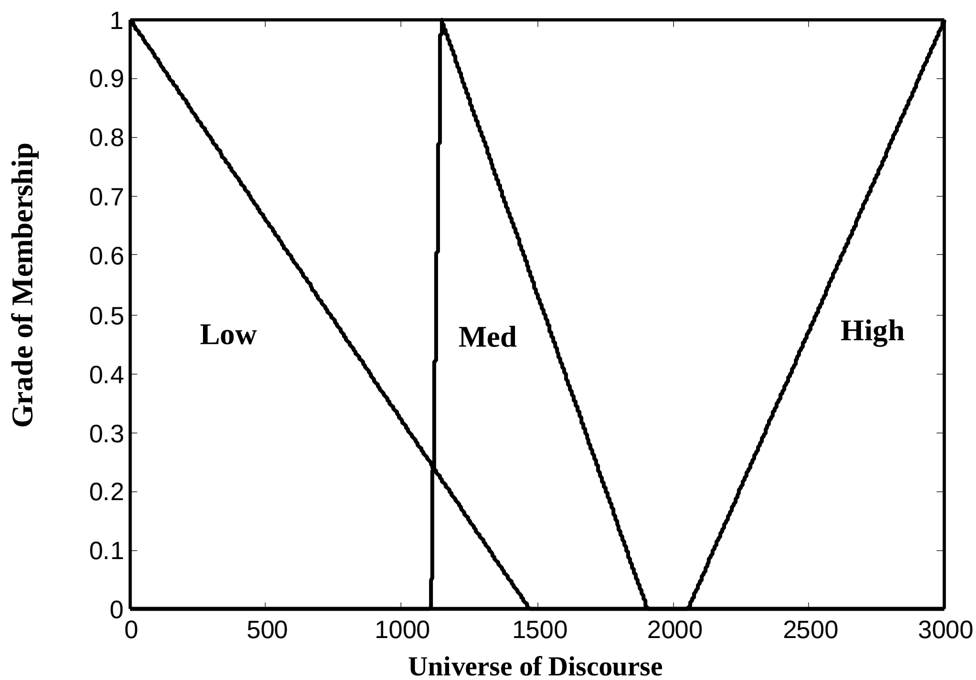
(5-a)



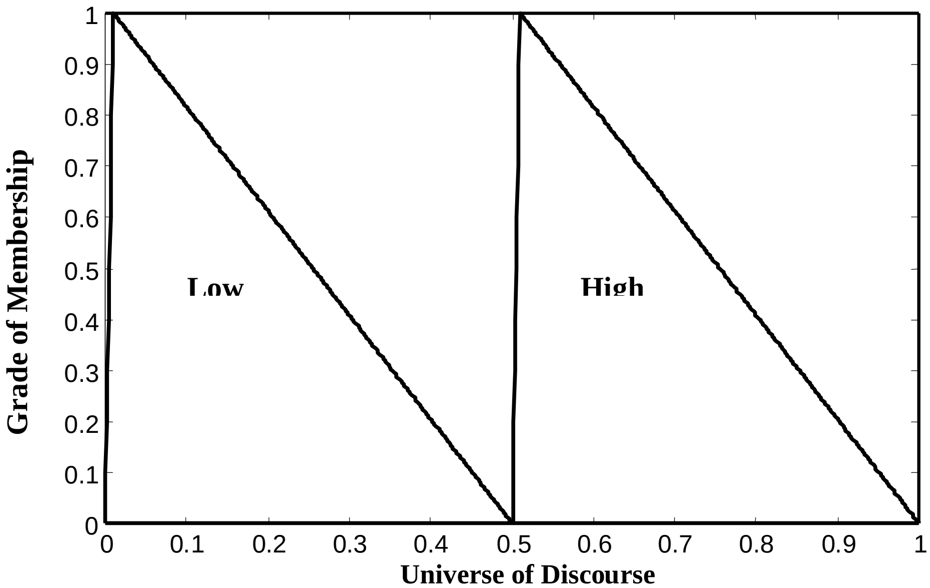
(5-b)

Figure (5): An example with acceleration limit 15g.
(a) Missile and target trajectories for PN, APN and CF guidance laws.
(b) Time histories of missile lateral acceleration for PN, APN and CF guidance laws.

It has been found that the parameters obtained by GAs represent triangle parameters that define the membership functions used in the proposed CF guidance law. For the example, figures (6-a,b,c,d) show the membership functions distribution for $\mathbf{R_{TM}}$, $\dot{\mathbf{R}}_{\mathbf{TM}}$, $\mathbf{K_1}$ and $\mathbf{K_2}$ respectively for saturation limit of 15g as a part from results. Whereas figure (6-e) shows, how GA operates during each generation until a termination condition (maximum generation no.) is reached, in order to achieve a minimum energy cost (J).



(a)


Low
High
Grade of Membership
Universe of Discourse
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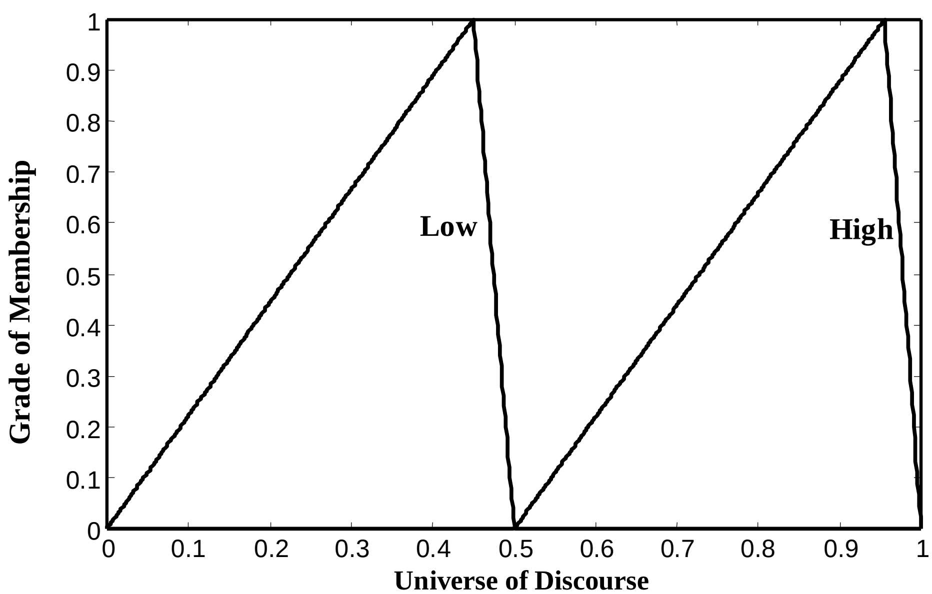
1

(c)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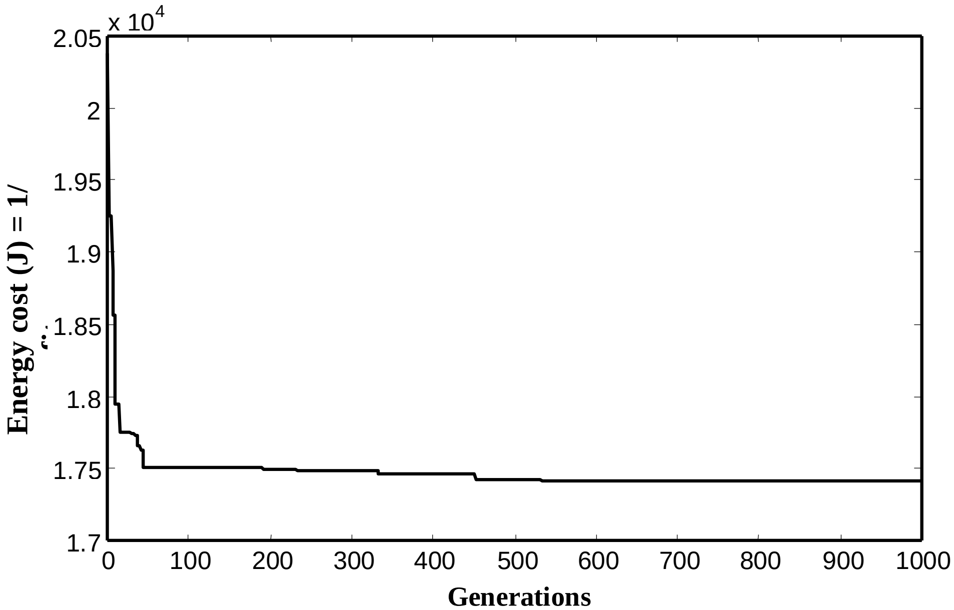
(d)



(e)

Figure (6): GA results for the example with acceleration limit 15g.
(a) Modified fuzzy sets of "Range". (b) Modified fuzzy sets of "Range Rate",
(c) Modified fuzzy sets of "K_1". (d) Modified fuzzy sets of "K_2".
(e) Energy cost (J) reduction during genetic operation.

CONCLUSIONS

Conclusions for further developments of the homing guidance laws, using fuzzy logic (FL) and genetic algorithms (GAs) are presented to suggest possible enhancement to the performance of the proposed design. Conclusions from the simulation results are pointed out in this section:

1. An engagement scenario, with 15g missile acceleration limits is chosen in the simulation of PN, APN and GA-CF guidance laws. It is verified that the performance of the proposed (GA-CF) guidance law, in terms of energy cost (J) and Miss Distance (MD) is superior to that of the other schemes (PN and APN). Whereas the use of APN leads to miss distance and energy cost less than that of PN.
2. Genetic algorithm (GA) is used to obtain a guidance law with minimum energy cost (J) to avoid missile saturation limits thereby producing a small Miss Distance (MD).
3. It is evident from results that the Proportional Navigation (PN) guidance law requires a larger acceleration advantage over the target than the Augmented Proportional Navigation (APN) and proposed guidance law to achieve a specific miss distance (MD). This reduction in the acceleration requirement extends the missile's

zone of effectiveness against maneuvering targets. This is a major advantage of the proposed guidance law over PN and APN guidance laws.

4. It is verified from results that the performance of the proposed guidance law, in terms of maximum acceleration requirement is superior to that of the other PN and APN guidance laws for any saturation limits.

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