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USING FUZZY LOGIC EXPERT SYSTEM FOR THE ESTIMATION OF THE PROBABILITY OF ARMOUR PENETRATION BY PGU-14 SHELLS FIRED FROM THE GAU-8/A CANNON

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Abstract

The article discusses the possibility of armour penetration by PGU 14 API shells fired from the GAU-8/A cannon. The considerations focus on questions with regard to the probability of armour penetration with the initially established conditions in the project. In the analysis, the authors took into account three parameters: armour thickness, armour slope and target distance. Based on the initial parameters, the authors estimated the probability of armour penetration. The designed a fuzzy expert system in the MATLAB software as well as conducting simulation of its performance in the Simulink programmes. The authors presented the performance of the system based on twenty samples for research, which simulate different thickness of the target armour, different distance from the target and different slope of the armour. The authors presented control surfaces, due to which it is possible to analyse the system performance. They also show the simulation process in the Simulink software package with the preset values. On the basis of the created controller, it is clear that a well-developed system, which had undergone testing and optimization, is capable of calculating near reality probability values. The designed system might improve fire effectiveness of ground targets during air training and combat tasks, as well as optimizing the consumption of air-to-ground armour piercing (AP) shells.

Keywords: *fuzzy logic, fuzzy expert system, armour penetration, GAU-8/A cannon, PGU 14 API shells*

1. Introduction

Fuzzy logic, introduced by Lotfi Zadeh, generalizes the classical bivalent zero-one logic. In fuzzy logic, a proposition with a truth-value of 0 is false and one with a truth-value of 1 is true. Truth-values that are between 0 and 1 indicate varying degrees of truth-values that determine the degree of membership of an element to a given set. Fuzzy logic is useful in engineering applications, where classical logic, which classifies in accordance with the criterion of true/false, is unable effectively to cope with a number of ambiguities and contradictions. It finds application, among others, in the construction of expert systems [1-5]. MATLAB package complemented by FuzzyLogic Toolbox served to create an expert system that calculates the probability of armour penetration by rounds fired from the GAU-8/A cannon, depending on several input signals. The signals are: shield thickness, armour slope and (target) distance.

2. Research platform

The GAU-8/A is a 30 mm air gun mounted on the American A-10 Thunderbolt II attack aircraft, designed in the 1970s [9]. The length of the barrel expressed in calibres is 80 (2.3 m). The cannon weigh is 281 kg and is over 6 m in length [10].

GAU-8 uses shells made with depleted uranium, which ensures high hardness and reduces the risk of destruction of the core of the shell after it strikes the armour. The muzzle velocity equals 1,036 m/s. The smaller 20 mm calibre M61A1 Vulcan cannon has a comparable muzzle velocity, however the PGU-28 SAPHEI shells (Semi Armour Piercing High Explosive Incendiary) fired from it lose the speed faster than in the case of the 30 mm PGU-14 ones, fired from the GAU-8 cannon.

Due to its high speed over long distances and greater projectile mass, the GAU-8 is the most powerful weapon system currently used in military aviation [7, 10]. The theoretical rate of fire is 7,000 rounds per minute. In practice, the pilot is free to choose between the modes of 2,100 and 4,200 rounds per minute. The A-10 aircraft carries 1,350 30 mm rounds. It is possible to use three types of ammunition: PGU-13 HEI (High Explosive Incendiary), PGU-14 API (Armour Piercing Incendiary) mentioned above, and PGU-15 TP (Target Practice) [8].

The basis for the calculation of armour penetration by 30 mm shells PGU-14 API is the data concerning armour penetration by rounds fired from various distances. For an angle of 30° of the armour slope, the penetration is as follows [7]:

– 76 mm from 300 metres,
– 69 mm from 600 metres,
– 64 mm from 800 metres,
– 59 mm from 1,000 metres,
– 55 mm from 1,220 metres.

Once the armour penetration from particular distances as well as the dependence between the effective armour thickness and the degree of its slope is known, it is possible to estimate armour penetration of varying thickness, mounted at any angles and from different distances.

3. Design of a fuzzy expert system

In order to design a fuzzy logic model controller, was used the FuzzyLogic Toolbox MATLAB programme. It allows easy adding of input signals, output signals, setting deduction rules as well as presenting them in a clear graphical form. The results of the controller's operation can be depicted on a three-dimensional surface or in a tabular form. Fig. 1 presents the general graphic layout of the fuzzy logic controller.

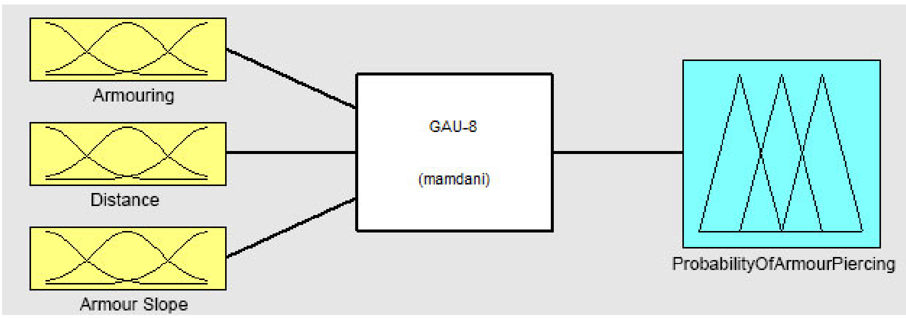


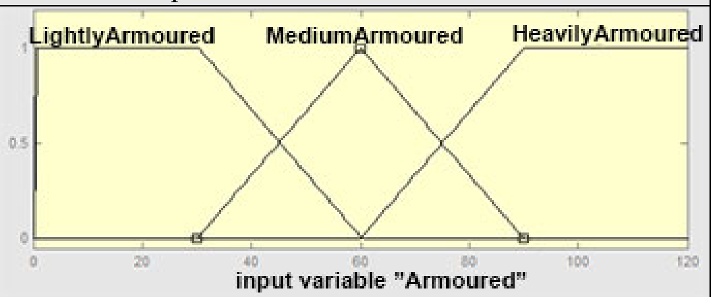
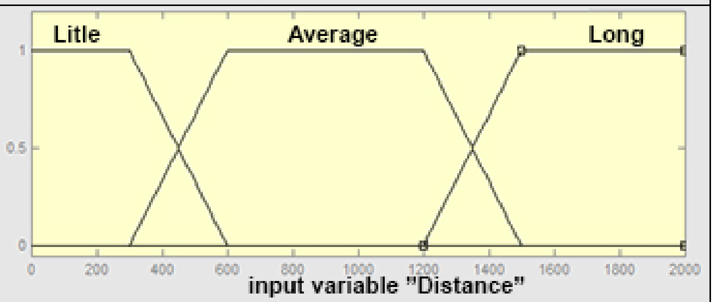
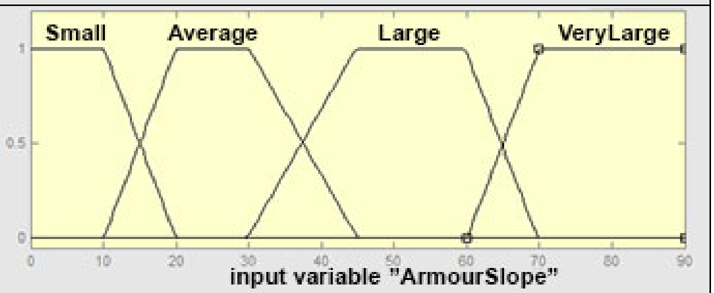
Fig. 1. General graphic layout of the fuzzy logic controller

Determination of input and output signals

The input signals selected for determining probability is armour thickness (Armouring), target distance (Distance), and armour slope (Armour Slope). The output signal is searching for the probability of armour piercing which is determined depending upon the combination of input signal values.

The first input signal is the thickness of the target armour [mm] described by two non--symmetric membership trapezoidal functions and one symmetric membership triangular function, which are referred to as light, medium and heavily armoured, respectively. The ranges of various membership functions were stipulated only for the needs of the project. There is no strict division of armour thickness into different ranges within the specified limits. The "lightly armoured" feature in the designed controller is included in the range of 0-30 mm, at a falling activation with the armour increase of up to 60 mm, where it ends entirely. The “medium armoured” feature is within the range of 30-90 mm, reaching its maximum at a thickness of 60 mm. The “heavily armoured” feature starts at 60 mm, with its maximum at 90 mm and reaching 120 mm (Tab. 1). 120 mm is the thickness of armour frequently found in modern tanks, and therefore the best-armoured targets for air cannons. The GAU-8/A practically does not have the ability to pierce such armour except for the situation of shooting from an extremely small distance at zero armour slope. The probability of such an event is extremely small. Therefore, it was pointless to include larger armour values. The cannon will not pierce such a thick layer of steel, not to mention modern ceramic-reinforced armour.

Tab. 1. Membership functions and their ranges for input signals

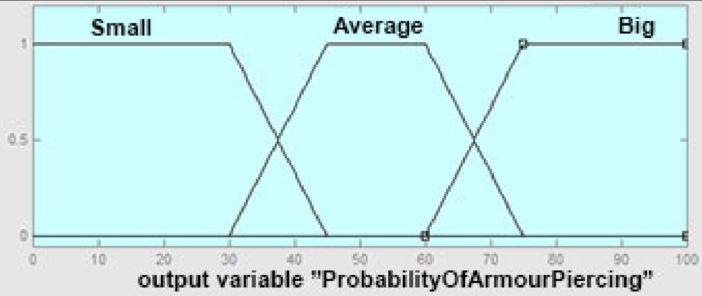
Input signal	Membership functions	
Armouring [mm]	Lightly Armoured [0.3175 0.3175 30.32 60.32] Medium Armoured [30.02 60.02 90.02] Heavily Armoured [60 90 120 120]	
Distance [m]	Little [0 0 300 600] Average [300 600 1200 1500] Long [1200 1500 2000 2000]	
Armour Slope [deg]	Small [0 0 10 20] Average [10 20 30 45] Large [29.76 44.76 59.76 69.76] Very Large [60 70 90 90]	

The second input signal is the distance from the target [m]. Firing from a greater distance does not ensure the required accuracy. In addition, it would be problematic to notice and identify the target by a pilot. Ultimately, in case of hitting, the shell would have too little velocity to penetrate the armour effectively. Therefore, was assumed the maximum range of effective firepower as 2,000 m, setting the boundaries between small, medium and high ranges, with regard to the GAU-8/A cannon. These relative values do not necessarily apply to other types of armament. In order to describe the distances, were used three trapezoidal functions. The low range distance was established within the 0-300 m with the decreasing activation, reaching 0 at a distance of 600 m. The range of the average distance is between 300-1,400 m, assuming maximum activation at 600-1,200 m. The large range distance starts at 1,200 m, assumes the maximum value of 1,400 m and ends at 2,000 m (Tab. 1).

The third input signal is the slope of the armour [deg]. When the armour is positioned vertically, at an angle of 0° (straight angle towards the rounds), the effective thickness of the armour is equal to its physical thickness. If the armour is angled, its effective thickness increases sinusoidally, with the angle increase (for the range of 0-90°). Tilting the armour is another way to improve vehicle protection, without the need to add millimetres of heavy steel. The input of the armour slope was described by 4 trapezoidal membership functions. The determined ranges of small, medium, large and very high slopes are approximate due to the fact that in this case there are no definite boundaries, either. We simply refer to inclined armour, not dividing the angles of slope into large and small ones, depending upon their exact values. The small slope of the armour was assumed to be included between 0 and 10°, with the falling activation reaching zero at 20°. The medium slope reaches its maximum activation values at 20-30°, and the total range remains within 10-45°. For a large slope, these values are 45-60° and 30-70°, respectively; and for a very large slope, it is included in the range of 60-90°, reaching its maximum for the range of 70-90° (Tab. 1).

The output signal is the probability of piercing the armour depending on the distance, thickness and the armour slope. The probability was described by three trapezoidal membership functions: small in the range of 0-45%, with its maximum in the 0-30% range; average in the range of 30-75%, with its maximum in 40-60% range; and large in the range of 60-100%, with its maximum of 75-100%. The membership functions of the output signal are presented in Tab. 2.

Tab. 2. Membership functions and their ranges for the output signal

Output signal	Membership functions	
Probability [%]	Small [0 0 30 45] Average [30 45 60 75] Big [60 75 100 100]	

Making the bases of principles

The next step in the design of the controller was to determine the deduction rules. The number of rules should be selected in such a way that all indications resulting from the input signals are reflected in the output of the system [6]. In order for the base of rules to be complete in the project, it was necessary to determine 36 deduction rules giving different probability of armour piercing. The following algorithm was used to determine the rules: was determined the effective thickness of the armour depending upon its physical thickness and the slope angle, and then compared it with the armour piercing data of anti-tank PGU-14s fired from the GAU-8/A cannon. On this basis was determined the probability of piercing the armour.

4. Analysis of proper system performance

Having determined the deduction rules and all the necessary parameters was obtained the control surfaces, as shown in Fig. 2.

The analysis of control surfaces clearly shows that the probabilities of penetration determined by the controller are too high. In addition, for very small armour thicknesses, the probability does not take high values, and increases linearly. Another controller error is an increase in the probability of penetration for larger angles of armour slope at large distances.

In order to verify the suspicions and make more thorough evaluation of the controller's operation, was selected twenty samples of the input signals for further investigation. The test results are presented in Tab. 3.

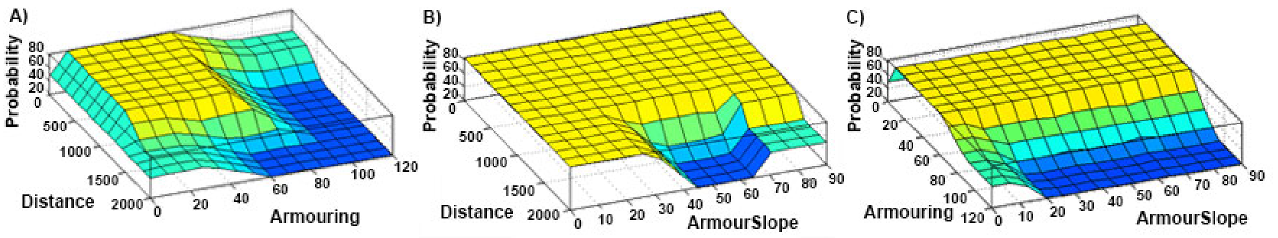


Fig. 2. Control surfaces: A) dependence of probability of armour piercing upon target distance and armour thickness, B) dependence of probability of armour piercing upon target distance and armour slope, C) dependence of probability of armour piercing upon armour slope and armour thickness

The combinations of high probability of armour penetration are marked with green colour; yellow colour is for medium penetration and red for the small one. It is possible to observe an overwhelming number of high probability values, which when referenced to the piercing data of the GAU-8/A cannon, point to an erroneous estimation by the controller. For example, determining the high probability of piercing a 60 mm thick armour, inclined at an angle of 30°, from a distance of 1,700 m seems unrealistic if the actual penetration of the cannon is 55 mm at a distance of 1,200 m. Moreover, merely three medium values from a given set assume the output values. Was proved the suspicions of the controller's malfunction and the need for its optimization.

Optimization

In order to improve the operation of the controller was changed the deduction rules for ones that are more stringent. The way of executing the logical implication of rules has also been changed: from the intersection of sets for the productive analysis and the way of realizing the logical aggregation of rules, performed as the maximum from the arguments to the disjunction. The number of input and output signals remained unchanged. Likewise, the membership functions in the signals were left in their original state. The control surfaces of the optimized system are shown in Fig. 3.

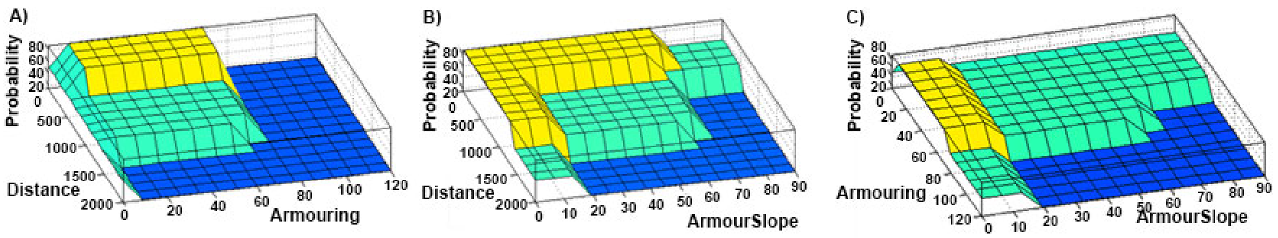


Fig. 3. Control surfaces after optimization of the system: A) Dependence of probability of armour piercing upon target distance and armour thickness, B) Dependence of probability of armour piercing upon target distance and armour slope, C) Dependence of probability of armour piercing upon armour slope and armour thickness

On the basis of the above surfaces, it is possible to deduce the following:

– optimization of the system was useful in diminishing the probability of armour piercing, specified by the controller. The dominance of the blue colour clearly indicates a low probability for large armour thicknesses and high distance values,
– optimization did not contribute to the elimination of the controller's error, where there was a linear increase in the probability of penetration for very small thicknesses. Probability should start with a high value, and not grow towards it,
– was failed to change the controller's properties of determining the medium value for a given range of probability. The values do not change smoothly.

After optimizing the system, 20 samples of input data were re-examined. The results are shown in Tab. 3.

Tab. 3. Findings of examining 20 data samples before and after system optimization

No.	Armouring [mm]	Distance [m]	Armour Slope [deg]	Probability of Armour Piercing [%]	
				before optimization	after optimization
1	20	130	10	**87.5**	**83.7**
2	20	130	60	**87.5**	**83.7**
3	20	130	80	**87.5**	**83.7**
4	20	900	30	**87.5**	**52.5**
5	20	900	45	**87.5**	**52.5**
6	20	900	60	**87.5**	**52.5**
7	20	1,600	20	**87.5**	**52.5**
8	20	1,600	70	**52.5**	**18.7**
9	60	150	20	**87.5**	**83.7**
10	60	150	70	**87.5**	**52.8**
11	60	950	25	**87.5**	**52.5**
12	60	950	75	**87.5**	**19**
13	60	1,700	30	**87.5**	**19**
14	60	1,700	70	**52.5**	**18.7**
15	105	200	15	**52.5**	**52.5**
16	105	200	70	**15**	**18.7**
17	105	1,000	20	**15**	**18.7**
18	105	1,000	75	**15**	**18.7**
19	105	1,550	25	**15**	**18.7**
20	105	1,550	75	**15**	**18.7**

The red colour, which dominates in the table, denotes little probability of armour piercing, particularly for large thicknesses (105 mm), but also in sample 8, where the thin armour is positioned at a large angle and fired at from a large distance. Optimization did reduce the probability set by the controller, while keeping high values logically – for small distances and thin armour. Making the deduction rules stricter gave the desired effect, since the determined probability assumes lower values. However, the controller still determines only three probability values, which are in the middle of particular ranges. Optimization did not eliminate this phenomenon since the input and output signals remained unchanged, being left in the form of trapezoidal functions.

5. Simulation

In order to perform the automatic simulation, was exploited the toolbox "Simulink" of the MATLAB programme. Toolbox allows designing any system and then conducting simulation of its work. The designed model of the controller estimating the probability of armour penetration is shown in Fig. 4.

The model consists of 3 input signal generators for the fuzzy controller: armour thickness, distance and armour slope. The signals coming from the generators combine and become an input signal for the fuzzy controller. Another element is the fuzzy controller itself, and then the displays. After importing the designed fuzzy controller to Simulink, it was possible to perform an automatic simulation of the system operation. Its result has been presented in Fig. 5a.

Simulation using the designed fuzzy controller allows automatic probability calculation of penetration depending upon changes in input signal values. In the simulation, the input signals increased from 0 to the maximum value in 10 seconds. The maximum values were 90 degrees for

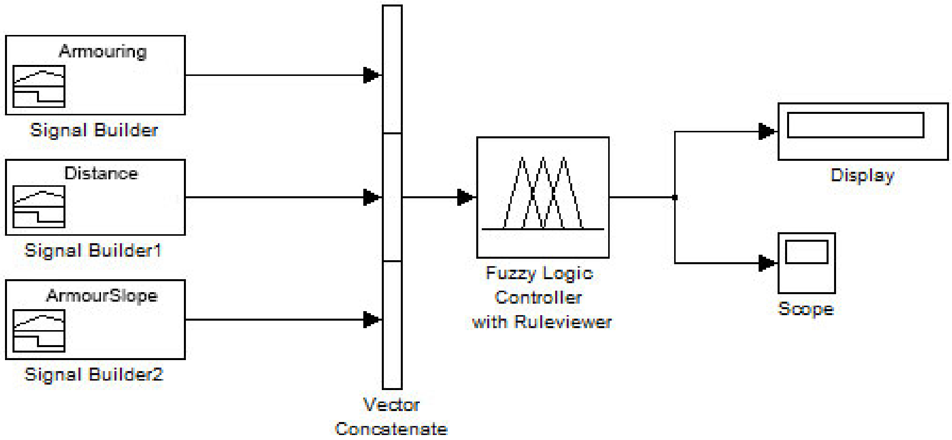


Fig. 4. Model of the designed system in Toolbox Simulink

the armour slope input signal; 2,000 m for the input distance signal; and 120 mm for the armour thickness. It is possible to create any pattern of changes in the input parameters for which the simulation is to be performed. In the above example, the conditions for piercing the armour were less and less favourable, therefore the probability of armour penetration gradually decreased, as seen in the display. It is also possible to observe the previously described controller's properties of leap-up and not smooth distribution of probability, as well as a linear increase of piercing probability for short distances.

Another simulation was performed with a linear change of input parameters from maximum to zero. Its result has been presented in Fig. 5b.

a) *b)*

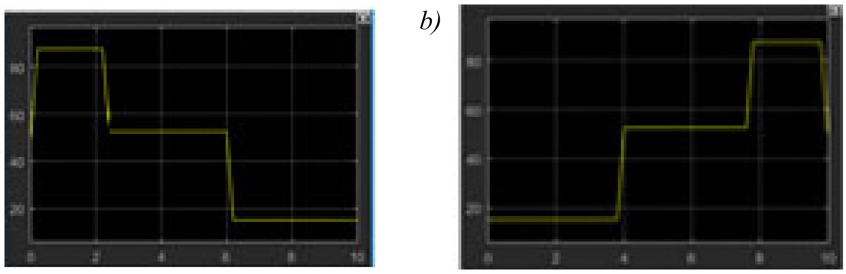


Fig. 5. Simulation in Simulink toolbox

For the second simulation, when changing the values of the input parameters, starting with the least favourable for piercing, with regard to the minimum distance, thickness and armour slope, the probability of piercing increases, as visualized on the display.

It turned out that the performed simulations brought results consistent with the established deduction rules. The imperfections (mainly leaps in changing the probability) are due to the nature of the created fuzzy controller, and not due to faulty simulation. The assumed trapezoidal functions lead to changing the input signals in huge leaps. This problem would most likely be eliminated, were the input and output signals used in the form of Gaussian curves.

6. Conclusions

On the basis of the created controller, it is clear that a well-developed system, which had undergone testing and optimization, is capable of calculating near reality probability values. After proper development of the deduction rules and appropriate specifying of the ranges of membership functions of the input and output signals, the system can operate in an accurate manner. In the described controller, optimization has resulted in a more realistic probability determination. The system, however, has still disadvantages that might be removed in the further process of its development. First of all, it is necessary to change the way of calculating the probability for more fluid one. Currently the controller only determines the middle data values of sets, instead of gradually decreasing/increasing the output value. The solution to this problem would probably be the creation of input and output signals in the form of Gaussian curves. In addition, as seen on the control surfaces, the controller is characterized by an undesired feature of distributing zero piercing probability to very low armour thicknesses, which then rise linearly to high values. This is an erroneous manner of operation, since the starting value should be reliable in the whole range. After the elimination of the above, the controller would work in accordance with the assumptions, giving quite credible results.

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