A Takagi-Sugeno Fuzzy Model of a Rudimentary Angle Controller for Artillery Fire

Jun Young Bae, Youakim Badr, Ajith Abraham
Institut National des Sciences Appliquées
INSA-Lyon, F-69621, France
{jun-young.bae, youakim.badr, ajith.abraham}@insa-lyon.fr

Abstract

Modern artilleries have the capability to hit targets with high level of accuracy. However, a problem arises with the current firing procedure when neither the Field Observer nor the Fire Direction Center is available to support the artillery crew with the necessary information. In this situation, the detection of environmental conditions would involve a number of uncertainties and due to this reason, conventional control techniques will not deliver satisfying solutions since the adjustment to the artillery's firing line will be based on data that is approximate rather than precise. In this paper, we propose a firing angle control system based on the Takagi-Sugeno fuzzy model. The advantage of fuzzy logic is the ability to tune certain variables easily by varying the linguistic rules or input variables. Experiments show that effective results can be obtained using a fuzzy model, while demonstrating that the model could come in handy when the firing angle has to be determined instantaneously with very vague information about the target.

1. Introduction

Nowadays, modern artilleries have the capability to hit and destroy a target with pin-point accuracy from distances where it cannot even be seen directly. This so-called "indirect fire" is achieved through an intricate collaboration between a Field Observer (FO), a fire Direction Center (FDC) and the artillery crew. The FO will first observe the target by using binoculars or laser rangefinders, and relay the necessary information, such as location and description, to the FDC. The FDC will process this information, usually with a computer, and come up with the "firing direction". This firing direction consists of a bearing, an elevation and the type of ammunition and fuse to be used. Finally this direction is passed down to the artillery crew, who will then use it to adjust their firing.

A problem arises with the above procedure when neither the FO nor the FDC are available to support the artillery crew with the necessary information. The crew will then have to engage the target by themselves when it comes within visual range (about 1 ~ 3 km away). Of course, any adjustment to the firing line will have to be made by the crew themselves. This adjustment will have to be computed with very vague data, since the crew will probably not be in possession of any precise measurement tools.

In the above situation, conventional control techniques will not deliver satisfying solutions [1] since the adjustment to the artillery's firing line will be based on data that is approximate rather than precise [2]. Fuzzy logic [3] allows a generalization of the conventional logic by using imprecise linguistic expressions of input variables such as high, medium or low. In this paper, we will employ the fuzzy logic theory to design and test a firing angle control system.

This paper begins by introducing the general design of the fuzzy firing angle control system in Section 2 and demonstrates the benefit of using the Takagi-Sugeno fuzzy model. Section 3 thoroughly covers the design steps based on fuzzy inputs, outputs and rules. The reasoning process and its implementation using MATLAB Fuzzy Logic Toolbox are shown in Section 4. Finally, Section 5 concludes the work and proposes further research directions.

2. Firing Angle Control System

In our model, fuzzy logic is used to compute the firing angle. As illustrated in Figure 1, the control system itself is relatively simple. Four linguistic input variables are issued from environmental conditions: distance from target, wind velocity, up/down hill angle and target velocity. Each input variable has three linguistic values and thus three different membership functions. The system has one output variable, the firing angle, which has five different linguistic values (i.e. very small, small, medium, large and very large).

When the firing angle is computed using these inputs, the firing line of the artillery will be adjusted accordingly. After the first shot, if the aim is not accurate, the operator can modify the inputs and try again until the target is hit.

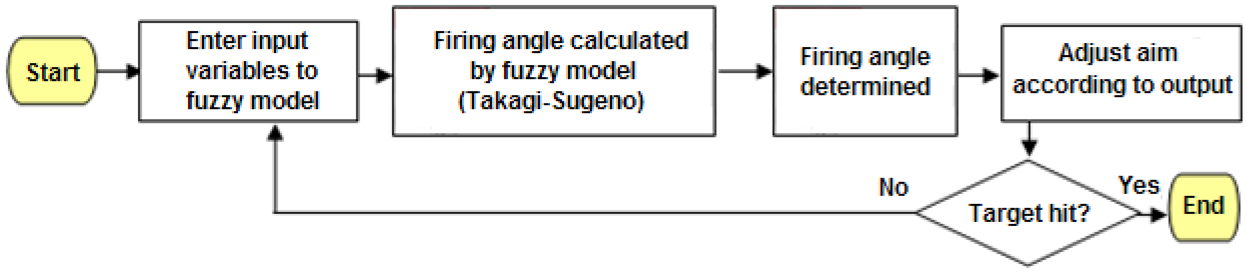

Figure 1. Fuzzy firing angle control system

We adopt the Takagi-Sugeno method [4] in order to implement the controller system instead of its counterpart, the Mamdani method [5], because it does not have to integrate across a continuously varying output function. The main difference between Mamdani and Sugeno is that the Sugeno output membership functions are either linear or constant. Therefore, the Takagi-Sugeno method is computationally more efficient and thus more likely to have a faster response, which is critical in situations where quick decisions should be taken, such as in a battlefield [6]. The Takagi-Sugeno provides efficient aggregation and defuzzification functions, which will be used to calculate the output angle [7].

3. Design of the Takagi-Sugeno Fuzzy Control System

The desired system behavior of the rudimentary Angle Controller can be defined through creation of the rules and linguistic variables [8]. In such case, four input variables have been chosen because they are factors relatively easy to approximate while being critical in the determination of the adjustments to be made for the artillery [9]. We introduce the system variables in terms of fuzzy sets and their ranges as illustrated in Figure 2.

Distance from target: The distance from target varies from 0 to 3 km. A distance between 0 and 500 meters is considered as definitely close whereas a distance between 2.5 and 3 km is considered as definitely far.

Wind velocity: This variable varies between 0 and 100 km/hour. Headwind is represented with a negative speed. Tailwind is represented with a positive speed. Any type of wind between 70 and 100 km/hour is considered as definitely strong.

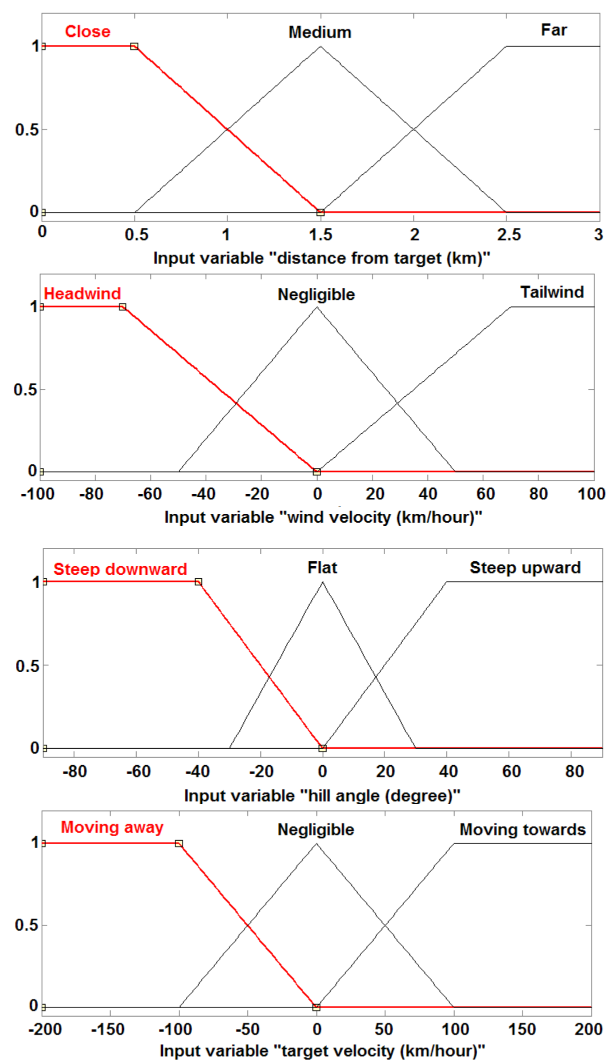

Figure 2. Membership functions and their input variables

Up/Down hill angle: The hill angle varies between 0 and 90º. A downward angle is denoted with a negative sign and an upward angle is denoted with a positive sign. Any angle larger than 40º is considered as definitely steep.

R1: IF distance from target is close THEN firing angle is very large.
R2: IF distance from target is medium THEN firing angle is large.
R3: IF distance from target is far THEN firing angle is medium.
R4: IF wind velocity is headwind OR hill angle is steep downward THEN firing angle is large.
R5: IF wind velocity is tailwind OR hill angle is steep upward THEN firing angle is small.
R6: IF distance from target is close AND target velocity is moving away THEN firing angle is large.
R7: IF distance from target is close AND target velocity is moving towards THEN firing angle is very large.
R8: IF distance from target is far AND target velocity is moving away THEN firing angle is medium.
R9: IF distance from target is far AND target velocity is moving towards THEN firing angle is large.
R10: IF distance from target is close AND target velocity is moving towards THEN firing angle is very large.
R11: IF distance from target is far AND target velocity is moving away THEN firing angle is medium.
R12: IF distance from target is far AND target velocity is moving towards THEN firing angle is large.
R13: IF distance from target is close AND hill angle is steep upward AND target velocity is moving towards THEN firing angle is very small.
R14: IF hill angle is steep upward AND target velocity is moving away THEN firing angle is very small.
R15: IF hill angle is steep downward AND target velocity is moving towards THEN firing angle is very large.

Table 1: List of the implemented fuzzy *if-then* rules

Target velocity: Target velocity takes a value between 0 and 200 km/hour. Targets moving away from the operator are represented with a negative speed. Targets moving towards are represented with a positive speed. Any speed higher than 100 km/hour is considered as definitely fast.

Firing angle: Five linguistic and discrete values distinguish the firing angle: *very small, small, medium, large* and *very large*. We suggest to define each value by increments of 16º (i.e. very small = 16º, small = 32º, medium = 48º, large = 64º, very large = 80º) as illustrated in Figure 1.

The fuzzy Set Theory defines fuzzy operators on Fuzzy Sets in terms of simple *if-then* rules. The controller could be described by using 3^4 (81) possible combinations of AND rules since we have four input variables that each has three linguistic values. Table 1 depicts the list of the fifteen rules that have been implemented into the model. Note that these rules have been set up without any particular expert knowledge.

4. Fuzzy Reasoning

In this paper, we use the MATLAB Fuzzy Logic Toolbox to implement the control system and demonstrate its basic operations. In addition, we registered the fuzzy rules in a database, which is queried to deduct fuzzy logic processing. Figure 3 illustrate the Takagi-Sugeno style rule evaluation, aggregation and defuzzification process. The AND operation is set as the minimum of the input membership values. The OR operation is set as the maximum. The defuzzification method used is the weighted average method. In this case, the inputs are set as following:

Distance from target: 2 km
Wind velocity: Headwind blowing at10 km/hour (-10 km/hour)
Hill angle: 10º upward (+10º)
Target velocity: Moving away at 10 km/hour (-10 km/hour)

As evident from Figure 3, after entering the above mentioned inputs, the output, which is the weighted average of the aggregation of all the singletons, is calculated to be 52.3º.

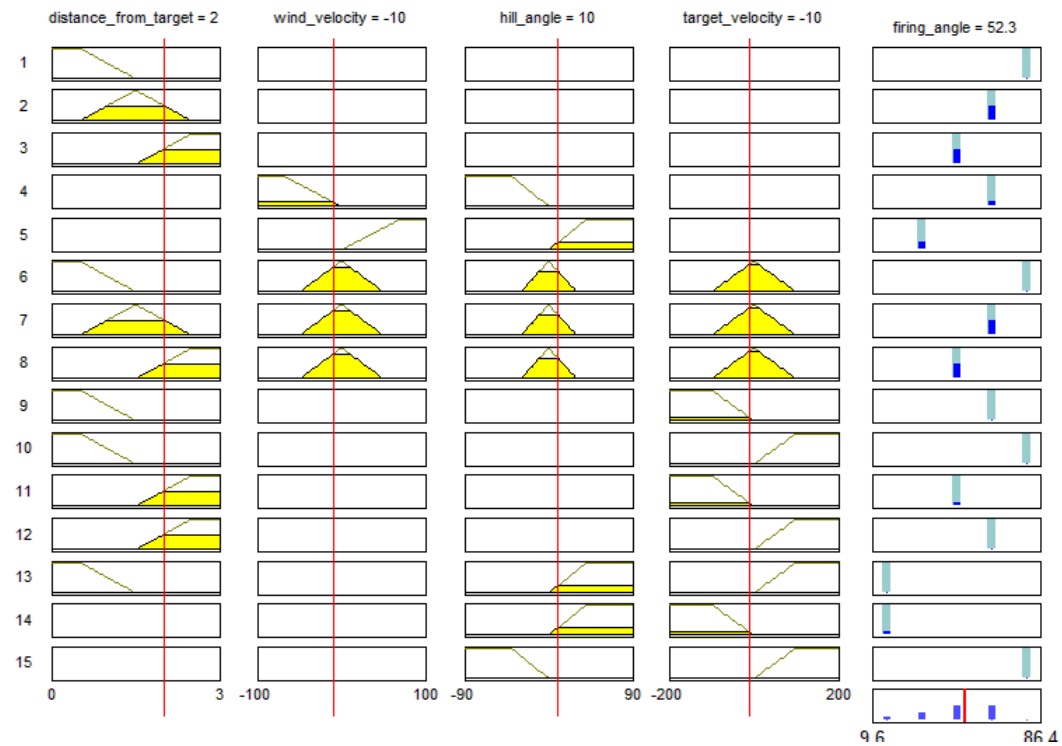

Figure 3. Diagram showing Takagi-Sugeno style rule evaluation, aggregation and defuzzification

5. Experimental Results and Discussion

After the controller was carefully designed, we test the system and discuss the impact of the input variables on the output variable.

1- Distance from target and wind velocity vs. firing angle

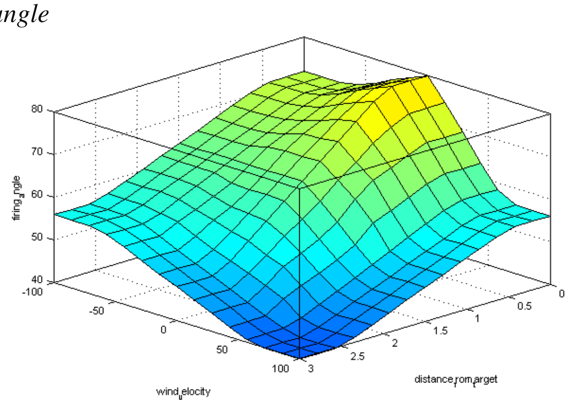

Figure 4. “distance from target” and “wind velocity” vs. “firing angle”

As illustrated in Figure 4, the firing angle (z-axis) is small when the target (x-axis) is far away and a strong tailwind blows (y-axis). The angle gradually grows bigger as the target gets closer and the headwind gets stronger. The firing angle is largest when the target is extremely close but no wind blows.

2- Distance from target and hill angle vs. firing angle

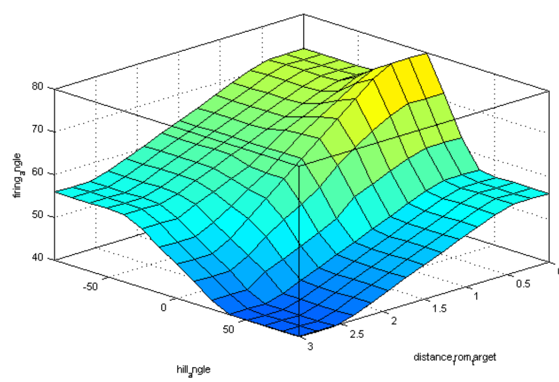

Figure 5. “distance from target” and “hill angle” vs. “firing angle”

The trend shown on Figure 5 is similar to Figure 4. The firing angle *(z-axis)* is small when the target *(x-axis)* is far away and the hill angle *(y-axis)* is steep upward. It gradually grows bigger as the target gets closer and hill angle becomes steeper downward. The firing angle is largest when the target is extremely close and the surface is flat.

3- Distance from target and target velocity vs. firing angle

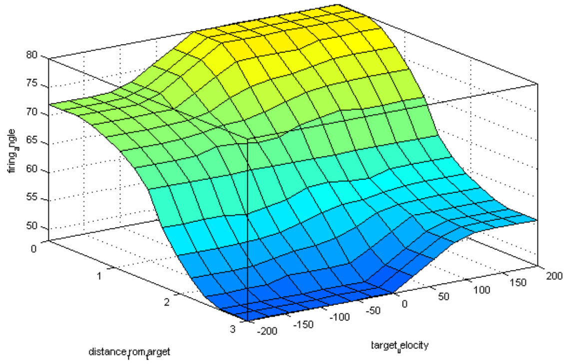

Figure 6. “distance from target” and “target velocity” vs. “firing angle”

As evident from Figure 6, the firing angle *(z-axis)* is set to a medium value when the target *(x-axis)* is moving away very fast from a far distance *(y-axis)*. This angle will gradually grow as the target gets closer at a faster speed. The angle is set to maximum when the target is moving towards the user at a very fast speed from an extremely close range.

4- Wind velocity and hill angle vs. firing angle

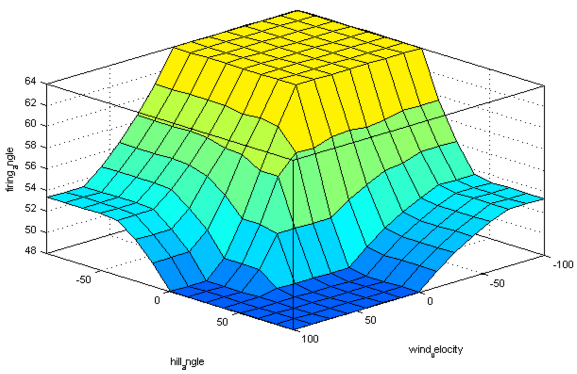

Figure 7. “wind velocity” and “hill angle” vs. “firing angle”

The firing angle *(z-axis)* is small when a strong tailwind *(x-axis)* is blowing and the hill angle *(y-axis)* is steep upward. This is illustrated in Figure 7. It gradually grows as the surface gets steeper downward and a headwind starts to blow. The angle is large when a strong headwind blows while the surface is steep downward.

5- Wind velocity and target velocity vs. firing angle

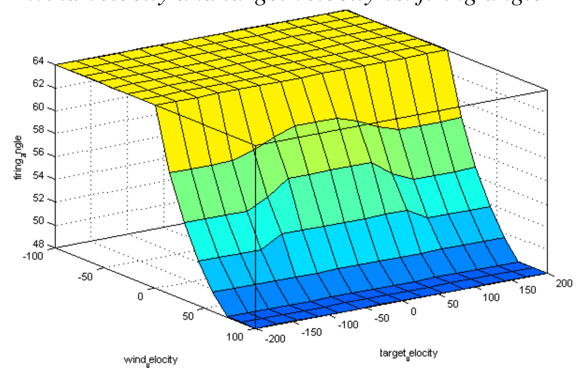

Figure 8. “wind velocity” and “target velocity” vs. “firing angle”

In Figure 8, the firing angle *(z-axis)* is mostly unrelated to the velocity of the target *(x-axis)*. It is set to a medium value when a strong tailwind *(y-axis)* blows and gradually grows to a larger value as the tailwind weakens. The angle becomes slightly larger when the target is moving slowly, but it is almost negligible.

6- Hill angle and target velocity vs. firing angle

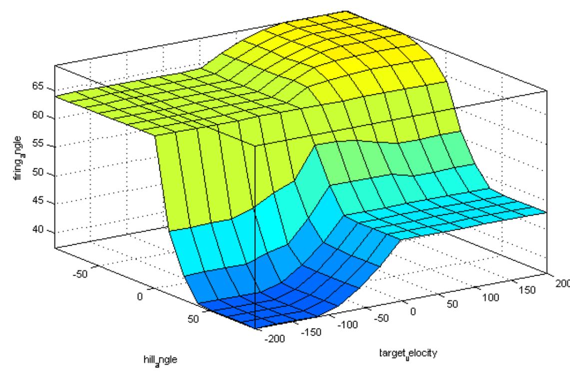

Figure 9. “hill angle” and “target velocity” vs. “firing angle”

As depicted in Figure 9, the firing angle *(z-axis*) is small when the target is moving away at a high speed *(y-axis)* and the surface is steep upward *(x-axis)*. It is set to a medium value if the target is moving towards the user. The firing angle gradually grows to a high value as the surface becomes steep downward. The largest firing angle is achieved when the surface is very steep downward and the target is moving towards the user at high speed.

From the simulation results, it may be observed that the fuzzy model can be successfully employed to instantaneously determine the firing angle with only four input specifications. With just fifteen rules, we were able to come up with a reasonable estimate of the firing angle. As we saw in the previous example, if the distance from target it 2 km, headwind is blowing at 10 km/hour, hill angle is 10º upward and target is moving away at 10 km/hour, then the firing angle is calculated to be 52.3º. This value seems reasonable indeed since the target is slowly moving away from a rather far distance. Therefore, we would expect an angle close to 45º. However, since there is a slight headwind, the angle is adjusted to be slightly higher.

6. Conclusions

The basis of the firing angle controller consists of imprecise expressions represented by fuzzy input variables. The advantage of fuzzy logic is the ability to modify and tune certain variables easily by varying the linguistic rules or variables. In this paper, we have proposed a firing angle control system based on fuzzy logic theory. Experimental results illustrate that effective results can be obtained using a fuzzy model, while demonstrating that the controller could be used as a handy last-resort tool, when no directions are given from the forward observation team or if the situation becomes too urgent to wait for them.

The system still requires substantial tuning before it can be truly effective with real-world problems. This tuning process could possibly include adding new rules and linguistic values, and adjusting membership functions. Additionally, in order to make the system more complete, it will be necessary to implement the azimuth (horizontal plane) in its reasoning process. Horizontal factors such as crosswinds will have to be taken into account too.

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