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TARGET TRACKING OF THE S-60 SINGLE-BARREL 57MM ANTI-AIRCRAFT GUN SYSTEM USING HYBRID CONTROL METHOD

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ABSTRACT

The barrel of a cannon is used to propel and stabilize the movement of a projectile out of its end at a high velocity. Some of the S-60 single-barrel 57mm anti-aircraft gun systems owned by the air defense artillery division of Indonesian army (Arhanud) still have to be operated manually to provide the direction course of the projectile following the target to be fired. This paper presents the design of target tracking control using PID-fuzzy logic hybrid method to be implemented on the anti-aircraft cannonry system. It is purposed to maintain the direction stability of the cannon barrel when it moves toward the desired direction, in terms of both azimuth and elevation of the target. It is shown that the implementation of PID and fuzzy-logic hybrid control method provides certain advantages, indicated with the conformity between the barrel movement along the azimuth and elevation directions and the input data given through a joystick.

Keywords: cannon barrel, fuzzy logic, PID, hybrid control, arduino mega 2560.

INTRODUCTION

One important factor determining the performance of an anti-aircraft gun is the control system of motion and stabilization of its barrel. Currently, the majority of such control systems owned by the Indonesian army have been procured and imported from abroad. Consequently, when certain repairs or spare parts are needed, the involvement of or dependence to foreign institutions cannot be avoided.

The air defense artillery division of Indonesian army (Arhanud) is in charge of organizing the active air defense to destroy, eliminate or to reduce the effectiveness and efficiency of all forms of threats to the air defense systems by using cannons and missiles, in the framework of the Air Defense (Hanud) in the war fields as well as the National Air Defense (Hanudnas).

The S-60 57mm cannon is one of the main weapons owned by the air defense artillery division of Indonesian army (Arhanud). As seen in Figure-1, it is a single-barrel anti-aircraft gun which works based on the use of gunpowder or other usually explosive-based propellants to launch a projectile. Some of the S-60 single-barrel 57mm anti-aircraft gun systems owned by the air defense artillery division of Indonesian army (Arhanud) still have to be operated manually to provide the direction course of the projectile following the target to be fired.

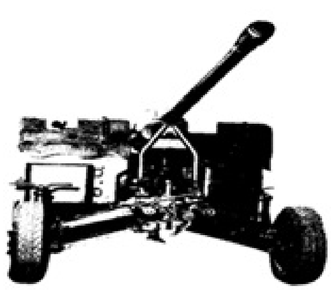

Figure-1. The S-60 57mm single-barrel anti-aircraft gun.

The research, the results of which are presented in this paper, has been purposed to find a method or helping system to facilitate the cannoneer to maneuver the cannon barrel in the direction of target to be fired. Figure-2 shows the barrel of S-60 57mm cannon. It is this barrel movement which needs to be controlled automatically to provide the direction course of the projectile following the target to be fired (Zaifei and Chunping, 2014; Yang *et al.* 2014). So far, eight persons are required to serve one S-60 57mm cannon in operation. The cannon can then be fired automatically or in a single fire by releasing the firing pedal if not equipped with a firing lever set.

Figure-2. The barrel of S-60 57mm cannon.

In this paper, the proposed method is in the form of combining the proportional-integral-derivative (PID) control method with the fuzzy-logic control method into a hybrid PID-fuzzy logic control method to control and adjust the motor rotation to actuate the barrel towards the target direction.

The PID control method has been chosen as historically it had been considered to be the most useful controller. This controller combines the benefits obtained from each of the proportional, integral, and differential control methods. It gives control output with high rise time and small error, as it is widely known that proportional controller has an advantage owing to its high rise time, integral controller is advantageous to reduce error, whereas derivative controller possesses benefits in reducing error and in damping overshoot/undershoot (Ogata, 2009; Coughanowr and Koppel, 1965).

The fuzzy logic method is applied to determine the gain constants of PID controller, which are the proportional gain constant K_p, integral gain K_i, and the derivative gain K_d.

Fuzzy logic can be used to treat computation based on perception and cognition, which is, uncertain, imprecise, vague, partially true, or without sharp boundaries. It enables the inclusion of vague human assessments in computing problems and becomes effective to deal with conflict resolution of multiple criteria and better assessment of options. Many recent computing methods based on fuzzy logic have been applied in the development of intelligent systems for decision making, identification, pattern recognition, optimization, and control (Yan *et al.* 1994; Singh *et al.* 2013), Sivanandam *et al.* 2007; Banks and Haywad, 2002; Cirstea *et al.* 2002).

DESIGN OF THE HYBRID CONTROL SYSTEM

The PID control

The PID controller is normally used to improve time response, to avoid steady-state error as well as to maintain stability (Ogata, 2009; Kessler and Phatak, 1976). The characteristics of this kind of controller is determined by the following parameters:

- K_p, which has an influence during the transient condition (settling time t_{ss}) and steady-state condition (steady-state error e_{ss})
- K_i, which improves the steady-state condition but could worsen the transient condition
- K_d, which improves the transient condition (settling time t_{ss}, overshoot) but has no influence on the steady-state condition of the system.

$$u(t) = K_p\left(e(t) + \frac{1}{T_i}\int_0^t e(t)\,dt + T_d\frac{d}{dt}e(t)\right) \quad (1)$$

By applying the Laplace transformation, calculation involving integration and differentiation can be done more easily using algebraic equation in terms of *s*,

$$U(s) = K_p . E(s)\left(1 + \frac{1}{T_i s} + T_d s\right) \quad (2)$$

Furthermore, the transfer function relating the control action to its the error can be expressed as,

$$\frac{U(s)}{E(s)} = K_p\left(1 + \frac{1}{T_i s} + T_d s\right) \quad (3)$$

Fuzzy-logic control principle

The controlling principle of fuzzy-logic method involves one or more inputs and results in one or more outputs to be fed into a plant or or other part of the system. The fuzzy control basic structure includes fuzzification unit, fuzzy inference system, knowledge base as well as de-fuzzification unit, as shown in Figure-3.

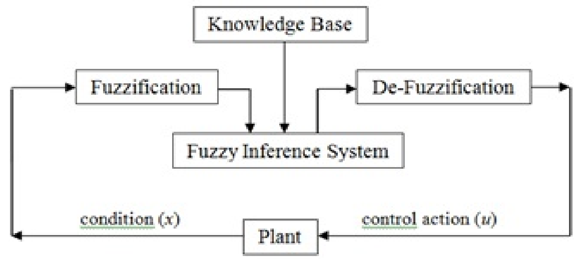

Figure-3. Basic structure of fuzzy-logic control (Yan, *et al.* 1994).

The first step in designing a fuzzy logic controller is to determine the input and output variables. The next steps will cover the fuzzification step and the determination of fuzzy rules, whereas the last step is the de-fuzzification process.

The fuzzy logic control being explored in this paper requires 2 crisp inputs and 3 crips outputs. The inputs are angular position error and delta error of the angular position, whereas the outputs are K_p, K_i, and K_d parameters. Error represents the difference between the desired value (set-point) and the actual value, whereas Δerror represents the difference between two consecutive errors.

The membership functions of error and delta error are indicated using 5 labels, which are Negative Big (NB), Negative Small (NS), Zero (Z), Positive Small (PS), and Positive Big (PB). Five labels have been designated in order to form more rules, implying more condition possibilities to achieve the desired results. The input data of the membership functions have been obtained from the angular values resulted in using the potentiometer and the rotary encoder sensor. The membership functions of error and delta error of both the azimuth and elevation angles are shown in Figure-4 and Figures-5.

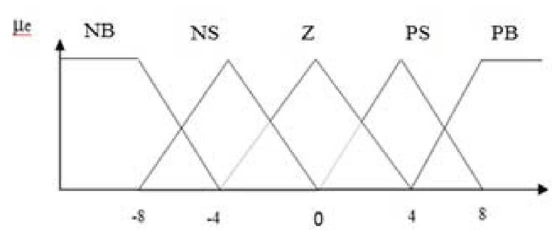

Figure-4. Membership function of input error for both azimuth and elevation angles.

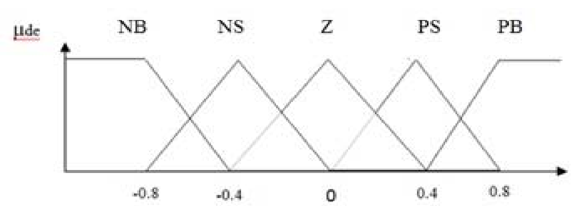

Figure-5. Membership function of input delta error for both azimuth and elevation angles.

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The fuzzy rules are used to determine the output of the fuzzification process, which is furthermore used in the de-fuzzification step. There are 25 rules, based on the fact that there are 5 membership functions of error and 5 membership functions of delta error. Fuzzy rules for the K_p, K_i and K_d values are shown in Table-1.

Table-1. Fuzzy rules for K_p, K_i and K_d values.

	NB	NS	Z	PS	PB
NB	PB	PB	PB	PS	PS
NS	PB	PB	PS	NS	NS
Z	PB	PS	NS	NS	NB
PS	PS	PS	NS	NB	NB
PB	PS	NS	NS	NB	NB

In order to change the fuzzy output into the crisp output, the de-fuzzification process is needed. The output of this process is used to adjust the K_p, K_i and K_d values. The Sugeno method has been chosen during this process, as it results in a monotonous value and is capable of overcoming the limited output range obtained using the weighted average method.

The output U is a function of the weight of each true value w_i and the linguistic value u_i of each of the output membership function, and is obtained using the following expression:

$$U = \frac{\sum_{i=1}^{n} w_i u_i}{\sum_{i=1}^{n} w_i} \quad (4)$$

with n is the membership degrees.

By applying (4) manually, the obtained de-fuzzification results are not of integer types. In order to get the K_p, K_i dan K_d values of integer types, a special instruction to round-up the results must be included during the programming step.

The resulted output membership functions for K_p, K_i dan K_d values required during the computation of both the azimuth ang elevation angles are shown subsequently in Figures-6, Figures-7 and Figures-8. The K_p values are 1,3,5,7, the K_i values are 1,2,4,5, whereas the K_d values are 1,0,2,3.

The membership function of the DC motor output represents the tracking error of the gun barrel. The PWM output values of the Arduino module have been resulted in from the singleton de-fuzzification method including the rounding-up process during the programming to obtain integer values. It is purposed to accelerate the program execution and in order not to burden the memory capacity of Arduino, which is limited to 256 kilobytes.

Hybrid PID-fuzzy logic control principle

The hybrid control method is obtained by integrating the output of the de-fuzzification unit into the PID control system. The results of de-fuzzification unit become the gain parameters using in the PID controller, as can be seen in Figure-9.

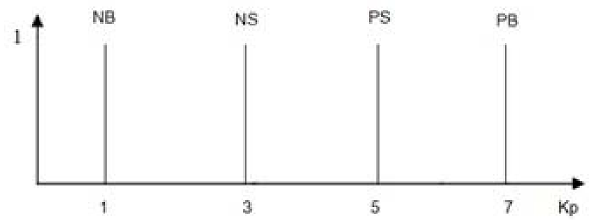

Figure-6. Membership function of output value K_p for both azimuth and elevation angles computation using Sugeno method.

Figure-7. Membership function of output value K_i for both azimuth and elevation angles computation using Sugeno method.

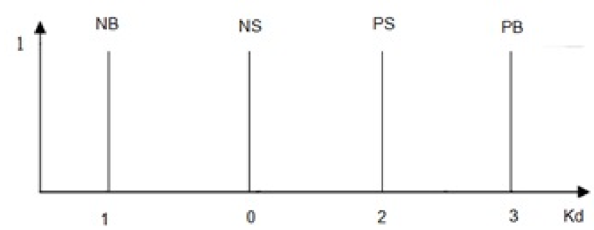

Figure-8. Membership function of output value K_d for both azimuth and elevation angles computation using Sugeno method.

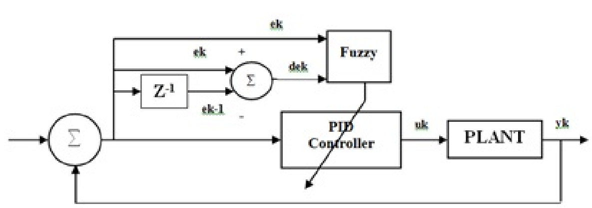

Figure-9. Block diagram of hybrid PID-fuzzy logic control method.

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The input variables of the PID controllers include the error ($e(t)$), the delta error ($\frac{d}{dt}e(t)$), and the summing error ($\int e(t)\,dt$), whereas the output variable is the duty-cycle of the PWM for the DC motors. The continuous PID equation must be discretized, resulting in the following equation:

$$\omega = K_p e_\omega(n) + K_i \sum e_\omega(n) + K_d \frac{(\theta_{sp}+\theta(n-1)-2\theta(n))}{T} \quad (5)$$

where:

ω the ADC angular velocity
$\omega(n)$ the current angular velocity
$\omega(n-1)$ the previous angular velocity
$\theta(n)$ the current angle value
$\theta(n-1)$ the previous angle value
θ_{sp} the desired angle values
e_ω error of the ADC angular velocity
$\sum e_\omega$ sum of ADC angular velocity errors
T time sampling

Computation of azimuth and elevation angles of the target direction

The computation of target direction angles is based on the block diagrams shown in Figures-10 and Figures-11, for the azimuth and elevation angles consecutively. The difference lies on the use of rotary encoder to obtain the feedback of azimuth angle value and the use of potentiometer to get the feedback from the elevation angle value.

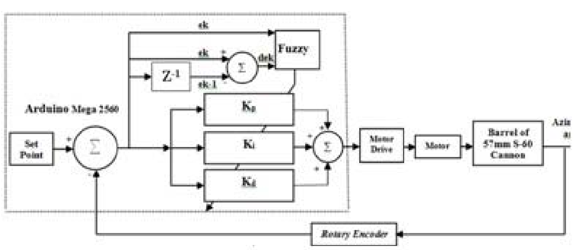

Figure-10. Block diagram for azimuth angle computation using hybrid PID-fuzzy logic method.

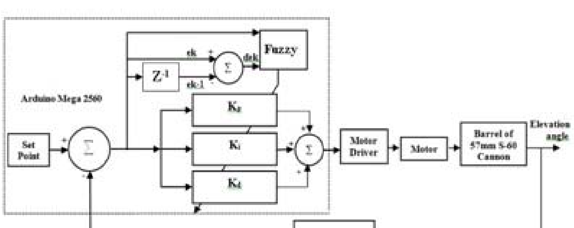

Figure-11. Block diagram for elevation angle computation using hybrid PID-fuzzy logic method.

CONSTRUCTION OF THE TRACKING SYSTEM

The mechanical construction of the system consists of a gun-barrel model, two DC motors, a rotary encoder sensor, a potentiometer and a joystick, being completed with an electric circuit panel box equipped with an LCD display, as seen in Figure-12. The two motors are used to actuate the gun-barrel along the azimuth and elevation angles direction. The movement along the azimuth direction is ranging from ± 360° with 0° is in the middle part, whereas along the elevation direction, it is limited to -2° up to 87°.

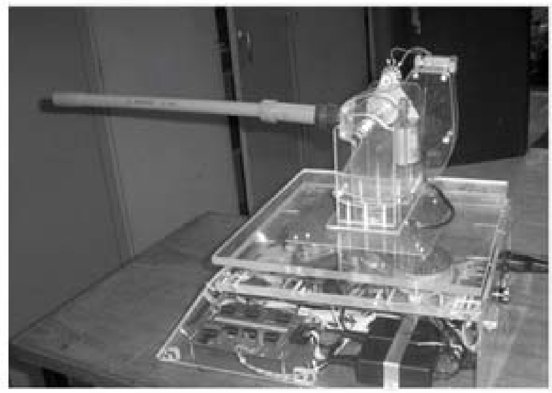

Figure-12. Mechanical construction of cannon-barrel motion-control system.

The working principle of the gun-barrel motion control is represented using the schema shown in Figure-13. The Arduino is a microcontroller board module using ATMega2560. It becomes the data central processing to actuate the motors during the positioning of the gun-barrel. This module contains 54 digital Inputs/Outputs, 14 of which are used as PWM outputs, 16 as analog inputs, 4 for UART, 16 MHz crystal oscillator, USB connection, power jack, ICSP header, and Reset button.

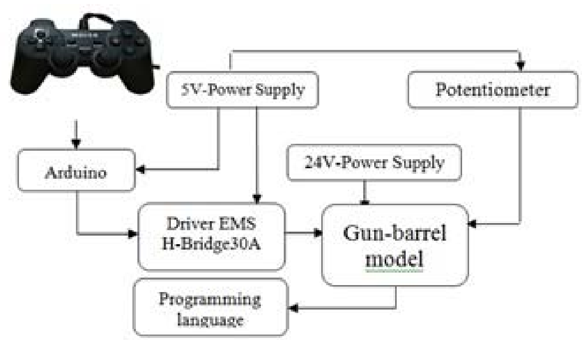

Figure-13. Block diagram of the gun-barrel motion-control system.

The EMS 30A H-Bridge module is used as the driver of the DC motors. This driver controls the direction and speed of DC motors rotation, based on the instruction given by the user using a joystick and interpreted by the Arduino Mega 2560 based on the previously designed hybrid PID-fuzzy logic control algorithm. The DC motor will rotate clockwise when being drive with 1-0 logic, and counterclockwise when being drive with 0-1 logic. The connections of this driver module are shown in Figure-14.

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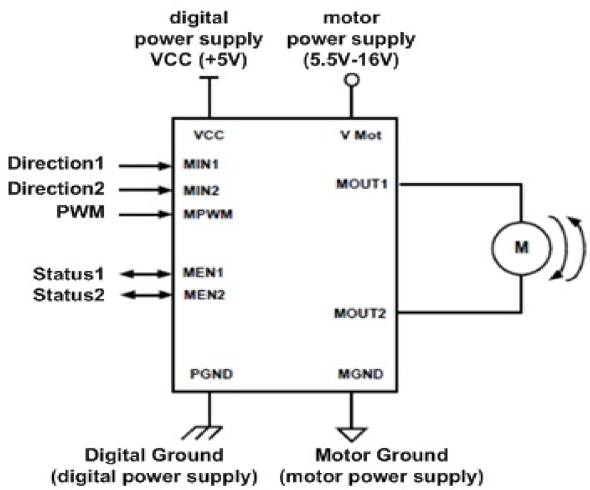

Figure-14. Module EMS 30A H-bridge connections.

Linear potentiometer is functioning to measure the position of DC motor rotation angle. Every change in rotation angle of the motor will affect the resistance change of the potentiometer, as seen in Figure-15.

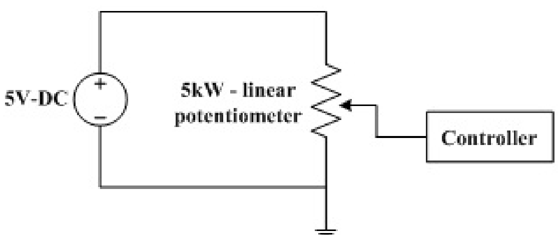

Figure-15. Potentiometer system used in the gun-barrel motion-control system.

Rotary encoder sensor is used to detect the DC motor rotation, being indicated by its voltage level based on the condition whether the emitted LED light is obstructed or not to reach the optocoupler. The circuit is shown in Figure-16.

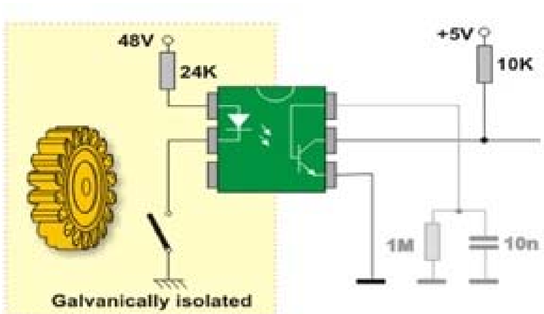

Figure-16. Design of rotary encoder circuit.

RESULTS AND DISCUSSION

The experiments have been done by using variable tuning for each value of NB, NS, PS and PB outputs, during both the azimuth and elevation angles computation.

Testing results on azimuth angle computation

Figure-17 shows the system response during the computation of azimuth angle using a set point value of 40^0. It is indicated that using the time sampling of 20ms, the rise time of 0.56 second is achieved after 28 samplings, the settling time of 0.76 second is attained at the 38th sampling.

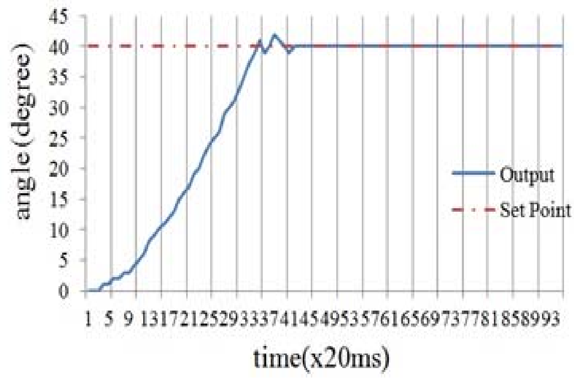

Figure-17. System response during azimuth angle computation using set point value of 40^0.

Using a set point value of 90^0, it is shown in Figure-18 that the rise time of 0.32 second is achieved after 16 samplings, the settling time of 0.48 second is attained at the 24th sampling.

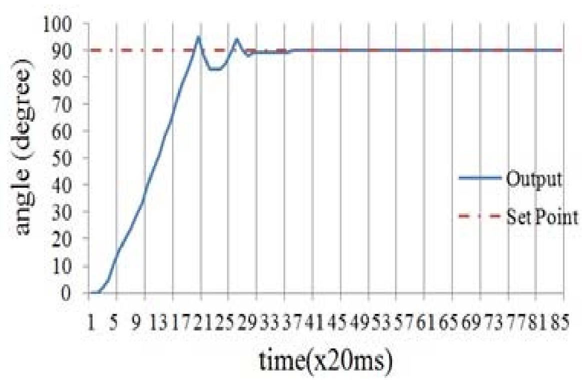

Figure-18. System response during azimuth angle computation using setpoint value of 90^o.

When the setpoint value is determined at 360^0, it is shown in Figure-19 that the rise time of 1.24 second is achieved after 62 samplings, the settling time of 1.34 second is attained at the 67th sampling.

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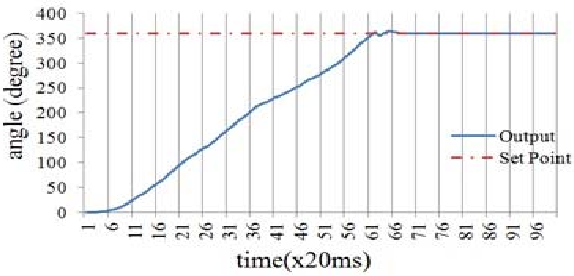

Figure-19. System response during azimuth angle computation using setpoint value of 360°.

Figure-20 indicates the NB, NS, PS and PB output values using variable setpoints, starting from 40^0, 60^0, 90^0, until 150^0. Sampling time used is 20ms. The graphic indicates that the system responds well to the changing of setpoint values of azimuth angle.

The system testing for azimuth angles computation shows that the larger the azimuth angle, the larger will the rise time and the settling time. The steady-state error is 0%, indicating that the system outputs are in conformity with the design, both in terms of fixed and variable setpoint values.

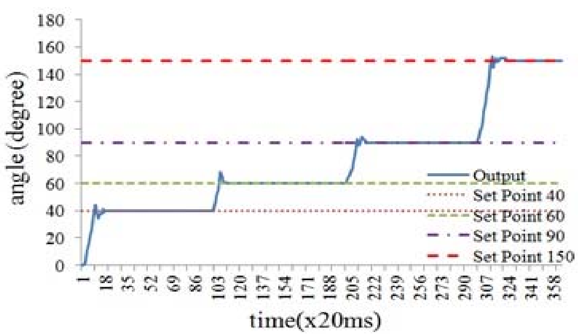

Figure-20. System response during azimuth angle computation using changing setpoint value.

Testing results on elevation angle computation

Figure-21 shows the system response during the computation of elevation angle using a setpoint value of 420. It is indicated that using the time sampling of 20ms, the rise time of 0.62 second is achieved after 31 samplings, the settling time of 0.84 second is attained at the 42th sampling.

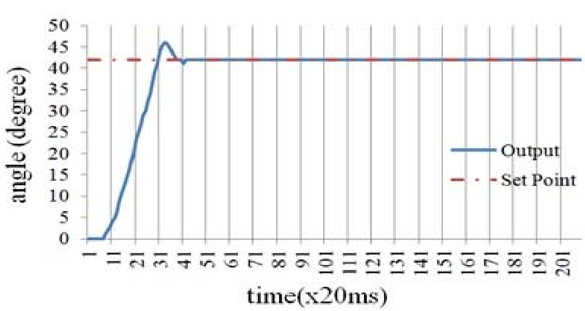

Figure-21. System response during elevation angle computation using setpoint value 42^0.

Using a setpoint value of 60^0, it is shown in Figure-22 that the rise time of 0.70 second is achieved after 35 samplings, the settling time of 0.90 second is attained at the 45th sampling.

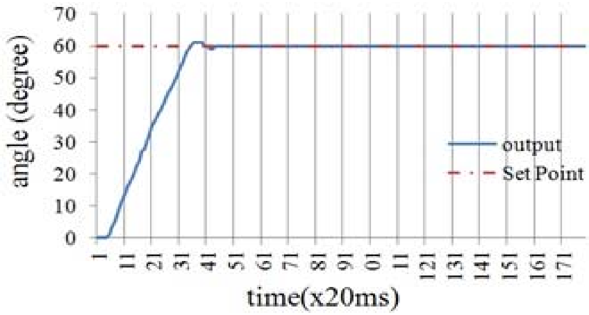

Figure-22. System response during elevation angle computation using setpoint value 60^0.

When the setpoint value is determined at 76^0, it is shown in Figure-23 that the rise time of 0.42 second is achieved after 21 samplings, the settling time of 0.76 second is attained at the 38th sampling.

Figure-24 indicates the NB, NS, PS and PB output values using variable setpoints, starting from 40^0, 60^0, 80^0, and back to 50^0. Sampling time used is 20ms. The graphic indicates that the system responds well to the changing of setpoint values of elevation angle.

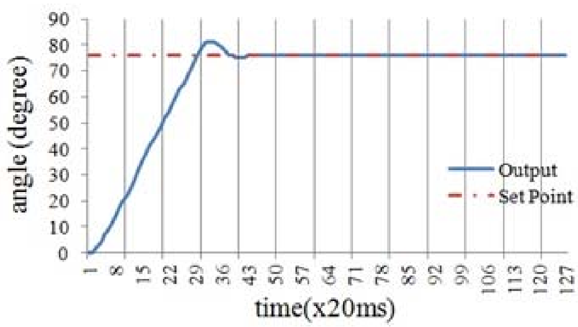

Figure-23. System response during elevation angle computation using setpoint value 76^0.

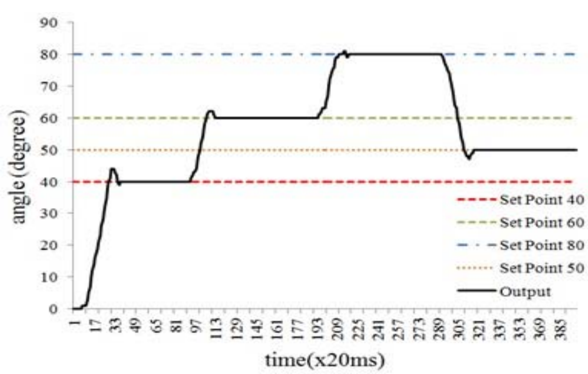

Figure-24. System response during elevation angle computation using changing setpoint value.

The system testing for elevation angles computation shows that the larger the elevation angle, the larger will be the rise time and the settling time. The steady-state error is 0%, indicating that the system outputs are in conformity with the design, both in terms of fixed and variable setpoint values.

The resume of some testing results is shown in Table-2, showing the average rise time of 0.626 second.

Table-2. Resume of testing results.

Movement direction	Setpoint	Output	Steady-state Error	Rise time (second)
Azimuth	60^0	60^0	0%	0.28
	90^0	90^0	0^0	0.54
	180^0	180^0	0^0	0.72
	360^0	360^0	0^0	1.24
Elevation	15^0	15^0	0^0	0.26
	45^0	45^0	0^0	0.62
	60^0	60^0	0^0	0.72
Average error			0%	0.626

ANALYSIS AND PERSPECTIVES

The analysis results based on the design and implementation of the method proposed in this paper proves that the hybrid of PID-fuzzy logic control method is applicable to control and to adjust the single-barrel motion system of the S-60 57mm anti-aircraft gun. It was indicated with the conformity between the input data given through the joystick to the barrel movement towards the pre-determined azimuth and elevation angles according to the desired target direction, with the average steady-state error of 0% and rise-time of 0.626 seconds.

This result also offers the perspective of further research involving the addition of aiming target from distance, and also the consideration concerning the weight of the barrel as well as the damping of recoil-force after firing.

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