AiMT Advances in Military Technology
Vol. 11, No. 1, June 2016

Sliding Mode Control of Target Tracking System for Two Degrees of Freedom Gun Turret Model

M. S. Rahmat*, K. Hudha, A. M. Idris and N. H. Amer

Department of Mechanical Engineering, Faculty of Engineering,
National Defence University of Malaysia, Kem Sg. Besi, 57000 Kuala Lumpur

The manuscript was received on 23 August 2015 and was accepted
after revision for publication on 10 June 2016.

Abstract:

This paper presents the detailed derivation of gun turret modelling along with the estimation of the ideal azimuth and elevation angles for accurate firing. A control strategy for the gun turret is developed to ensure the capability of an actuator to provide sufficient torque and accurate firing angle for the gun platform and turret. A DC motor model is constructed to actuate the gun platform and turret in high accuracy for firing angle according to the desired target angle. The desired target angle is designed based on the three-dimensional (3D) projectile motion to obtain an accurate firing angle by depending on the distance parameter x, y and z plane coordinates. The control structure for the system is controlled using the Propotional Integral Derivative (PID) and sliding mode control (SMC). The controllers are evaluated based on the performance to generate the drive torque and reduce the error of the system in tracking the desired target angle accurately. The simulation result shows that the SMC controller has advantages of high precision and accuracy for tracking the trajectory of firing angle. A comparison between PID and SMC is also presented to indicate the effectiveness of the SMC controller in terms of tracking performance and firing accuracy.

Keywords:

Gun turret modelling, control strategy, gun turret target tracking, modelling and simulation

1. Introduction

The gun turret is the mechanism of a projectile firing weapon and it can simultaneously be aimed and fired in many directions. The gun platform and turret elevation mechanism is driven by hydraulic system. The hydraulic system is an

* *Corresponding author: Department of Mechanical, Faculty of Engineering, National Defense University of Malaysia, Kem Sg. Besi, 57000, Kuala Lumpur.*
Phone: +6012-7349488, E-mail: sabirin.rahmat@gmail.com

efficient system for military purposes to produce rotational motion of gun platform and to elevate the turret to aim the target. However, the system has several disadvantages, which are high maintenance cost, complex system and compensated energy efficiency due to fluid flow resistance and leakage along fluid transmissions.

Due to the drawback of the hydraulic system, military researchers have been using electrical system to drive the gun platform and turret elevation, where an electric motor is utilized as an actuator. Previous works have given positive feedback in using electrical system [1]. At the initial stage of the development of the system, the gun turret should be modelled and simulated. Many researchers have done their modelling and simulation for the gun turret system for armoured vehicle such as [2]. To improve the electrical system, especially the electric motor, a control strategy is employed into the system. The implementation of the control strategy can enhance the performance of the system.

The gun turret control system is an imperative part of the fire control system and specifically on its tactical and technical performance. Therefore, an efficient control system produces accuracy, stability and speed of response to trace the target. Considerable work has been done on the design of gun control system, i.e. variable structure control [3], back-stepping control [4], adaptive control [5], model predictive control [6], fuzzy control [7] and robust control [8]. Tao et al. (2001), [9] proposed the use of optimal control scheme for backlash and nonlinear feedback control for control of nonlinear dynamics. The control scheme was implemented on a gun turret-barrel system. Meanwhile, Kumar et al. (2009), [10] studied the disturbance problem for linear gun turret model using model predictive control (MPC) due to its ability to handle constraints. And more recently, Nasyir et al. (2014), [11] discussed various control methods for automatic turret gun (ATG) in cancelling the disturbance.

In this study, the modelling, simulation and control for gun turret of armoured vehicle is proposed. The detailed derivation of the gun turret modelling is constructed to examine the performance behaviour of the gun turret. MATLAB-Simulink software is selected as the simulation tool to simulate the model behaviour and assess the effectiveness of the control structure. The PID controller and sliding mode control (SMC) are employed as the control strategy of gun turret to measure the performance and effectiveness of the controller in tracking the target according to the desired target angle. The performances of the two controllers indicated in the response are compared to evaluate its effectiveness in controlling the torque of the electrical motor to actuate the gun platform and barrel. In this system, the desired input is estimated by analysing the projected projectile motion without air resistance. From analysing this, platform azimuth angle and elevation angle can be estimated.

This manuscript is organized as follows: the first section contains the introduction and review of some related works, followed by the estimation of ideal firing angle for gun turret in section two. The third section presents the gun turret modelling, including the implemented control structure into the system. The next section presents the simulation result of the effectiveness of the PID and SMC controller in controlling the angle of azimuth and elevation of gun turret by using the electric motor. Lastly, conclusion of this paper is given in the final section.

2. Gun Turret Modelling

In this study, the mathematical modelling of gun turret system is derived based on two degrees of freedom (2 DOF) model of a small scale gun turret system illustrated in

Fig. 1. The two degrees of freedom consists of rotational azimuth angle, θ, and gun elevation angle, α.

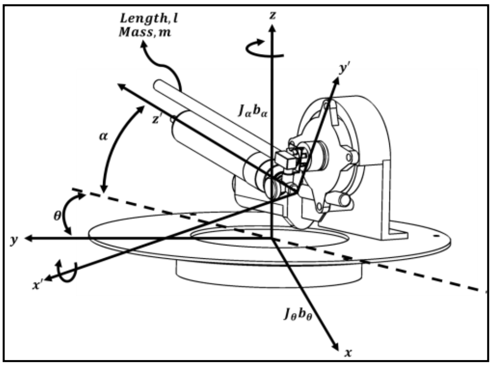
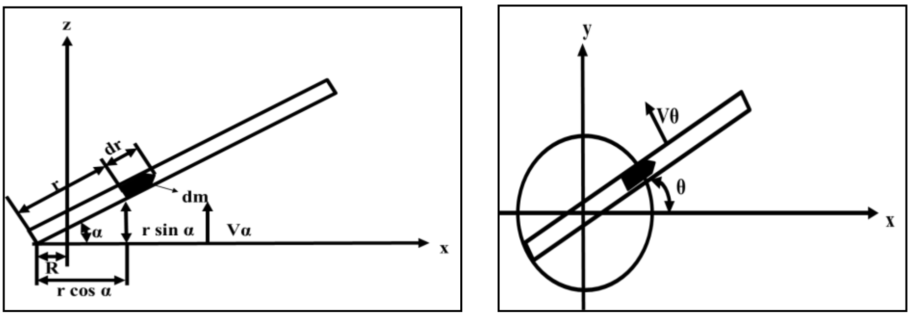


Fig. 1 Gun turret design

In Fig. 1, there are two main parts on the gun turret system, which are the gun platform and turret system. The gun platform produces the rotational angle in azimuth while the turret system provides the elevation angle. In order to derive the mathematical modelling for gun turret, schematic diagrams depicting the design in two different planes are developed as shown in Fig. 2. The diagram considers the mass and length of the calibre that are used in this simulation while recoil force from the firing effect is neglected.



(a) x-z plane (front view) (b) x-y plane (top view)

Figs. 2(a) and 2(b) Schematic diagram for gun turret system

Figs. 2(a) and 2(b) indicate the general coordinates used to derive the equation of motion for the dynamic load of the gun turret system. However, the definition for each coordinates in Figs. 2 are defined as, *r*, denotes distance along the gun relative to centre rotation of turret, *R*, represents the distance from the centre of gun platform to centre of rotation of the turret, *dm,* defined the mass of an infinitesimal element of the projectile and, *dr*, serves as the length of the infinitesimal element along the gun. However, both θ and α represent azimuth and elevation angle respectively. The Lagrange mechanics is used to develop the mathematical model for the gun turret. To set up the Lagrange, the potential and kinetic energies for the system are expressed as a function of the general coordinates [12]. The potential energy of the projectile, E_p, along the gun turret of length, *l*, is derived as a function of general coordinates:

$$E_p = \int_0^l grd_m \sin\alpha , \tag{1}$$

$$= \frac{1}{2} mg \cdot \sin\alpha . \tag{2}$$

The total kinetic energy is given by the sum of the gun platform and turret kinetic energies. Here, ρ, is the density of calibre.

$$E_{ktotal} = E_{kBase} + E_{kBarrel} , \tag{3}$$

$$E_{ktotal} = \frac{1}{2} J_\theta \dot{\theta}^2 + \frac{1}{2} mR^2 \dot{\theta}^2 - \frac{1}{2} mlR\dot{\theta}^2 \cdot \cos\alpha + \frac{1}{2} J_\alpha \dot{\theta}^2 \cdot \cos^2\alpha + \frac{1}{2} J_\alpha \dot{\alpha}^2 . \tag{4}$$

The Lagrange is calculated as:

$$L = E_{ktotal} + E_p , \tag{5}$$

$$= \frac{1}{2} J_\theta \dot{\theta}^2 + \frac{1}{2} mR^2 \dot{\theta}^2 - \frac{1}{2} mlR\dot{\theta}^2 \cdot \cos\alpha + \frac{1}{2} J_\alpha \dot{\theta}^2 \cos^2\alpha + \frac{1}{2} J_\alpha \dot{\alpha}^2 - \frac{1}{2} mg \cdot \sin\alpha , \tag{6}$$

where,

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{\theta}}\right) - \frac{\partial L}{\partial \theta} = \sum T_{m,Base} , \tag{7}$$

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{\alpha}}\right) - \frac{\partial L}{\partial \alpha} = \sum T_{m,Barrel} . \tag{8}$$

The equation for the loads on the motor is defined by Lagrange equation of motion as in [13]

$$T_{m,Base} = \left(mlR\dot{\alpha}.\cos\alpha - 2.J_\alpha \dot{\alpha} \cdot \cos\alpha.\sin\alpha\right)\dot{\theta} + \left(J_\theta + mR\dot{\theta} - mlR\dot{\theta}\cos\alpha + J_\alpha \dot{\theta}\cos^2\alpha\right)\ddot{\theta} \tag{9}$$

$$T_{mBarrel} = J_\alpha \ddot{\alpha} - \left(\frac{1}{2} mlR \cdot \sin\alpha - J_\alpha \cos\alpha \cdot \sin\alpha\right)\dot{\theta}^2 + \frac{1}{2} mg \cdot \cos\alpha . \tag{10}$$

The mathematical modelling is simulated within Matlab-Simulink software to be used for the controller development purpose. General block diagram for the simulation of the gun turret system is illustrated in Fig. 3. The input of the Simulink diagram is the rotational torque of azimuth and elevation that is produced by the electric motor. The electric motor model will be discussed in section 4.1. The output of the simulation of this model is the azimuth and elevation angles.

3. Estimation of Ideal Firing Angle for Gun Turret

In this section, there are two desired inputs for control structure, which are azimuth and elevation angle. The desired angle of two systems is derived based on the three-dimension (3D) projectile motion equation. These two systems are developed to determine the accurate angle with a distance to the target. The detailed derivation of the two systems will be discussed, where each system includes the Simulink model. The 3D general coordinates for the projectile is shown in Fig. 4.

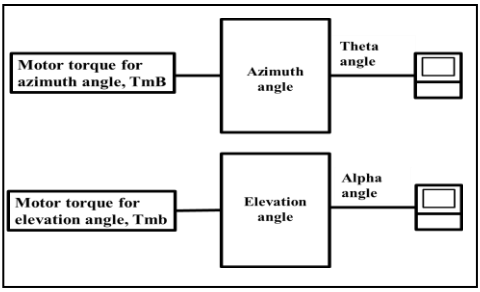


Fig. 3 Diagram for gun turret system

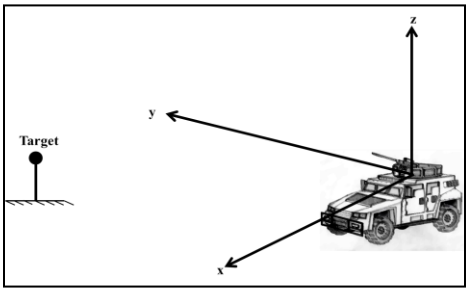


Fig. 4 3D projectile diagram

3.1. Ideal Azimuth Angle

The desired input of the rotational angle of gun platform is developed using the x-y plane as a reference plane for developing the equation of gun platform angle in order to move the turret parallel with the target. The projection rotational angle of the gun platform is explicitly illustrated in Fig. 5.

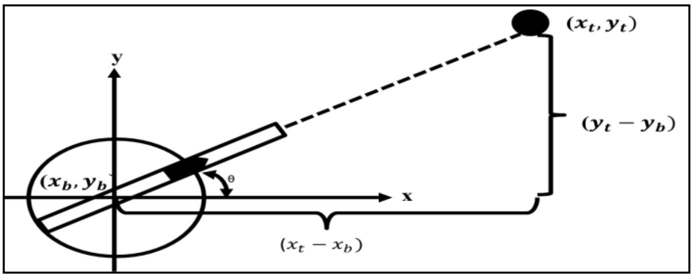


Fig. 5 Projection of desired azimuth angle

Based on Fig. 5, x_b and y_b represent the coordinate of gun platform while x_t and y_t denote the coordinates of the target. The trigonometry function was implemented to obtain the equation for desired angle. The equation of azimuth angle is as follows:

$$\tan\theta = \frac{y_t - y_b}{x_t - x_b}\,, \tag{11}$$

$$\theta = \tan^{-1}\left(\frac{y_t - y_b}{x_t - x_b}\right). \tag{12}$$

3.2. Ideal Elevation Angle

In this system, the desired input for gun elevation angle is calculated by considering a 2D projectile of the bullet on the x-z plane. A precise estimation of the required elevation angle is important to improve the accuracy of the bullet hitting the target and hence ensuring optimum precision of the armoured vehicle. The angle is then as the input to control the electric motor in producing the actuating torque in the elevating of the gun turret. Fig. 6 illustrates the ballistic trajectory to obtain the accurate elevation angle, α.

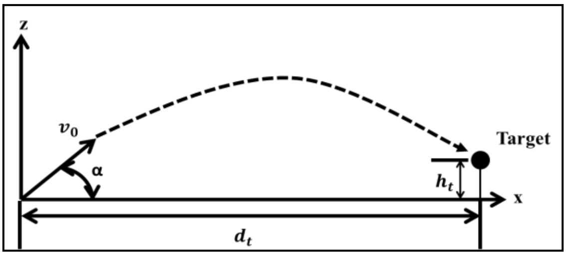


Fig. 6 Projectile of the calibre

To derive the equation of the projectile of ballistic trajectory, the basic equation of projectile motion is implemented to provide greater accuracy. The equation of the turret trajectory is defined as below:

$$d_t = V_o t \cdot \cos\alpha \ , \tag{13}$$

$$h_t = V_o t \cdot \sin\alpha - \frac{1}{2} g t^2 \ . \tag{14}$$

Solving (14) for t and substituting this expression in (15):

$$t = \frac{d_t}{V_o \cos\alpha}, \tag{15}$$

$$h_t = V_o \cdot \sin\alpha \left(\frac{d_t}{V_o \cdot \cos\alpha} \right) - \frac{1}{2} g \left(\frac{d_t^2}{V_o^2 \cdot \cos^2\alpha} \right), \tag{16}$$

$$0 = d_t \cdot \tan\alpha - \left(\frac{g d_t^2}{2V_o^2} \cdot \tan^2\alpha \right) + \left(\frac{g d_t^2}{2V_o^2} \right) - h_t \ . \tag{17}$$

Solving equation (19) to quadratic formula and defined the equation as given below:

$$\alpha_{12} = \tan^{-1} \left(\frac{-d_t \pm \sqrt{d_t^2 - 4\left(-\frac{g.d_t^2}{2.V_o^2} \right)\left(\frac{g.d_t^2}{2.V_o^2} - h_t \right)}}{2\left(\frac{g.d_t^2}{2.V_o^2} \right)} \right). \tag{18}$$

The final equation, α_{12}, generates positive and negative values of the elevation angles. So, the exact value of elevation angles is obtained based on the simulation result of the elevation turret angle, where the output shows a positive value.

3.3. Estimation of the Firing angle with Projectile Motion

In this study, the verification of the firing angle is assessed with the equation of the projectile. The equation is developed using the 3D projection. There are two cases that have been employed for the evaluation of the angle which are with and without air resistance. For the initial stage, in section 3.2, air resistance was neglected. The range of firing angle depends upon the initial velocity and elevation angle. Fig. 7 illustrates the effect of elevation angle, α, on the range of projectile.

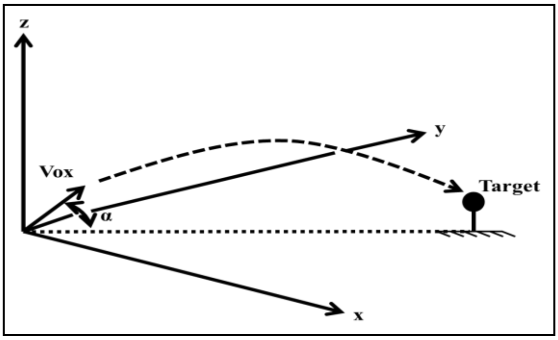


Fig. 7 Trajectory of projectile motion

The equation of the distance travelled can be developed by referring to Fig. 7. The equation is derived through the three axes, namely *x*, *y* and *z*, to examine the firing angle produced by gun turret. The angle is utilized to feed the input of the projectile model to ensure that the distance travel of the calibre and the set parameter of *x*, *y* and *z* is equal. The equation of the distance travel for the three axes can be derived as below:

$$x_t = V_o \cdot t \cdot \cos\theta \cdot \cos\alpha , \tag{19}$$

$$y_t = V_o t \cdot \sin\theta \cdot \cos\alpha , \tag{20}$$

$$z_t = V_o t \cdot \sin\alpha + \frac{1}{2} g t^2 . \tag{21}$$

The derivation of the equation considers 2 DOF that acts on the gun turret, i.e that the actuator will rotate the gun platform parallel to the target and the turret actuator elevates the barrel according to the required angle. Referring to the equation above, x_t, y_t and z_t represent the horizontal and vertical range to the target, V_o denotes the initial velocity while α, θ and g describe the gun elevation angle, azimuth rotational angle and gravity respectively. The value of x_t, y_t and z_t refers to the distance travel of the calibre to the target from the origin. Next, the equation will be developed in Matlab Simulink to verify the angle following the initial condition. The simulation parameters are tabulated in section 5.

However, the dependence of the horizontal range on the firing angle of the projectile in negligible air resistance is addressed by many introductory courses in mechanics. Since, in practice, some resistance should be presented, it ignites interest to evolve the solution of the projectile motion to include the drag force. The drag force is typically modelled as proportional to the projectile velocity (linear drag force) or projectile speed [14]. Therefore, the linear drag force model is approached to the real motion. The model has created a number of questions that have attracted attention and sometimes gives predictions that agree with observation [15].

In analysing the trajectory of a projectile with air resistance, the equation of motion can be derived according to the free body diagram as shown in Fig. 8. The projectile with air resistance is employed to verify the result of the projectile without air resistance effect. The result will show the difference between the two methods.

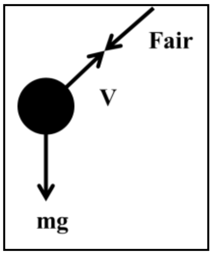


Fig. 8 Free body diagram of gravity and air resistance acts

The equations of motion of the linear projectile motion are [14]:

$$F_{air} = -k \cdot V_{ox}, \tag{22}$$

where k is the drag factor. These equations can be solved with the initial conditions

$$V_{ox}(0) = V_o \cdot \cos\theta \cdot \cos\alpha, x(0) = 0, \tag{23}$$

$$V_{oz}(0) = V_o \cdot \sin\theta \cdot \cos\alpha, z(0) = 0, \tag{24}$$

where v_o and θ are the initial velocity and the elevation angle respectively. The solutions of these equations are [14]:

$$x = \frac{m}{k} \cdot v_o \cdot \cos\theta \cdot \cos\alpha (1 - e^{-\frac{k}{m}t}), \tag{25}$$

$$z = -\frac{m \cdot g}{k} \cdot t + \left[\frac{m}{k} \left(v_o \cdot \sin\theta \cdot \cos\alpha + \frac{m \cdot g}{k} \right) (1 - e^{-\frac{k}{m}t}) \right]. \tag{26}$$

The initial conditions of the projectile are shown in Tab. 1:

Tab. 1 Initial condition

No	Description	Value
1	Initial velocity V_{ox}=V_o	82.7 m·s^{-1}
2	Distance target from origin on x-axis	241 m
3	Distance target from origin on y-axis	201 m
4	Heights of the target on z-axis	100 m
5	Drag factor, k	0.00002365
6	Initial azimuth angle, θ	40°
7	Initial elevation angle, α	32.5°

4. Control Structure of Gun Turret Target Tracking

In developing the complete system of gun turret, the control strategy for the gun turret actuator is designed. The control structure consists of two loops, namely inner and outer ones. Outer loop controller will control the rotating base and turret considering the target distance and the projectile analysis to estimate the required azimuth and elevation angles to move the gun turret. Meanwhile, inner loop controller governs the tracking control of the electrical motors in producing desired torques. The PID controller is implemented for inner loop control to control the rotating shaft of the motor while the outer loop control, the PID and Sliding Mode Control are employed to assess gun turret in tracking the accuracy of firing angle. Complete control structure is shown in Fig. 9.

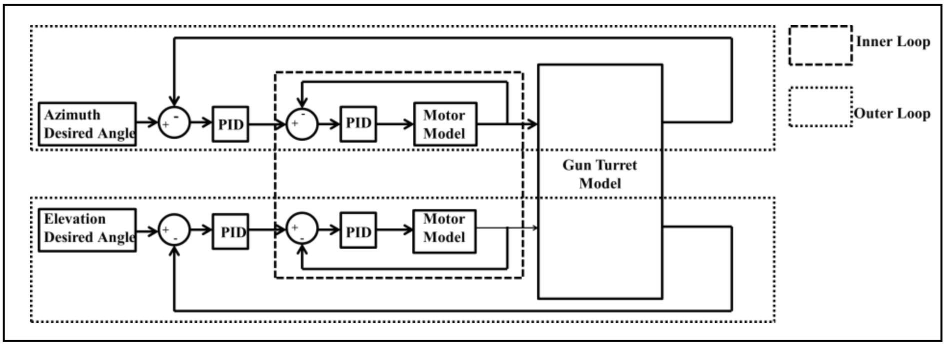


Fig. 9 Control structure for gun turret system

4.1. Inner Loop

The inner loop control is the electric motor control to provide the rotary motion for base and turret. The simple model Brushless DC motor is constructed to incorporate the gun turret system. The motor is widely used in applications requiring adjustable speed, good speed regulation, as well as frequent starting, breaking and reversing. In this study, the detailed derivation of mathematical model of gun turret is developed to ensure the capability of the motor to provide sufficient torque. To obtain a practical motor model simulation, the brushless DC motor for car power window motor specification is considered. The maximum torque and speed of the motor are 6 Nm and 163 revolutions per minute (RPM) respectively. The mathematical model for the motor is developed from the motor schematics diagram as shown in Fig. 10.

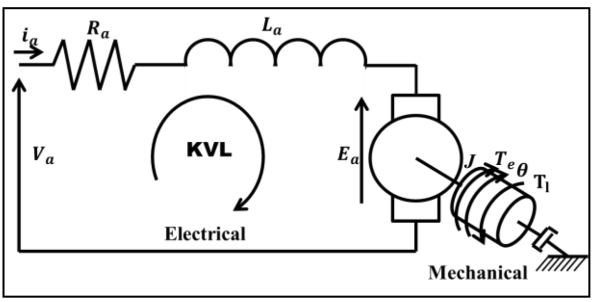


Fig. 10 DC motor schematic diagram

The motor torque, T, is related to the armature current, i_a, by a constant factor, K_t. The back emf, E, is related to the rotational velocity, ω, by the constant factor, K_e as in the following equations [16]:

$$T_e = K_t \cdot i_a , \tag{27}$$

$$E_a = K_e \cdot \omega . \tag{28}$$

The dynamic of the DC motor can be expressed as given:

$$V = R_a \cdot i_a + L_a \frac{di_a}{d_t} + K_e.\omega , \tag{29}$$

$$K_t \cdot i_a = J \frac{d\omega}{d_t} + B \cdot \omega + T_e . \tag{30}$$

From the equations (32) and (33), it can be defined by choosing the electric current, i_a, $R_a, L_a, K_e, K_t, T_e, J, B$ is constant parameter and rotational speed, ω, as an input and the output of the motor model. The state-space form is provided as below:

$$\begin{bmatrix} \dot{i}_a \\ \dot{\omega} \end{bmatrix} = \begin{bmatrix} -\frac{R_a}{L_a} & -\frac{K_e}{L_a} \\ \frac{K_t}{J} & -\frac{B}{J} \end{bmatrix} \begin{bmatrix} i_a \\ \omega \end{bmatrix} + \begin{bmatrix} \frac{1}{L_a} & 0 \\ 0 & -\frac{1}{J} \end{bmatrix} \begin{bmatrix} V \\ T_e \end{bmatrix} . \tag{31}$$

The equation above can be changed in terms of s-function by using Laplace Transforms. The armature current can be defined as below:

$$I_a(s) = \left[\frac{1}{L_a s + R_a} \right] \left[V(s) - K_e \cdot \omega(s) \right] . \tag{32}$$

Therefore, the equation of rotational speed becomes:

$$I_a(s) = \left[\frac{1}{Js + B} \right] \left[K_t . i_a - T_l \right] . \tag{33}$$

4.2. Outer Loop

In gun turret control system, there are two important components necessary to control in achieving high accuracy of firing angle, which are azimuth and elevation angles. The angles are calculated to gain the accurate angle to aim the target and the detailed derivation of ideal firing angle has been explained in section 3. Therefore, the angles are also controlled by the outer loop to provide the input for the inner loop control. The electric motor will be actuated based on the output of the outer loop control to produce the accurate firing angle to the target.

The outer loop control is employed to control the rotating angle in azimuth and elevation. In this study, there are two types of the controllers, namely PID controller and Sliding Mode Control (SMC), which are implemented to the system to determine the best controller by evaluating its performance in firing accuracy separately. The first order of sliding surface, σ, is defined as follows [17]:

$$\sigma = \dot{e} + Ce \tag{34}$$

where, e denotes the error; $\dot{e}$ denotes the error rate and C represents the constant value. The control input is given below.

$$u = -U\frac{\sigma}{|\sigma| + \varepsilon} \tag{35}$$

where ε denotes the boundary layer thickness which is to reduce chattering problem; U the design parameter. Fig. 9 indicates the completed diagram for the control system of gun turret that consists of inner and outer loops.

5. Simulation Parameter

In simulating the gun turret model and its control structure, few parameters were specified to accurately evaluate the system. The parameter is obtained based on the small scale design of the gun turret. The numerical values of the 2 DOF gun turret tracking are given in Tab. 2.

Tab. 2 Gun turret parameter

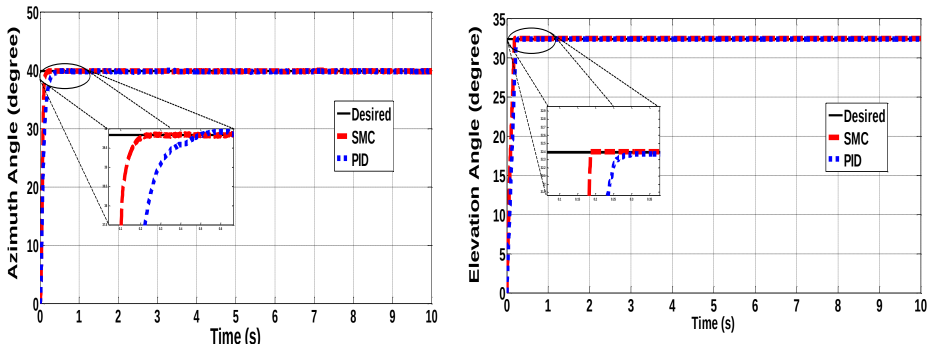
No	Description	Values
1	Moment inertia of gun platform, J_θ	0.05 kg·m^2
2	Moment inertia of turret, J_α	0.000875 kg·m^2
3	Mass of turret	0.145 kg
4	Length of origin of the turret to datum, r	0.0687 m
5	Length of origin of the turret to centre of gun platform, R	0.0045 m
6	Length of turret, l	0.2150 m
7	Gravity, g	9.81 m·s^{-2}

6. Simulation Result

In this section, the simulation result will be presented in two sections, which are gun turret tracking performance and firing accuracy. The gun turret tracking performance indicates the performance of the gun turret in order to track the high precision position of the firing angle. The ability and capability of the electric motor in tracking the desired input based on the distance of the target are also examined in this section. However, for the firing accuracy, two assessments are evaluated during firing; one is firing without air resistance and the other with air resistance. In that case, the equation of projectile motion is a reference of the assessment to verify the performance of the gun turret modelling for tracking and detecting the target to obtain high firing accuracy. In that case, the performance of the two controllers, which are PID and SMC, is evaluated. The evaluation is to compare the performance of the controllers in terms of response and capability to achieve the desired input.

6.1. Gun Turret Tracking Performance

The gun turret tracking performance is to assess the ability of the gun turret to achieve the desired angle of azimuth and elevation. The 3-dimension projection of target trajectory is a platform of the computational desired angle with the distance coordinates x, y and z. The performance of outer loop controller using PID and SMC controller in predicting the desired azimuth angle and elevation angle are shown in Fig. 13(a) and Fig. 13(b), respectively. Here, the observation is assuming ideal actuator by neglecting the inner loop controller. The result shows the comparison performance between two controllers, PID and SMC, to provide a rotational angle for gun platform. The desired angle for rotational gun platform is 40°. This value is generated by calculating the desired azimuth angle from Eq. 13 and the estimation of the distance parameter is based on the target location. From the result below, the graph indicates fast response for SMC and slower response for the PID, while both controllers represent the underdamp performance in tracking the desired input. The RMS values of azimuth angle for both controllers are similar. The small deviation has occurred in a second of time required to reach the desired angle.



(a) azimuth angle (b) elevation angle

Fig. 13 Controllers performance using ideal actuator

From the observation, the ideal desired angle of elevation for the gun turret is 32.5°. The angle is obtained from the calculation of the ideal elevation angle, equation 23 to equation 33. From the quadratic formula in section 2, the positive value is stated and negative value is neglected. However, the percentage of root mean square (RMS) for both controllers, PID and SMC is 32.2 and 32.4 respectively. Thus, the percentage error for the controllers is 0.06 %. However, the time required to reach the desired angle for SMC is 0.064 second and PID response is 0.17 second.

Fig. 14 (a) and Fig. 14(b) show the performance of outer loop controller in predicting the azimuth angle gun elevation angle, respectively. This time, the DC motor is considered and inner loop controller is employed. The inner loop controller will ensure DC motor to produce torque as predicted by the outer loop controller in rotating the gun platform and elevating the gun turret. From the result, the PID and SMC controllers represent the outer control of the system while the DC motor is controlled by a PID controller for inner loop control. The graph pattern for both controllers is likely similar showing underdamped system and has a percentage error of 10 % between two controllers. The times required for both controllers to reach the desired gun elevation angle are 0.05 and 0.15 seconds, respectively. Meanwhile, the times required for the torque tracking performance for the azimuth angle are 0.1 and 0.2 seconds, respectively. The RMS value in Fig. 14 (a) is 39° and 39.7 for PID and SMC, respectively with percentage error 20 %. Meanwhile, the RMS value in Fig. 14 (b*)* is 32.2° and 32.3° for PID and SMC respectively with percentage error 3 %.

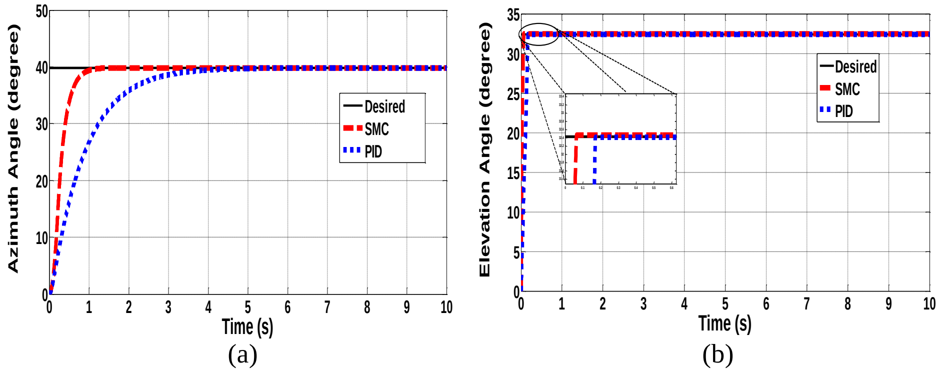


Fig. 14 Rotational angle of gun turret

6.2. Firing Accuracy

In firing accuracy result, the firing angle is obtained from the calculation and simulation before. The verification result is assessed to ensure the gun platform and turret has obtained accurate angle to the target aim. The projectile motion equation with and without air resistance are considered in this case to examine the accuracy of the angle trajectory to the target. The result is analyzed to measure the initial angle of turret produced compared to the accurate target distance when the coordinate is established. Fig. 15 illustrates the trajectory of projectile during firing without air resistance.

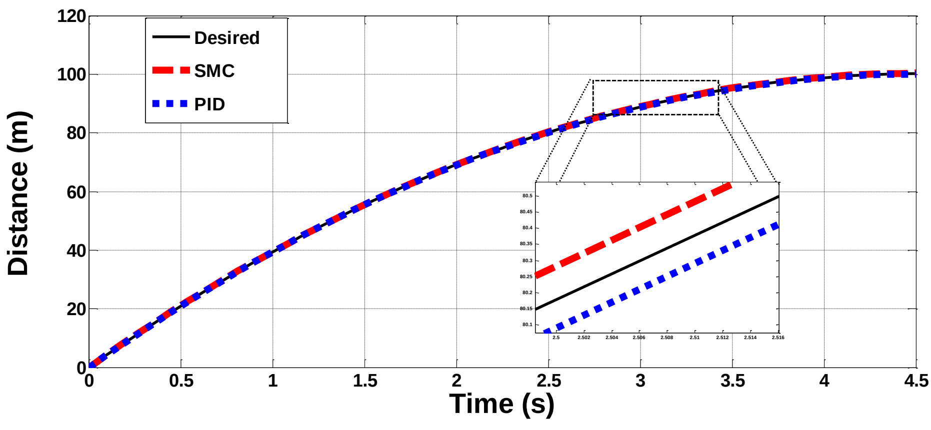


Fig. 15 Trajectory of projectile without air resistance

Based on the graph, the trajectory of projectile is evaluated to verify the distance traveled by calibre during firing. Fig. 15 (a) represents the trajectory of projectile motion in 3D. However, Fig. 15 (b) to (d) indicates the distance traveled by the projectile on the x-axis, y-axis and z-axis respectively. The effectiveness of the controllers to achieve the desired distance is assessed in order to compare againts the desired distance of the target. The small deviation occurred in the verification result since the two controllers is fine-tuned using the Nicholas Ziegler method. The performance of the controllers plays in important role in improving the rotational and elevation response of the gun turret. The distance deviation of the projectile trajectory is given in Tab. 3.

Tab. 3 The standard deviation of each axis using PID and SMC controller

Controller	Deviation on x-axis	Deviation on y-axis	Deviation on z-axis
PID	0.2 m	0.1 m	0.4 m
SMC	0.1 m	0.1 m	0.0 m

The result of the projectile trajectory with air resistance indicates that the simulation result for the distance traveled is relatively in good agreement as shown in Fig. 16. The result is analyzed to verify the performance of projectile with considered and neglected the air resistance. The performance is examined by using the two controllers, PID and SMC. Both controllers are also implemented into this two cases. The trend of the controllers is almost similar with small deviation where the SMC provided a better response. The performance of the controllers is assessed in term of RMS and percentage error. The maximum error in the angle of the projectile is 39.9° and 51.3° for SMC and PID controller, respectively. In terms of RMS performance, SMC controller can be achieved 99.99 meter of the distance in vertical displacement and 241.1 meter of distance travelled in x-direction. Meanwhile, PID controller manage to track the desired distance with RMS values of 99.96 meter in vertical displacement and 240.8 meter of distance travelled in x-direction. It can be concluded that the performance for both controllers are evaluated in term of firing accuracy, effectiveness and responses. However, all the criteria are showed similar performance result with acceptable error and has small deviation in achieving a desired distance to the target aim. The deviation of the RMS values is given in Tab. 4.

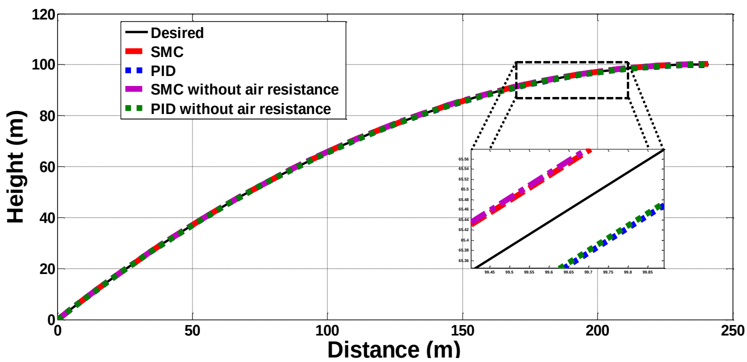


Fig. 16 The trajectory of projectile with air resistance

Tab. 4 Percentage error using RMS value for firing accuracy

Controller	Root Mean Square (RMS) Value		Percentage Error (%)
	With air resistance	Without air resistance	
PID	99.96	100.4	0.0034
SMC	99.99	100	0.0001

7. Conclusion

This paper presents the development of a gun turret system with its actuating DC motor. Also, this paper proposes a control structure to control the rotational elevation angle of the gun turret to achieve high precision in hitting a remote target. Simulation of the developed model and implementation of the control structure were carried out within Matlab-Simulink software. Both PID and SMC controllers were evaluated in this study where their performance in tracking the accurate firing angle was observed. In this case, the control structure of the gun turret system consists of inner and outer loops, where the desired target angle of the control system has been calculated to produce an accurate firing angle for the gun turret and actuated by DC motor. The DC motor model was designed to rotate and elevate the gun platform and turret, controlled by the inner loop controller while the outer loop control is to provide the desired target angle for the electric motor to rotate and elevate as required. Further, the verification of the firing angle was carried out using the projectile motion equation to verify the precision angle during firing. In the simulation result, the SMC controller performs better compared to the PID controller.

Acknowledgement

This work is supported by National Defence University of Malaysia through a scholarship and financial support under Long term Research Grant Scheme (L.R.G.S.) with project number LRGS/B-U/2013/UPNM/DEFENSE & SECURITY-P1 “Robust Stabilization of Armored Vehicle Firing Dynamics using Active Front Wheel Steering System”, led by Associate Professor Dr. Khisbullah Hudha. This financial support is gratefully acknowledged.

References

[1] Balaban, E. Saxena, A. Bansal, P. Goebel, K. F. Stoelting, P. and Curran, S. A diagnostic approach for electro-mechanical actuators in aerospace systems. In *IEEE Aerospace Conference Proceedings*, Big Sky: USA IEEE, 2009, p. 1–13.

[2] Balla, J. Double Motor Equipments in Guns Loading Systems 2 Problem Formulation. In *Proceeding of the 12th WSEAS International Conference on Automatic Control, Modelling and Simulation*, Wisconsin: USA ACM, 2010, p. 287–293.

[3] Dana, R. and Kreindler, E. Variable structure control of a tank gun. In *Proceedings 1992 The First IEEE Conference on Control Applications*, Dayton: USA IEEE, 1992, p. 1–6.

[4] Ji-Hong, Q. and Hong-Yan, W. Backstepping control with nonlinear disturbance observer for tank gun control system. In *2011 Chinese Control and Decision Conference (CCDC)*, Mianyang: China IEEE, 2011, p. 251–254.

[5] Petrov, P. Modeling and adaptive path control of a differential drive mobile robot. In *Proceedings of the 12th WSEAS international conference on Automatic control, Modelling and Simulation*, Wisconsin: USA ACM, 2010, p. 403–408.

[6] Varun, M. and Kumar, C. Problems in Electric Vehicles. *Int. J. Appl. Res. Mech. Eng.*, vol. 2, no. 1, p. 63–73, Jun. 2012.

[7] Jia, Z. Lihua, D. and Chen, J. Research on Man-Machine Function Allocation of Tank Fire Control System. *Adv. Mater. Res.*, vol. 580, no. 2, p. 160–164, 2012.

[8] Lin, S. and Goldenberg, A. A. Robust Damping Control of Mobile Manipulators. *IEEET ransactions Syst. Man, Cybern. B Cybern.*, vol. 32, no. 1, p. 1035–1041, 2002.

[9] Tao, G. Ma, X. and Ling, Y. Optimal and nonlinear decoupling control of systems with sandwiched backlash. *Automatica*, vol. 37, no. 1, p. 165–176, 2001.

[10] Kumar, G. Tiwari, P. Y. Marcopoli, V. and Kothare, M. V. A study of a gun-turret assembly in an armored tank using model predictive control. In *Proceedings of the American Control Conference*, St Louis: USA IEEE, 2009, p. 4848–4853.

[11] Moh Nasyir, T. Pramujati, B. Nurhadi, H and Pitowarno, E. Control Simulation of An Automatic Turret Gun Based on Force Control Method. In *IEEE International Conference on Intelligent Autonomous Agents, Networks and Systems*, Bandung: Indonesia IEEE, 2014, p. 13–18.

[12] Cederwall M. and Salomonson, P. An Introduction to Analytical Methods. *Egypt. Mummies Mod. Sci.*, vol. 4, no. 1, p. 133–161, 2009.

[13] Ahmad Abu Hatab, R. D. Dynamic Modelling of Differential-Drive Mobile Robots using Lagrange and Newton-Euler Methodologies: A Unified Framework. *Adv. Robot. Autom.*, vol. 2, no. 2, p. 1–7, 2013.

[14] Morales, D. A. Exact expressions for the range and the optimal angle of a projectile with linear drag. *Can. J. Phys.*, vol. 83, no. 1, p. 67–83, 2005.

[15] Chudinov, P. S. Approximate formula for the vertical asymptote of projectile motion in midair. *Int. J. Math. Educ. Sci. Technol.*, vol. 41, no. 1, p. 92–98, 2010.

[16] Chowdhury, D. Chattopadhyay, M. and Roy, P. Modelling and Simulation of Cost Effective Sensorless Drive for Brushless DC Motor. In *International Conference on Computational Intelligience: Modelling, Technique and Applications (CIMTA)*, Kalyani: India Elsevier, 2013, vol. 10, p. 279–286.

[17] Edwards, C. and Sarah, K. S. *Sliding Mode Control: Theory and Applications*. Taylor & Francis, 1998.