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Control Simulation of An Automatic Turret Gun Based on Force Control Method

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***Abstract*—Automatic Turret Gun (ATG) is a weapon system used in numerous combat platforms and vehicles such as in tanks, aircrafts, or stationary ground platforms. ATG plays a big role in both defensive and offensive scenario. It allows combat engagement while the operator of ATG (soldier) covers himself inside a protected control station. On the other hand, ATGs have significant mass and dimension, therefore susceptible to inertial disturbances that need to be compensated to enable the ATG to reach the targeted position quickly and accurately while undergoing disturbances from weapon fire or platform movement. The paper discusses various conventional control method applied in ATG, namely PID controller, RAC, and RACAFC. A number of experiments have been carried out for various range of angle both in azimuth and elevation axis of turret gun. The results show that for an ATG system working under disturbance, RACAFC exhibits greater performance than both RAC and PID, but in experiments without load, equally satisfactory results are obtained from RAC. The exception is for the PID controller, which cannot reach the entire angle given.**

Keywords:AutomaticTurret Gun (ATG); PID;RAC; RACAFC

I. INTRODUCTION

Combat vehicles are important component in the battlefield. Since the times of the World Wars many countries have been constantly developing ground combat vehicle (GCV), because of their speed and mobility to turn the tide of battle. Various researches has been conducted to improve the overall combat mobility, structural stability, and effectiveness of GCVs. Advances in the field of computing technology, robotics, and control systems have made it feasible and practical to design and develop more advanced ground combat vehicles

One of the latest additions to current generation GCVs is the Automatic Turret Gun (ATG). This technology removes the need of a human operator to directly control the movement of the turret. While being highly responsive and accurate with trained operator, the manual turret exposes the operator to risk of enemy fire. The ATG is designed to be remotely operated using joysticks and camera vision, safely from inside a protected control station. Two important aspects of ATG performance are accuracy and speed to reach the designated angle position.

Figure 1 shows an Automatic Turret Gun (ATG) developed by Korean Department of Defense. With two Degrees of Freedom in direction of azimuth and elevation, this turret gun is capable of targeting and firing upon a target at a distance up to 3 kilometers.

Fig.1 Automatic Turret Gun (ATG)

To reach such distance with satisfactory precision, accuracy, speed, and stability despite the inherent mechanical disturbance, an ATG needs a good control scheme. Various researches regarding stability control of a turret gun have been conducted for a long time. A very popular conventional control scheme which has been widely and successfully applied in various fields is the PID controller. It is generally accepted that 90 percent of current industrial equipment use this control method to operate within some extent since this controller was introduced. The characteristic **P** factor function as the gain to accelerate in reaching the targeted set point, **D** factor to deal with error rate by summing + and - error, and also **I** factor to handle steady state error, make it possible to work in virtually any kind of plants, including ATGs. However, if the system requires very high degree of accuracy and precision, sometimes PID controller is not an adequate solution. But for initial analysis in identifying the system characteristics and for knowing what control scheme needs to be chosen or added, using PID controller is preferable.

Ref. [1] used PID controller in comparison with proposed method active disturbance rejection control (ADRC) which compared the response of speed control and position control. Under same parameters, simulation results of ADRC control system and PID control system show that the ADRC controller has better dynamic performance and higher rejection ability in presence of disturbances. Other researcher[2] used a novel Disturbance Observer (DOB)-based Fractional Order PD (FOPD) control scheme to develop gun control equipment (GCE). By adopting the DOB, the control system behaves as if it were the nominal closed-loop system in the absence of disturbances. As a result in speed tracking, the tracking error of the system with the DOB is $\pm$0.5 mil or 26.32% better than the reference system without DOB and demonstrated that the proposed DOB-based FOPD control strategy can work efficiently. For the same purpose of stabilizing the turret gun, other research has applied the same method with different approach. As the systems design of a turret gun becomes more complex with additional payload and functionalities, the system can be approached as a multi-input and multi-output (MIMO) system. Ref. [3] proposed a Fuzzy Logic Controller (FLC) to work with such kind of system, in regard of the system being affected by disturbances, nonlinearities, and uncertainties. The results demonstrated that this approach could improve the rising time and mitigate the overshoot.

II. RESOLVED MOTION CONTROL AND FORCE CONTROL

A. Resolved Motion Control (RMC)

Resolved motion control (in robotics) means that the motions of the various joint or degrees of motors are combined and resolved into separately controllable motions along the world coordinate axes [4]. This implies that the motors must run simultaneously at different time-varying rates in order to achieve the coordinated motion in the workspace. In general, there are two types of RMC, namely the Resolved Motion Rate Control (RMRC) and Resolved Motion Acceleration Control (RMAC) or simply RAC. Fig. 2 show the schematic diagram and RAC.

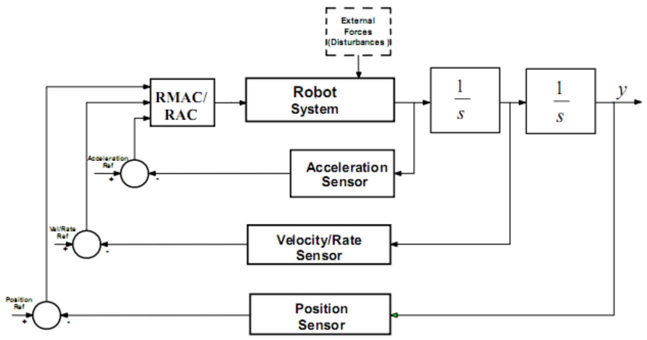


Fig.3 Schematic diagram of RMAC/RAC

From fig. 2, by removing the acceleration the system becomes RMRC. It can be seen that RMRC employs both position and velocity as feedback. This is one of the simplest methods incorporated with other control scheme [5][6][7]. The actuation signal is stated in eq. 1

$$u(t) = kp.\left(\theta_{ref}(t) - \theta_{act}(t)\right) + kd.\left(\dot{\theta}_{ref}(t) - \dot{\theta}_{act}(t)\right) + ka.\left(\ddot{\theta}_{ref}(t) - \ddot{\theta}_{act}(t)\right) \qquad (1)$$

RAC uses additional feedback 'acceleration' in the control loop. The purpose of adding acceleration as a feedback is to compensate the effect of inertia as the system with dynamics is even harder to control.

B. Active Force Control (AFC)

As the aforementioned that the system is affected by the presence of disturbances which affects the actuator as external torque, thus the research begins to occupy inertia. AFC is a method which is close to this concept. The schematic diagram of AFC is shown in fig. 3.

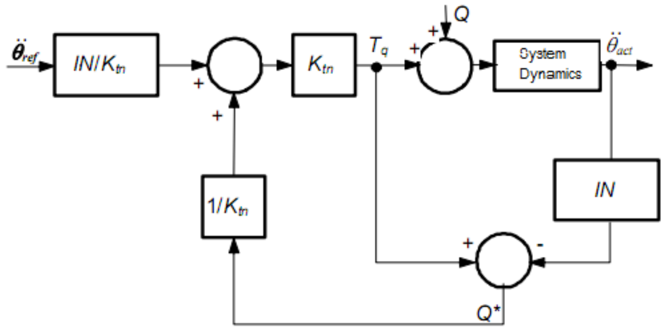


Fig.3 Schematic diagram of AFC

AFC works by continuously monitoring torque applied by actuator compared to actual torque after the present of disturbance. From Fig.4 $\ddot{\theta}_{act}$ is the reference acceleration signal(s), K_{tn} is motor torque constant, T_q is the torque applied, Q are known and/or unknown (bounded) internal and external disturbances including payload, Q^* is the disturbances observed, and IN is the estimated inertia matrix. By using this concept the applied disturbance is estimated more easily by calculating acceleration using accelerometer sensor and estimating matrix of inertia. Here, the mathematical complexity is reduced. Then the difference between current and actual torque can be used as a feedback on how much torque from actuator should actually give.

AFC comes from the basic Newton's second law for rotating mass, where

$$\sum \tau = I\ddot{\theta} \qquad (3)$$

The recommended torque will be as follow

$$\tau + Q = I(\theta)\ddot{\theta} \qquad (4)$$

Where τ is the applied torque, $I(\theta)$ is mass moment of inertia, θ is the joint angle, and $\ddot{\theta}$ is the angular acceleration. A measurement of $Q'$of Q can be obtained as

$$Q' = I'\ddot{\theta}' - \tau' \qquad (5)$$

The superscript ' denotes a measured, computed or estimated quantity. I' maybe obtained by assuming a perfect model, crude approximation method or by any other suitable means. AFC deeply rely on estimating matrix of inertia that is used to trigger to compensating action of the controller. Several methods such as fuzzy logic [8], neural network [9], knowledge based system [10] were successfully applied for this purpose as AFC succeeded to solve the problem of mobile manipulator, wheeled mobile robot, two link arm robot and so on [9][11][12].

III. SYSTEM MODELING

The system model is based from the basic dynamic equation stated as follow:

$$D(\theta)\ddot{\theta} + C(\theta,\dot{\theta})\dot{\theta} + G(\theta) = \tau \qquad (6)$$

Where τ is the torque, $D(\theta)$ is matrix of inertia, $C(\theta,\dot{\theta})$is coriolis and centrifugal force, and $G(\theta)$ is gravity loading force. Fig. 5 shows the simplification of a turret gun.

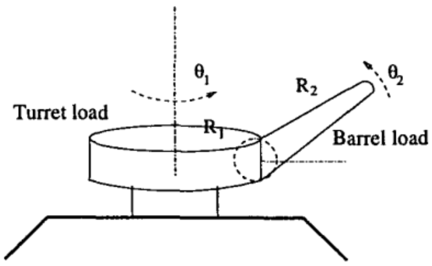


Fig.4 Coordinate of turret gun [4] [14]

As mentioned before, the system consists of two component, turret and gun. Each component is driven by an actuator (motor). Parameter as mass, radius, and angular position are used for the turret. Similarly parameter as mass, radius, and angular position are used for the gun. From [4] [14] we got several equation as follows:

$$\theta = [\theta_1, \theta_2]^T, \tau = [\tau_1, \tau_2]^T \tag{7}$$

$$D(\theta) = \begin{bmatrix} D_{11} & 0 \\ 0 & D_{22} \end{bmatrix}, C(\theta, \dot{\theta}) = \begin{bmatrix} C_{11} & C_{12} \\ C_{21} & C_{22} \end{bmatrix}, \tag{8}$$

$$G(\theta) = \left[0, \frac{1}{2} m_2 g R_2 \cos\theta_2\right]^T \tag{9}$$

$$D_{11} = \frac{1}{2} m_1 R_1^2 + m_2 R_1^2 + m_2 R_1 R_2 \cos\theta_2 + \frac{1}{3} m_2 R_2^2 \cos^2\theta_2$$

$$D_{22} = \frac{1}{3} m_2 R_2^2$$

$$C_{11} = -m_2 R_1 R_2 \cos\theta_2 \, \dot{\theta}_2$$

$$C_{12} = \frac{1}{3} m_2 R_2^2 \sin(2\theta_2) \, \dot{\theta}_1$$

$$C_{21} = \left(\frac{1}{2} m_2 R_1 R_2 \sin\theta_2 + \frac{1}{6} m_2 R_2^2 \sin(2\theta_2)\right) \dot{\theta}_1$$

$$C_{22} = 0$$

From equation (6) we can derive the equation to calculate torque for each component.

$$\tau_1 = D_{11}\ddot{\theta}_1 + C_{11}\dot{\theta}_1 + C_{12}\dot{\theta}_2 \tag{10}$$

$$\tau_2 = D_{22}\ddot{\theta}_2 + C_{21}\dot{\theta}_1 + C_{22}\dot{\theta}_2 + G(\theta) \tag{11}$$

In order to get acceleration, velocity, and position then we should modify into the following equation:

$$\ddot{\theta}_1 = \frac{\tau_1 - C_{11}\dot{\theta}_1 - C_{12}\dot{\theta}_2}{D_{11}} \tag{12}$$

$$\ddot{\theta}_2 = \frac{\tau_2 - C_{21}\dot{\theta}_1 - C_{22}\dot{\theta}_2 - G(\theta_2)}{D_{22}} \tag{13}$$

From eq. 9 and eq. 10 we can arrange the SIMULINK model of ATG as seen in fig. 5.

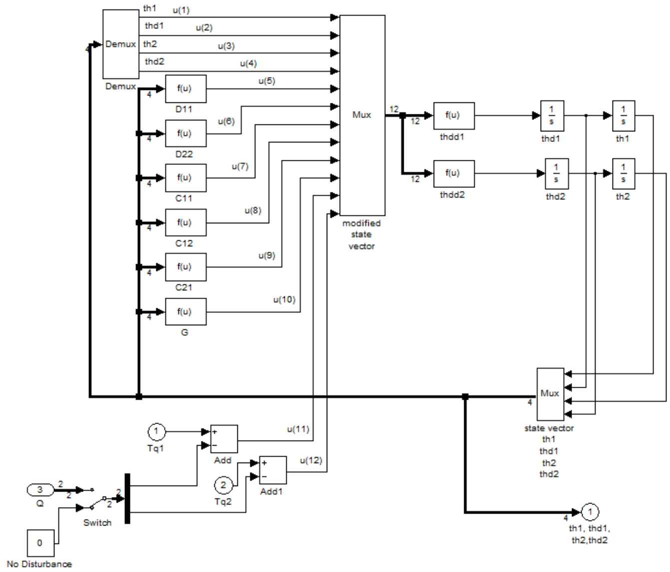


Fig.5 SIMULINK model of ATG

Fig.5 depicts that the inputs of dynamic system of ATG are notated as $Tq1$ and $Tq2$ represents torque for motor turret and motor gun. The present of external disturbances is notated as Q. the output of dynamic system is acceleration, velocity, and position each for turret and gun.

IV. Simulation of Control of ATG

This chapter discusses the method and result of several simulations conducted by using several proposed control method. Each method is simulated both with and without load/disturbance. The simulation parameter is listed below:

Parameters of ATG:

Radius of turret (r_1)	: 0.25 m
Length of gun (r_2)	: 0.135 m
Mass of turret (m_1)	: 75 kg
Mass of gun (m_2)	: 25 kg

A. PD Controller

Fig.6 shows the SIMULINK block of PD controller for ATG. The input is position azimuth and elevation respectively for turret and gun. Each input separately goes to subsystem PD controller, then goes to block of dynamic system considered as torque.

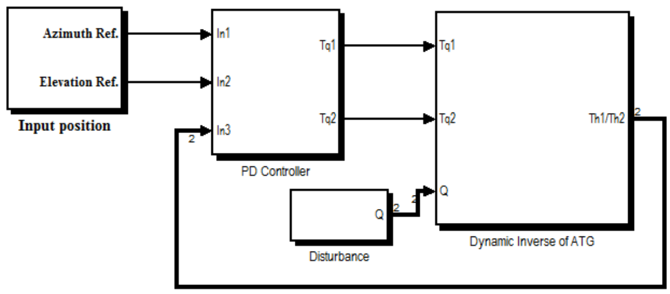
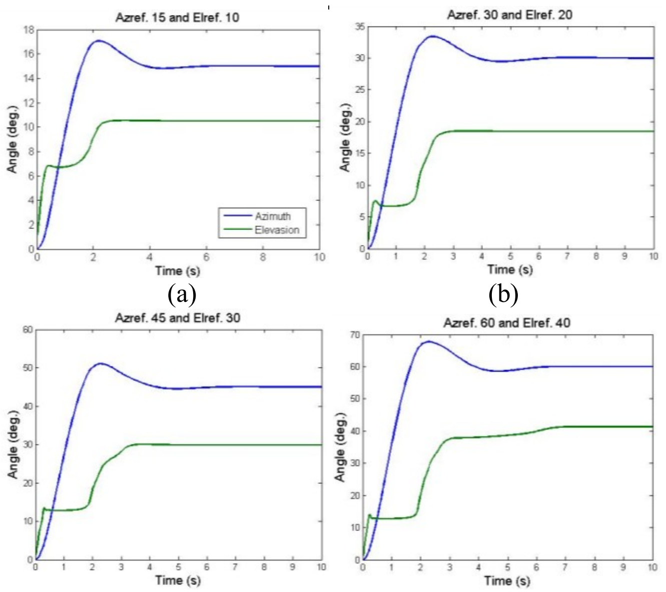


Fig.6 SIMULINK block of PID controller

Some angular positions is tested in this controller with unit in degree. The results are shown in fig.7(a) to fig.7(d).



(a) (b) (c) (d)

Fig.7 Experiment result using PD controller

Parameter used in this simulation are P=10 and D=7 for turret and P=10 and D= 5 for gun.

B. *Resolved Acceleration Control (RAC)*

The second controller to be applied is RAC. In this scheme the input parameter of acceleration is left zero as considered that the system should not conduct any acceleration. The input is position plus velocity derived from position equation. Fig. 8 shows the SIMULINK control block of ATG. The result of simulation is shown in fig. 9(a) to 9(d).

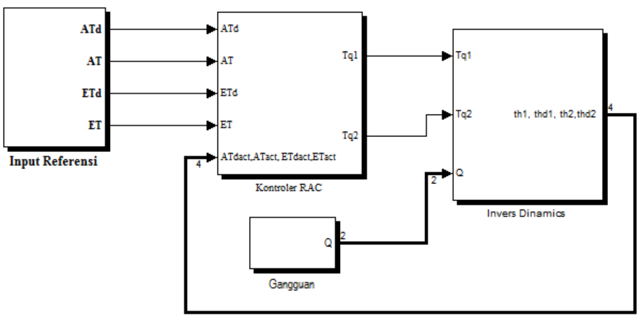
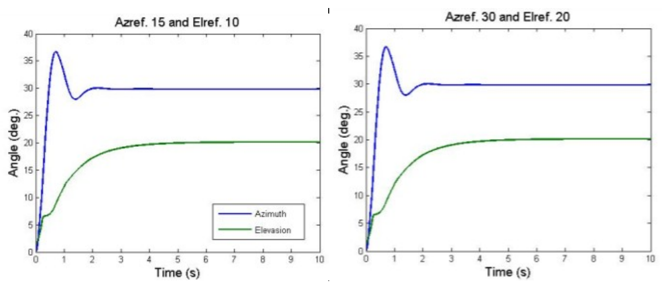
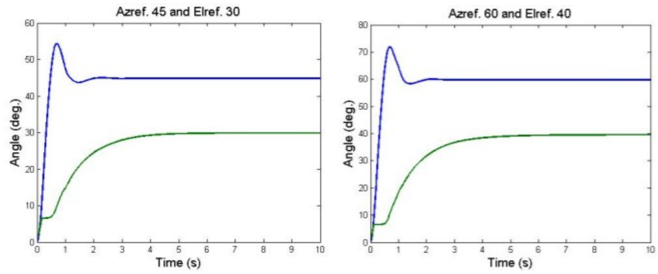


Fig.8 SIMULINK block of RAC



(a) (b)



(c) (d)

Fig.9 Experiment result using RAC scheme

The controller parameter respectively for turret and gun 100, 20 and 100, 102 each for position gain and velocity gain feedback.

C. *Active Force Control (AFC)*

AFC scheme with crude approximation (CA) method to estimate the mass of inertia is implemented. AFC is considered as inner loop control and for the outer loop we can use various controller which can be related to control plant. Here, we use RAC. the SIMULINK block of AFC scheme is shown in fig. 10. Fig. 11 depicts the experiment result of control ATG using AFC scheme.

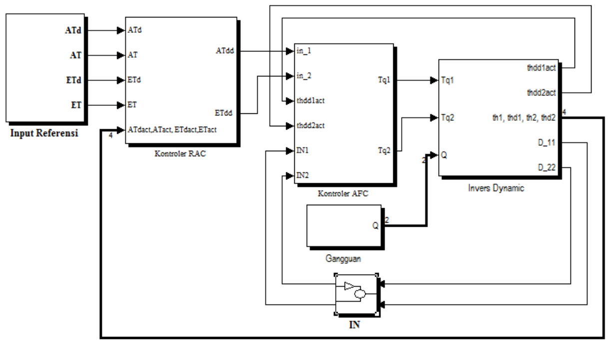
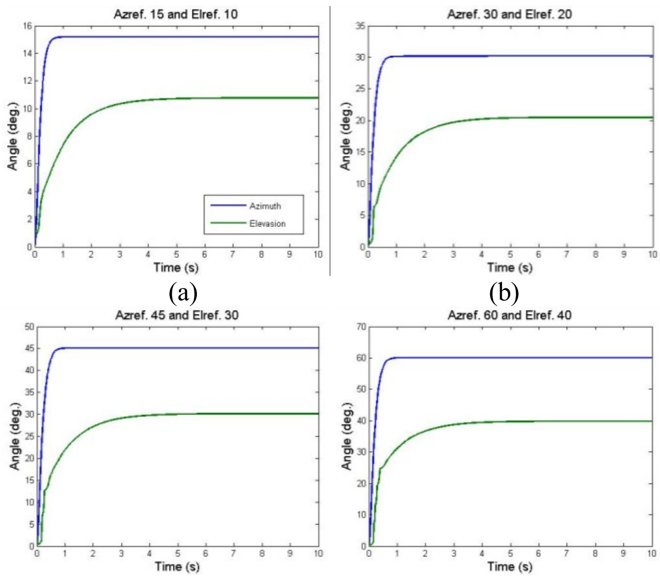


Fig.10 Experiment using RACAFCCA controller



(a) (b) (c) (d)

Fig.11Experiment result using AFCCA

As mentioned above that AFC is hugely dependent on the estimation value of inertia matrix (IN) due to disturbance acting on the dynamic system. Subsystem **IN** in fig.10 is a block where the estimation is placed. Here, we use 0.925 of IN. The following figure shows the steps of how to estimate the matrix of inertia using CA method.

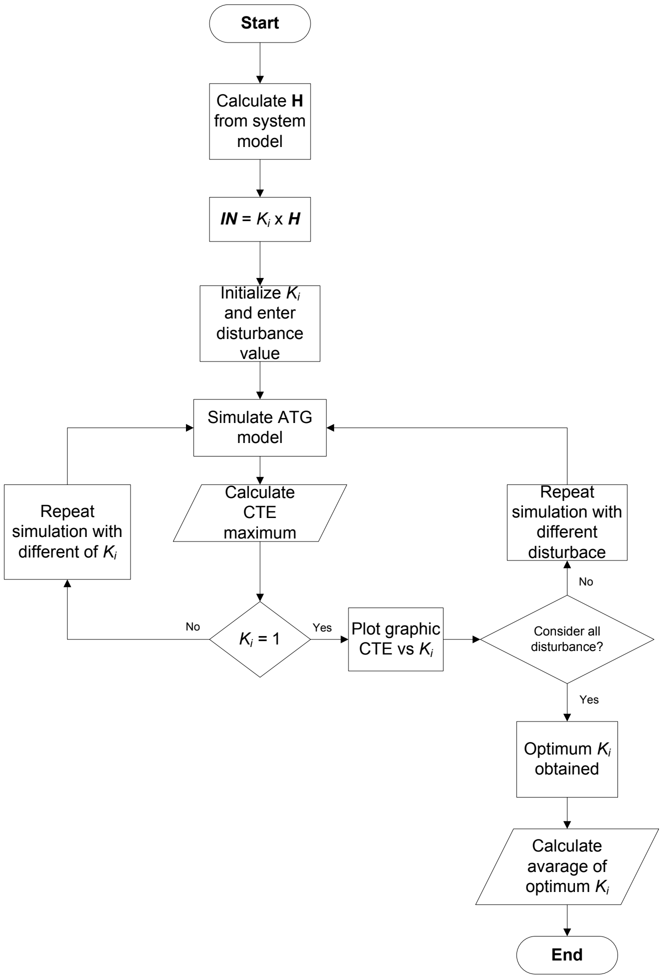
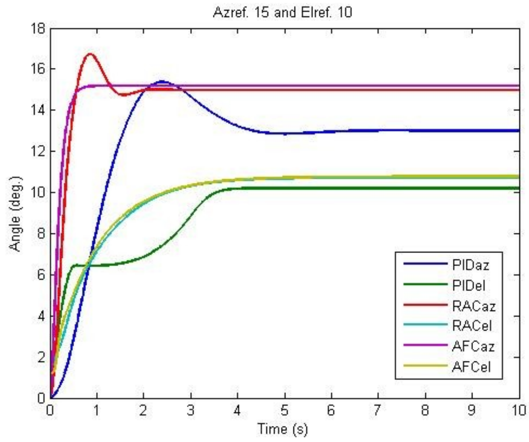


Fig.12 Experiment result using AFCCA

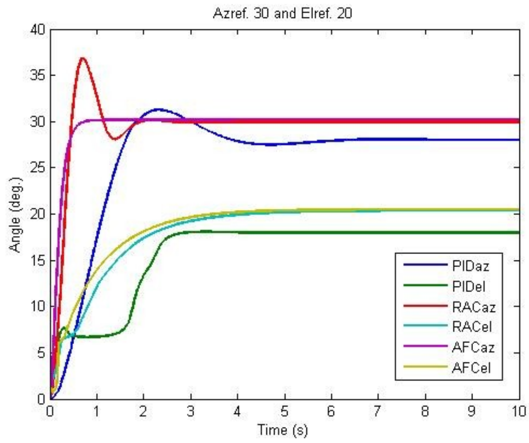
From fig. 12 parameter **H** is inertia matrix calculated from the mechanical structure, *Ki* is variable with value between 0 and 1 as multiplier to get the IN (estimated inertia matrix).

V. Simulation of Control of ATG with Disturbance

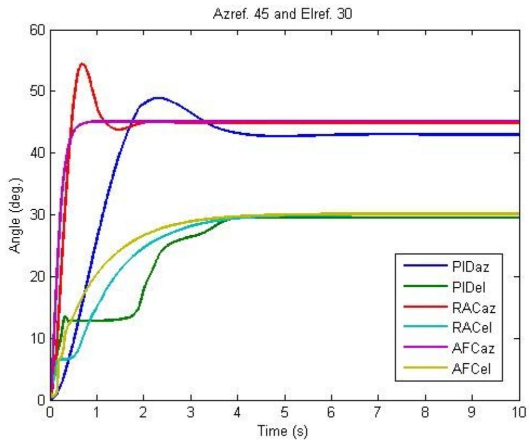
The actual performance of ATG in the battlefield with dynamic payload changes over time which can be considered as disturbance, such as ammunition, camera, grenade launcher, and other additional device/equipment. Not only carried load, but disturbance also comes from all terrain which cannot be guaranteed being flat all the way. All type of disturbances will of course affect the main turret and gun, in this term the change of mass of inertia of a system. Because of the change of parameter of inertia, the controller performance should be able to adapt or stay robust in such condition in order to maintain the target pointing and firing. In this section we will study the comparison of each controller for constant force or torque regarded as dynamic payload with limitation that the vehicle where ATG is attached is not moving. Its value can be adjusted to find maximum condition where the controller cannot perform accurately and/or precisely, or where the speed is degraded out of required specification. With the same outer loop control parameter, in this section the simulation disturbance is set each for turret and gun 30 Nm and 20 Nm. The result is shown in fig.13 (a) to 13 (d). From Fig.13, this needs to note that index az and el respectively stand for azimuth and elevation.



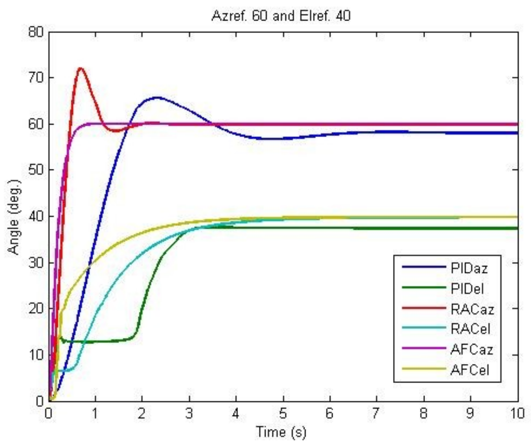
(a)



(b)



(c)



(d)

Fig.13 Controller performance with disturbance

VI. Result and Discussion

Several simulations have been performed in order to compare different control method applied in ATG with purpose as mentioned above. For a system with high inertial effects, PD controller lacks the required performance. This can be seen from simulation result in fig.7 (a) to (d) which indicated overshoots in azimuth movement and erratic movement in elevation. Besides, time response to reach target takes approximately 3 – 6 seconds both for azimuth and elevation. On the other side, RAC shows a noticeable improvement in performance compared to previous method (PID). With improvement in time response to 2 and 5 seconds, it demonstrated both faster and more precise movement. Turret undergoes significantly lower overshoots, in trade-off with slightly longer response time. The superior performance in this simulation is shown in fig. 11 (a) to (d), control ATG using AFC method. By combining RAC with AFC, this method has completely eliminated overshoots, and also improved the response time for reaching the targeted angle. It shows that the system is able to reduce time to 1 and 4 second.

The next section is the simulation of ATG control with added external disturbances. External disturbance can be considered as additional payload which can change over time. For simplicity, disturbances caused by such kinds of payload are represented by constant additional force/torque. Fig. 13 (a) to (d) depicts the simulation result. It can be seen that within range of disturbance RACAFC shows superiority in performance without being affected by external disturbances. On the contrary, the performance of PD controller is adversely affected by showing increases by 2 to 3 degrees in error. The same performance as RACAFC is conducted by RAC. The figures show that RAC method is not affected by disturbance. It performs equally well in fully loaded and unloaded condition. In other word, the RACAFC controller is able to gracefully handle the added disturbances. Interestingly, after further investigation by adding value of constant torque, AFC shows domination over RAC in terms of effect.

VII. Conclusion and Suggestions

Based on equation 12 and 13 the model simulation of Automatic Turret Gun (ATG) has been built in SIMULINK. Several simulations by using PD controller, RAC, and RACAFC have been performed according to the model. The result shows superiority of AFC above other methods by eliminating overshoot and smoothing the trajectory tracking. Moreover AFC has also showed some success in cancelling disturbances. As mentioned before that the performance of AFC depends on the estimation of mass matrix. Here,a crude approximation method based on trial and error has predicted the optimal value of **IN** by 0.925 of *Ki*.

The estimation of **IN** in the loop of AFC based on CA method is done by trial and error, thus the estimation process takes longer as it is done manually. It is suggested that several intelligent methods could be applied in order to estimate **IN** online and faster based on learning systems.

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