Setpoint Weighted PID Controller for the Electromechanical Actuator in Spacecraft

R. Sumathi[1] and M. Usha[2]

[1]Research Scholar, Anna University Chennai, Tamil Nadu, India

[2]Professor & Dean (Research), Sona College of Technology, Salem, Tamil Nadu, India

[1]elakkiyasumi@gmail.com

[2]ushaanu@ieee.org

Abstract—An intelligent control system for the rocket engine during electromechanical stage is designed and scrutinized in this paper. The rocket is the only vehicle that lift-offs the spacecraft in the space. But, the motion of the rocket can be influenced by internal and external disturbances. Furthermore, the rocket is a multi-input and multi-output nonlinear system whose dynamics are unstable and poorly understood. So the orientation of the spacecraft in precise position is so critical. Hence, attitude control of the rocket is a big challenge with real time. To make the rocket stable against the influences, this paper has examined the control technology such as linear quadratic regulator theory and setpoint weighted proportional integral derivative controller based on the two degree of freedom mathematical model. The transient behaviour of the LQR controller is not smooth and takes more time to settle in the defined position. Specific to the deficiencies of LQR, a setpoint weighted PID controller is proposed to improve the setpoint response. In conclusion, this paper compares the performance analysis of linear quadratic regulator and setpoint weighted PID controller. The simulation results indicate that the setpoint weighted PID controller has a remarkable improvement in terms of overshoot and settling time besides reducing steady state error. The proposed setpoint weighted PID controller enhances the system performance and produces enormous stability to the rocket engine.

Keyword-Setpoint weighted PID, LQR, rocket, attitude control, MATLAB/Simulink

I. INTRODUCTION

Rocket attitude control has been an active research topic for quite sometime. The rocket produces pitch and yaw motions by gimballing the exhaust nozzle. In a gimbaled thrust system, the thrust direction can be controlled by controlling the nozzle gimbal angle so that the rocket can be launched in the exact path. The parameters which characterize the dynamics of the rocket are usually an approximation [1] and this leads to ambiguity in the empirical representation. Furthermore, a small perturbation kicks the rocket out of alignment and diminishes the stability of the rocket. Making the rocket stable requires some form of control system.

Many controllers on attitude controlling of satellites and rockets have been proposed but very few of these controllers can be applied to deal with many issues simultaneously. Debabrata Roy, Ragupati Goswami, Sourish Sanyal and Amar Nath Sanyal designed proportional-derivative feedback controller for pitch attitude control of a rocket [2]. However, here the interference and non-linearities have not been taken into account. Le Zhang, Shaojie Bi and Hong Yang proposed Fuzzy-PID control algorithm for attitude control of the helicopter model flight [3]. Venkata Narayana, Vidya Sagar Bonu and Mallikarjuna Rao designed fuzzy logic based intelligent controller for a non-linear satellite's attitude control [4]. Beni Kusuma Atmaja and Endra Joelianto proposed MIMO PID robust integral back stepping method to improve the stability of the rocket in the presence of wind disturbance. But none of these methods eliminate the overshoot entirely.

In spite of various advancements in process control techniques, till today proportional integral derivative controller is widely used due to its simple design and tuning [5]. Here an intelligent controller is required to control the rocket position which is a non-linear and time varying system. But, the PID controller is developed based on the linear control theory so that the controller provides inconsistent performances for different condition due to some non-linearities. Also PID controller requires a precise mathematical model of the rocket. So, the classical PID controller cannot achieve the desired control results for a nonlinear system [6] and it will produce more overshoot and steady state error. To improve the performance of the conventional PID controller, a new technique is needed. In order to overcome this problem, the setpoint weighted PID algorithm is the best controller [7] and it is introduced to control the rocket gimbal angle in this paper. The nonlinear rocket engine control system is designed by using another linear controller such as a linear quadratic regulator method. The performances of setpoint weighted PID controller are compared with LQR. Based on the excellent qualities, the proposed SW-PID controller produces less steady state error and very less overshoot which means that the stability of the rocket is magnificent.

II. PROBLEM STATEMENT

As mentioned above, the rocket gimbal angle control of pitch and yaw axis during electromechanical (EM) stage is more important for orientation of the spacecraft. This will be achieved by using engine gimbal control (EGC) system. The block diagram of the EM EGC system is shown in Fig. 1. The linear electromechanical actuators are mounted orthogonally for pitch and yaw axis control. The drive bar of the actuator is rigidly connected to the nut of the ball-screw and is attached to the engine with a gimbal. A Brushless DC torque motor which is powered by external battery supply is the driving element of the actuator. The motor is driven by pulse width modulator power amplifier. A high gain analog current loop around the PWM power amplifier with a bandwidth of the order of few KHz is used to ensure the linear power amplifier characteristics. A dual redundant linear variable differential transformer is used for sensing the actuator position. The output of the position sensor is the feedback to the controller which provides adequate relative stability and robustness to the system [8].

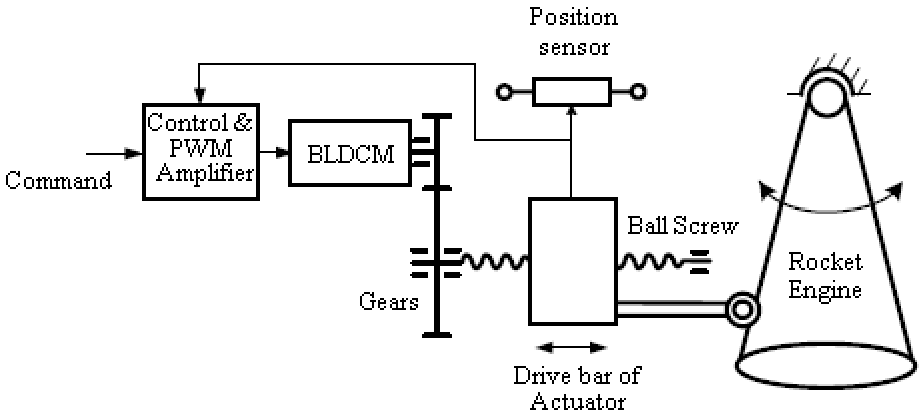

Fig. 1. Electro Mechanical Engine Gimbal Control System

The rest of the paper is arranged as follows: In section 3, a mathematical model of the EM EGC system is done. In section 4, LQR theory and setpoint weighted PID controller are designed and simulated. The results and the discussion on the results are shown in section 5. And the concluding work of the paper is presented in section 6.

III.EM EGC SYSTEM MODEL

A. BLDC torque motor current loop

The torque motor current is determined by the PWM power amplifier characteristics and current loop dynamics. Power amplifier remains in the linear zone as long as,

$$|R_m\, i_{mc} + K_b \omega_m| < V_s \qquad (1)$$

Once the above condition is violated, the power amplifier gets saturated and the current loop effectively gets opened. The motor coil inductance is neglected as the coil time constant is relatively small. Under this condition the coil current is,

$$i_{mc} = (V_s\, sign(V_i) - K_b \omega_m)/R_m \qquad (2)$$

Where, V_i, K_A, R_m, K_b, ω_m and V_s denote power amplifier input voltage, power amplifier gain which is the inverse of current loop sensor gain, DC torque motor coil resistance per channel, motor back EMF constant, angular velocity of motor and voltage applied across the coil. Let N_{ch} is the number of channels. Then the total motor current is,

$$i_m = i_{mc} N_{ch} \qquad (3)$$

B. Rocket Model

The mechanical portion of the EM EGC system is the rocket engine. Rocket is a non-linear, high order system with multiple inputs and multiple outputs that has unstable dynamics and sensitive to external disturbances.

In a rocket engine, the combustion chamber produces great amounts of exhaust gas at high temperature and pressure. It is passed through a nozzle which accelerates the flow and thrust is produced according to Newton's third law of motion. The nozzle of the rocket can be swiveled from side to side so that the direction of the thrust is changed relative to the center of gravity of the rocket. The rocket thrust is directed using two actuators. There will be some parameter variation in the linear models because of engine rotation. These effects are neglected because of small angles, so that the coupling between the dynamics of the two actuators is neglected [9]. The nozzle and actuator configuration for gimbal angle control is illustrated in Fig. 2.

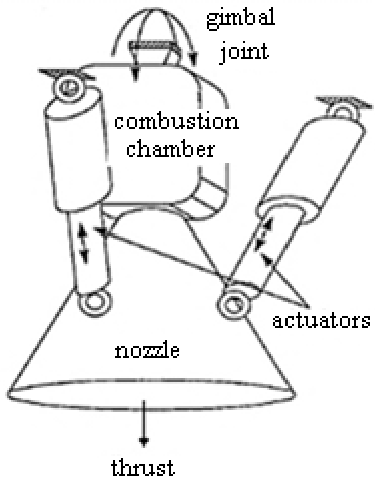

Fig. 2. Nozzle and Actuator placement

The model of the rocket engine can be attained by using its moment of inertia, rotational friction co-efficient and stiffness. The transfer function of the rocket engine is derived as (4),

$$G(S) = \frac{1}{526s^2 + 1000s + 100} \quad (4)$$

C. Electro Mechanical Actuator

The electrical portion of the EM EGC system is an electromechanical actuator. It is the driving element of the rocket which is the combination of brushless direct current motor and ball screw [10]. Brushless direct current motors have been proven to be the best [11], [12] in all around type of motors for aerospace applications.

The brushless DC motor is broken down into its essential dynamic elements such as inertia, back EMF and resistance. The load parameters such as moment of inertia, friction and stiffness are included in the load model. The driving amplifier is essentially an on-off switching network which is time modulated at the PWM frequency. The pulse width modulation block includes the appropriate non-linear switching circuitry. For power and heat considerations it is desirable to limit the voltage to the motor and thus voltage limiting is included. The specifications used in the simulation are given in Table I.

TABLE I.
Model Specifications

Device	Parameters	Description	Range
Rocket	J_e	Moment of inertia	526 *Kg-m*^{2}
	B_e	Frictional co-efficient	1000 *N-m*
	K_e	Stiffness	100 *N-m/rad*
PWM Amplifier	V_i	Input voltage	-10*V* to +10*V*
	K_A	Gain	1
Electro Mechanical actuator	N_{ch}	Number of channels	3
	R_m	Resistance per channel	1 *Ω*
	V_s	Voltage applied across the coil	-70*V* to +70*V*
	K_b	Back EMF constant	0.2
	J_m	Moment of inertia	2260e^{-6} *kg-m*^{2}
	B_m	Frictional co-efficient	0.15 *N-m*
	gr	Engine to DC motor gear ratio	293.01 *rad*
	lm	Lever arm length	0.56 *m*
	nb	Ball screw gear ratio	2e^{-3}/(2**pi*)

D. *MATLAB Simulink Model*

The Matlab/Simulink model without any controller is developed for analysis. The open loop electro mechanical actuator system which is presented in Fig. 3 is simulated. From the response, it is observed that the transient response is linear with the time and there is no control in the gimbal angle. An unstable rocket flies along an unpredictable path or sometimes falling. So, it is essential to design an intelligent control system for the attitude control of a rocket engine.

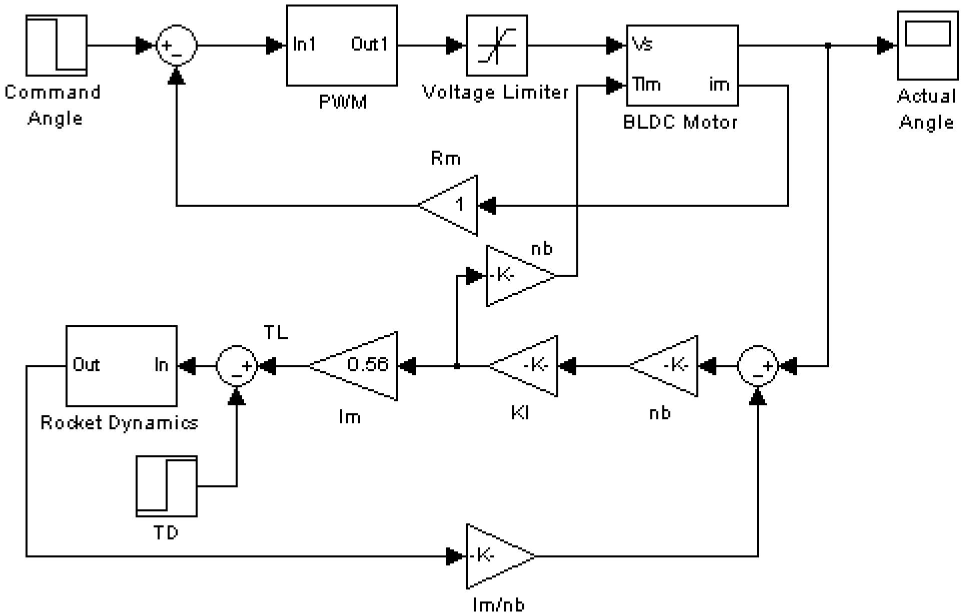

Fig. 3. Open Loop Electro Mechanical Actuator System

IV. Design of Controllers

A. Linear Quadratic Regulator

The optimal linear quadratic regulator method is a powerful technique for designing controllers for complex systems [13]. Here, the challenge lies in how the weighting matrices are chosen.

For the rocket engine gimbal control, an optimal displacement feedback control law is derived. Analytical expressions of the linear quadratic regulator feedback gains can be derived by using MATLAB command. The LQR design and analysis involve linearizing the nonlinear equations which describe the plant behavior and developing the state space model. The state space model together with an optimality criterion is used to control the engine gimbal angle.

1) Model Development and Analysis: For state space representation, the given nonlinear equations are presented in the state diagram with suitable blocks which are shown in Fig. 3. From this state diagram, by invoking the MATLAB command [*A B C D*] = linmod (‘filename’), the state space model of the given system is determined. The state space model of the electromechanical actuator system is,

$$\mathrm{A} = \begin{bmatrix} 0 & 0 & 1 & 0 & 0 \\ 0 & -0.2381 & 0.04762 & 0 & 0 \\ -7917 & 12.64 & -68.9 & 2321000 & 0 \\ 0 & 0 & 0 & 0 & 1 \\ 10.01 & 0 & 0 & -2936 & -1.908 \end{bmatrix}$$

$$\mathrm{B} = \begin{bmatrix} 0 \\ 0.2381 \\ 252.8 \\ 0 \\ 0 \end{bmatrix}$$

$$\mathrm{C} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \end{bmatrix}$$

$$\mathrm{D} = [0]$$

By using MATLAB commands, the taken system is tested whether it is completely controllable, observable and stable. It gives an optimistic result which means the EM EGC system is eligible for arbitrary pole placement [14].

2) LQR Control Law Development: The LQR development involves finding the optimal control law *u(t).* The design parameters have been chosen as,

$$Q = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

$$R = 1$$

Where Q is positive semi-definite matrix and R is strictly positive scalar. In MATLAB, [K p E] = lqr(A,B,Q,R) command calculates the optimal feedback gain matrix ‘K’ such that the feedback control law minimizes the performance index. The LQR controller simulink model developed based on the above design is shown in Fig. 4 and Fig. 5. In designing LQR, the control law *u(t)* and the matrices are selected as,

$$u(t) = [0\ K2\ K3\ K4\ K5]x + K1(r - x) \tag{5}$$

$$AA = A - B * K \tag{6}$$

$$BB = B * K1 \tag{7}$$

$$CC = C - D * K \tag{8}$$

$$DD = D * K1 \tag{9}$$

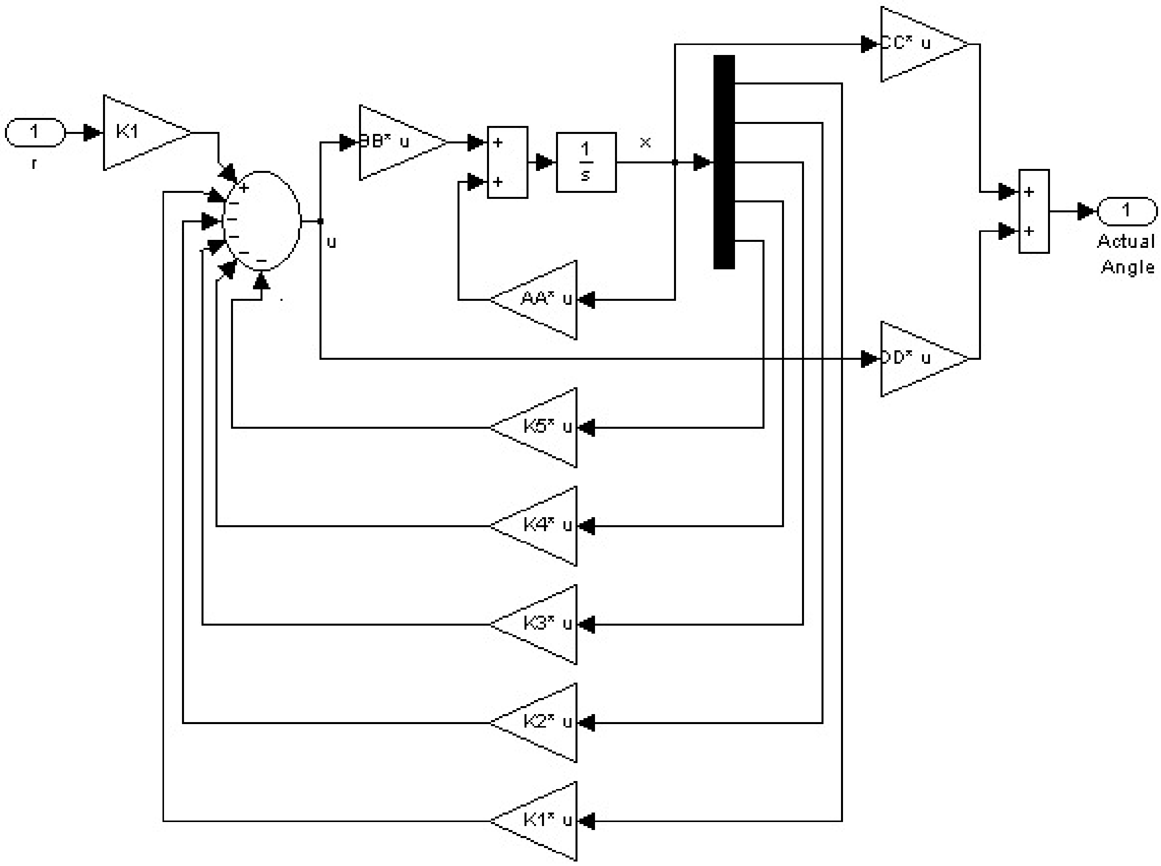

Fig. 4. Linear Quadratic Regulator

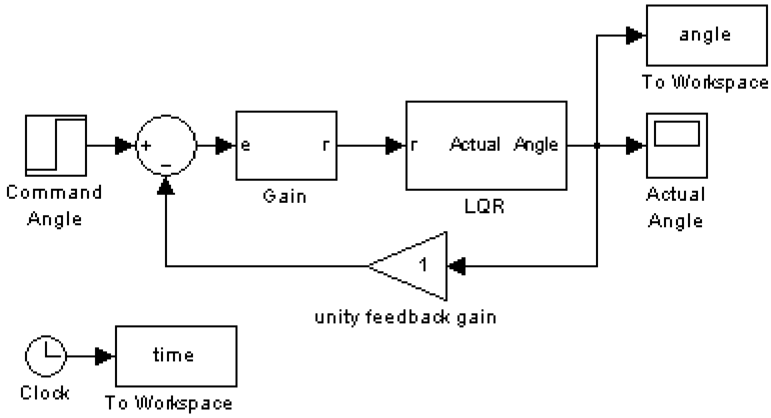

Fig. 5. Gimbal angle control by LQR

Here, the designing methodology is complex and choosing the weighted matrix, control law is difficult. Since it produces an oscillatory response at the initial time, the rocket will not be stable for sometime. Therefore, the system has a bad adaptability. Also, the linear quadratic regulator approach is more effective for linear systems. Since the rocket system is nonlinear, the LQR approach limits the performances. The drawbacks faced here is that the settling time is too high. Also it produces more overshoot and error. So, it is necessary to design an effective controller for this sensitive application.

B. PID controller

The majority of feedback control applications uses PID controller. This is because the implementation of PID controller is fairly easy to understand, build and tune [15]. But a common problem occurred in PID control is the noise produced by any real sensor which gives the measurement of the output shaft position. In rocket gimbal control system, the actuator position sensor is LVDT that produces a high frequency noise which implies that it has high values of derivatives of that noise. This results too large input to the plant. To avoid this problem, a first order low pass filter is placed on the derivative term and its pole is tuned. Since it attenuates high frequency noise, the chattering due to the noise does not occur. The final modified derivative term is,

$$G_{md}(s) = \frac{K_d N}{\frac{1}{N}s + 1} \tag{10}$$

Here another problem arises in PID control is the proportional and derivative kick in the controller results large overshoot and larger settling time. In order to reduce these effects and to improve the time response characteristics, it is essential to consider a two degree of freedom PID structure [16]. The setpoint weighted PID discussed by most of the researchers. In a closed loop system, it is necessary to track a constant reference called as the setpoint. The conventional PID controller is reformed into a setpoint weighted PID controller by introducing the parameter ‘b’ and ‘c’ which shapes the error in the proportional and derivative terms respectively. Based on the setpoint weighting parameter b and c, it is possible to obtain a variety of modified PID controller structure. The SWPID controller is equivalent to an error feedback PID controller with a PD controller in the inner loop.

Fig. 6 depicts the rocket engine gimbal control system with SW-PID controller. It has 2DOF structure and the parameters to be tuned are Kp, Ki, Kd, N, b and c. The SW-PID controller with derivative filter is mathematically expressed as,

$$u(t) = K_p e_p(t) + K_i \int_0^t e_i(\tau)d\tau + K_d \frac{de_d(t)}{dt} \frac{N}{\frac{1}{s}N + 1} \tag{11}$$

Where,

$$e_p(t) = b\, r(t) - y(\mathrm{t}) \tag{12}$$

$$e_i(\tau) = r(\tau) - y(\tau) \tag{13}$$

$$e_d(t) = c\, r(t) - y(t) \tag{14}$$

Where, Kp, Ki, Kd and N denote proportional gain, integral gain, derivative gain and derivative filter constant respectively. The term b is setpoint weighting parameter for P controller and c is for D controller. In this controller proportional and derivative actions only acts on a fractions b and c. The integral action has to act on the error to make sure that the error goes to zero in steady state. The controller parameters are all squared up using trial and error method. After several trial and error runs, the nominal values of the PID controller parameters are set as *Kp* = 5, *Ki* = 20, *Kd* = 0.1 and *N* = 15 to provide the desired response. There is no systematic method given for the selection of the setpoint parameters [17]. When $b \in (0,1)$ and $c \in (0,1)$, the PID controller functions as a PID-PD controller [18]. It improves the performance where a high robust regulatory control system is required. So the setpoint weighting parameters are chosen as b = c = 0.3238 to maintain the guaranteed accuracy.

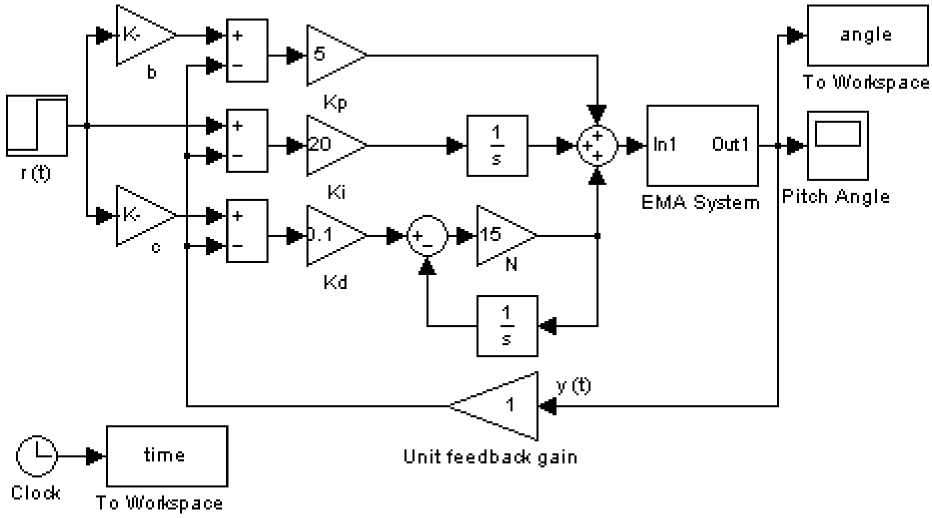

Fig. 6. Gimbal angle control by SW-PID Controller

While the rocket is in flight, the controlling parameters of the model change with the different flying states and also the three parameters of PID controller are variable because of the setpoint weighting parameters. Comparing to LQR, SW-PID controller's settling time is low and produces very less overshoot.The setpoint weighted PID controller provides better results for the setpoint tracking and error minimization in an electromechanical actuator system in spacecraft.

V. Results and Discussion

The simulations are carried out for various deflection angles in Matlab-simulink using the solver ODE45 to examine the performance of the proposed control system. The corresponding trajectories are illustrated in Fig. 7 to Fig. 12. The value of time domain specifications such as settling time, peak overshoot and the Integral Square Error (ISE), Integral Absolute Error (IAE) are summarized in Table II. The most required quality of the controller is to have less overshoot, settling time and error. From the table, it is observed that the LQR controllers have good static performance, while its response rate is not quick enough and produces more steady state error, overshoot in their response and settling time is high.

The proposed SW-PID controller has effectively eradicating these dangerous oscillations. It provides smooth operation in transient period and has less settling time. It produces very less overshoot and less steady state error that is unachievable with LQR controller. Hence, it can be concluded that the setpoint weighted PID controller is more robust than the other controller.

TABLE II.
Quantitative Analysis

Set Point (Degree)	**Settling Time**		**Peak Overshoot**		**ISE**		**IAE**	
	PID	**LQR**	**PID**	**LQR**	**PID**	**LQR**	**PID**	**LQR**
-5	0.9609	10.6	0.024	5	2.45	4.331	0.846	1.773
-4	0.9634	8.6	0.028	5	1.56	2.772	0.677	1.418
-3	0.9547	7.8	0.023	5	0.88	1.559	0.507	1.064
3	0.9516	7.8	0.023	5	0.88	1.559	0.507	1.064
4	0.9491	8.6	0.028	5	1.56	2.772	0.677	1.418
5	0.9569	10.6	0.022	5	2.45	4.331	0.846	1.773

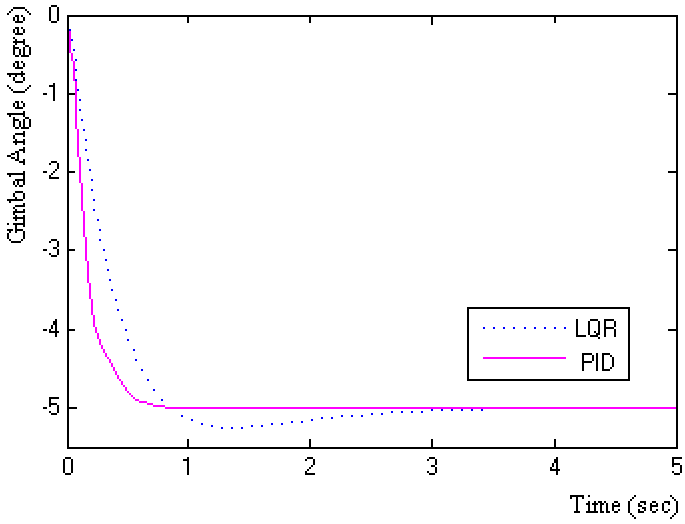

Fig. 7. Response for Deflection of -5^0

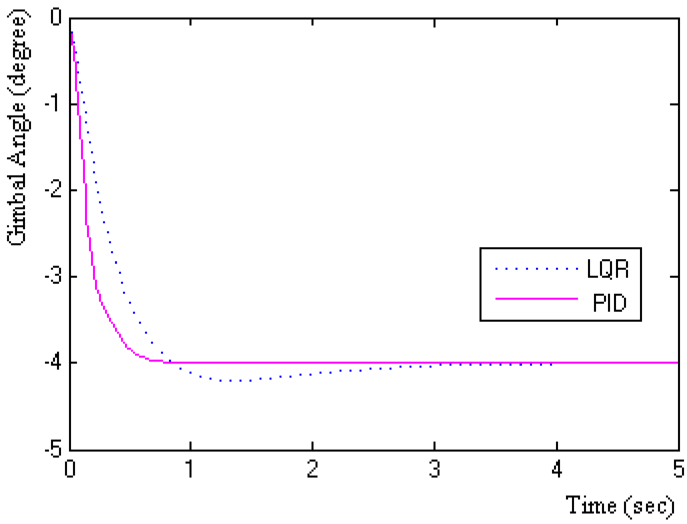

Fig. 8. Response for Deflection of -4^0

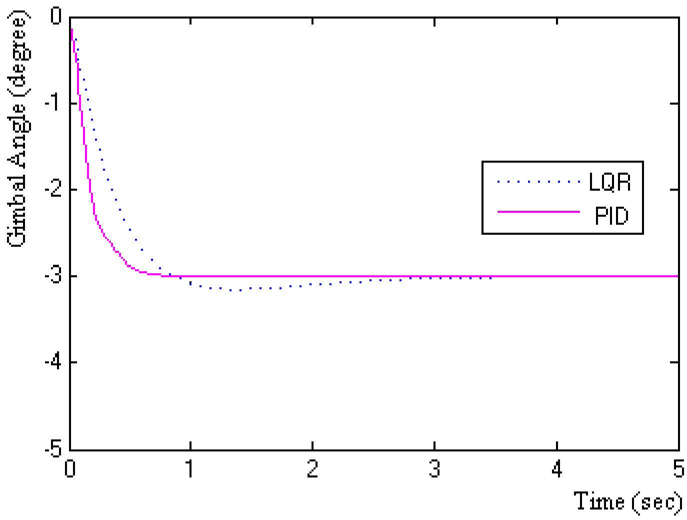

Fig. 9. Response for Deflection of -3^0

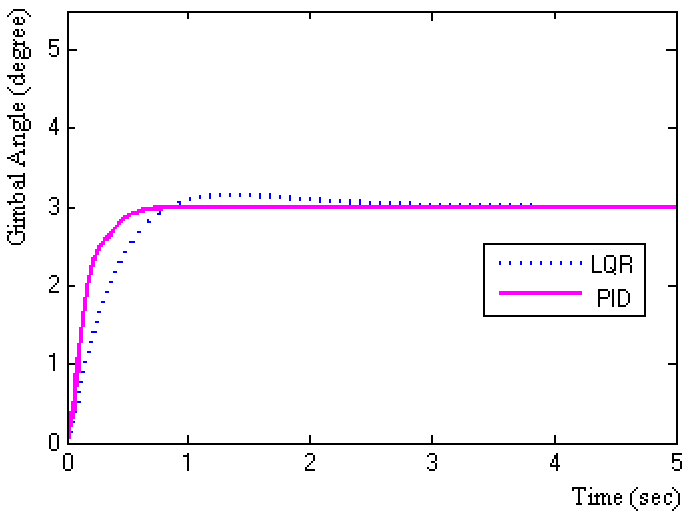

Fig. 10. Response for Deflection of $+3^0$

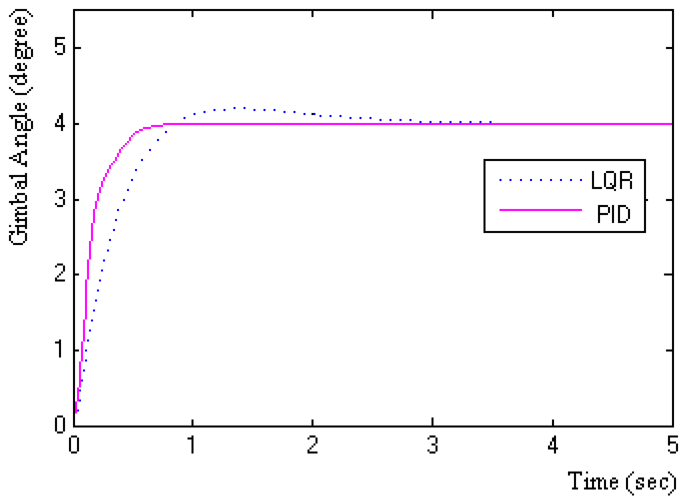

Fig. 11. Response for Deflection of $+4^0$

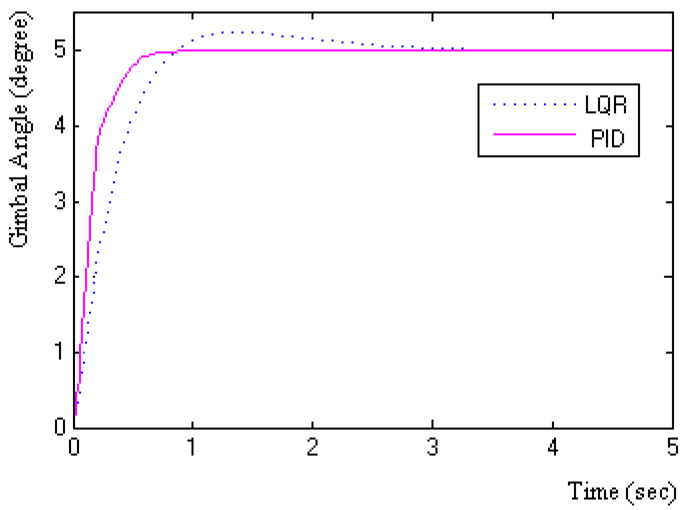

Fig. 12. Response for Deflection of $+5^0$

VI. CONCLUSION

The primary aim of this paper is to control the gimbal angle of rocket nozzle within a specified range and to make the rocket stable in flight. It has succeeded in the design of setpoint weighted PID controller. In this paper an improved LQR controller and setpoint weighted PID controller are designed which can greatly improve the dynamic performances of the rocket control system. The Matlab/simulink model for electromechanical engine gimbal control system is developed with these two controllers.

In LQR controller designing, it requires more knowledge about the system and takes more time to design. LQR controller has high settling time and produces an overshoot resulting in the reduction of the stability of the rocket during the maneuver. In the case of the conventional PID controller, it is suitable for linear systems, the effects of non-linearities in the electromechanical actuator such as saturation and fiction could degrade the performance of conventional controllers. The performance of the PID controller is increased by setpoint weighted technique. The simulation result shows that the reference tracking performance of SW-PID controller is better than LQR controller.

To conclude, the setpoint weighted PID controller designed present is having more advantages with respect to LQR. Here it has less settling time and steady state error. As a result, the system exhibits a fast transient response with less overshoot. The performance measure is found to be satisfactory. So, the proposed setpoint weighted PID controller is a preferable choice for pitch and yaw attitude control of a rocket engine during electromechanical stage.

ACKNOWLEDGMENT

The authors would like to thank Mr. Baby Sebastian, Scientist-Engineer-SF, Vikram Sarabhai Space Centre, Thiruvananthapuram, Kerala, India and Mr. M. Suresh Kumar, Scientist-Engineer-SE, ISRO Inertial System Unit, Thiruvananthapuram, Kerala, India for their suggestions and encouragement throughout the research.

REFERENCES

[1] Beni Kusuma Atmaja and Endra Joelianto, “Surface Control Design of Rocket using MIMO PID Robust Integral Backstepping”, 2nd International Conference on Instrumentation Control and Automation, pp. 162-169, Bandung, Indonesia, November 2011.

[2] Debabrata Roy, Ragupati Goswami, Sourish Sanyal, and Amar Nath Sanyal, “Pitch Attitude Control of a Booster rocket”, International Journal of Engineering and Science, Vol. 2, pp. 8-12, 2013.

[3] Le Zhang, Shaojie Bi and Hong Yang, “Fuzzy-PID Control Algorithm of the Helicopter Model Flight Attitude Control”, Chinese Control and Decision Conference (CCDC), Chinese, pp. 1438 – 1443, May 2010.

[4] E. Venkata Narayana, Vidya Sagar Bonu and G. Mallikarjuna Rao, “PID Versus Fuzzy Logic Based Intelligent Controller Design for a Non Linear Satellite’s Attitude Control: Performance Analysis using MATLAB/Simulink”, International Journal of Advanced Engineering Sciences and Technologies, Vol. 11, No. 1, pp.190 – 195, 2011.

[5] K. J. Astrom and T. Hhgglund, "The future of PID control," Control Engineering Practice , vol. 9, no. 11, pp. 1163-1175, 2001.

[6] M.M. Rashid and Ahmad Wali, “Fuzzy-PID Hybrid Controller for Point-to-Point (PTP) Positioning System”, American Journal of Scientific Research, Vol. 9, pp. 73-81, 2010

[7] Chanchal Dey, R. K. Mudi and T.T. Lee, “A PID controller with dynamic set-point weighting”, IEEE International conference on Industrial Technology, 15-17 Dec’ 2006, 1071-1076.

[8] M.A. Davis, “High Performance Electromechanical Servo Actuation Using Brushless DC Motor”, Moog Technical Bulletin 150, Motor-Con’84 Conference Proceedings, Atlantic City, April 1984.

[9] Dale E. Schinstock, Douglas A. Scott, and Tim A. Haskew, “Modeling and Estimation for Electromechanical Thrust Vector Control of Rocket Engines”, Journal of Propulsion and Power, Vol. 14, No. 4, pp. 440-446, July–August 1998.

[10] Hao Lu, Yunhua Li and Chenglin Zhu, “Robust synthesized control of electromechanical actuator for thrust vector system in spacecraft”, Computers and Mathematics with Applications, Vol. 64, pp. 699–708, 2012.

[11] R.P. Praveen and M.H. Ravichandran et al., “Design and Analysis of Zero Cogging Brushless DC Motor for Spacecraft Applications”, ECTI Transactions on Electrical Eng., Electronics and Communications, Vol. 9, No. 1, pp. 113-120, 2011.

[12] United States, “Selection of Electric Motors for Aerospace Applications”, Marshall Space Flight Center, Huntsville, USA, Practice No. PD-ED-1229, pp. 1-6, 1999.

[13] Desineni Subbaram Naidu, “Optimal Control Systems”, CRC Press, USA, 2009.

[14] Katsuhiko Ogata, “Modern Control Engineering”, Third edition, Prentice-Hall of India Private limited, New Delhi, 1999.

[15] Farrukh Nagi, S.K. Ahmed, A.A. Zainul Abidin and F.H. Nordin, “Fuzzy bang-bang relay controller for satellite attitude control system”, Fuzzy sets and systems, Vol. 161, pp. 2104-2125, 2010.

[16] V. Rajinikanth and K. Latha, “Setpoint weighted PID controller tuning for unstable system using heuristic algorithm”, Archives of Control Science, 22 (4), 2012, 481-505.

[17] M. Chidambaram, “Setpoint Weighted PI/PID Controllers”, Chemical Engineering Communications, 179, 1-13, 2007.

[18] CH-CH. CHEN, H.-P. HAUNG and H.-J. LIAW, “Setpoint Weighted PID Controller tuning for time-delayed unstable processes”, Ind. Eng. Chem. RES., 47 (18), 2008, 6983-6990.