**Australian Journal of Basic and Applied Sciences**, 8(9) June 2014, Pages: 88-95

AENSI Journals

**Australian Journal of Basic and Applied Sciences**

ISSN:1991-8178

Journal home page: www.ajbasweb.com

# A Modified Structured PID Controller for Rocket Engine Gimbal Angle Control System

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

*[1]Research Scholar, Anna University Chennai, Tamil Nadu, India*
*[2]Professor & Dean (Research), Sona College of Technology, Salem, Tamil Nadu, India*

**ARTICLE INFO**

***Article history:***
*Received 2 March 2014*
*Received in revised form*
*13 May 2014*
*Accepted 28 May 2014*
*Available online 23 June 2014*

***Keywords:***
*Setpoint weighting, PID, FLC, rocket, attitude control, MATLAB/Simulink*

**ABSTRACT**

Rocket is the only vehicle that lift-offs the payload into the space. But, in flight a rocket is subjected to various forces, thrust and aerodynamics. Also, the rocket is a multi-input and multi-output nonlinear system whose dynamics are unstable and poorly understood. So the orientation of the payload in precise position is so critical. Hence, attitude control of the rocket in pitch and yaw axis is a big challenge with real time. This paper presents a hybrid fuzzy-PID controller and a modified structured PID controller to control the gimbal angle of rocket engine during maneuver. The self-tuning fuzzy-PID controller is the combination of a classical PID and fuzzy controller. It is designed based on the expert knowledge of the system. From the response it is clear that the fuzzy-PID controller takes more time to settle in the defined position and provides more error which is not looked-for. A modified structured PID controller based on the two degree of freedom mathematical model is developed to overcome the presence of nonlinearities and uncertainties in the system. In conclusion, this paper compares the performance analysis of both the controllers. The simulation results indicate that the modified PID controller has a remarkable improvement in terms of settling time besides reducing steady state error. The proposed modified structured PID controller enhances the system performance and produces enormous stability to the rocket engine**.**



**To Cite This Article:** R.Sumathi, M.Usha., A Modified Structured PID Controller for Rocket Engine Gimbal Angle Control System. ***Aust. J. Basic & Appl. Sci.**, 8(9): 88-95, 2014*

## INTRODUCTION

The payload systems of a rocket are satellites, explosives, to launch people into earth orbit and onto the surface of the Moon, for communications, weather monitoring, spying and environmental exploration etc. The orientation of the payload in exact location is so crucial. But, rocket is a non-linear, high order system with multiple inputs and multiple outputs that has unstable dynamics and sensitive to external disturbances. So rocket attitude control has been an active research topic for quite sometime. Usually, the controlled variables in the control system of small-scale unmanned vehicle are the attitude angle or velocity. The attitude angle is the controlled variable in the inner loop, and the velocity is for the outer loop (La Civita, 2002). 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 particular path. The parameters which characterize the dynamics of the rocket are usually an approximation (Beni Kusuma Atmaja and Endra Joelianto, 2011) 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. Stability means making sure the rocket follows a smooth path in flight. If it wobbles, the ride will be rough and extra fuel will be burned to get back on course. An unstable rocket is dangerous. Making the rocket stable requires some form of control system.

Many controllers on attitude controlling of satellites, helicopters and rockets have been proposed but very few of these controllers can be applied to deal with many issues simultaneously. Debabrata Roy *et al.* (2013) designed proportional-derivative feedback controller for pitch attitude control of a rocket. However, here the interference and non-linearities have not been taken into account. Pei-zhi Liu *et al*. (2011) applied the technique of robust control loop shaping in the design of unmanned-vehicle control system. Le Zhang *et al.* (2010) proposed Fuzzy-PID control algorithm for attitude control of the helicopter model flight. Venkata Narayana *et al*. (2011) designed fuzzy logic based intelligent controller for a non-linear satellite’s attitude control. Beni Kusuma Atmaja and EndraJ oelianto (2011) proposed MIMO PID robust integral back stepping method to

**Corresponding Author:** R. Sumathi, Research Scholar, Anna University, Chennai, Tamilnadu, India,
E-mail:elakkiyasumi@gmail.com

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 (Astrom and Hhgglund, 2001). 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 (Rashid, 2010) 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 (Chanchal Dey *et al.*, 2006) and it is introduced to control the rocket gimbal angle in this paper. Also a nonlinear fuzzy logic controller combined with classical PID controller by blending mechanism is used to control the rocket engine gimbal angle. The performances of the setpoint weighted PID controller are compared with fuzzy-PID controller. Based on the excellent qualities, the proposed SPW-PID controller produces less steady state error and less settling time which means that the stability of the rocket is magnificent.

## MATERIALS AND METHODS

***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 electromechanical engine control system is shown in Fig. 1. Two 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 to provide linear output motion 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 to provide efficient proportional control required for good servo performance. 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. The current limiting loop is available to protect the transistors and the motor from damage due to excessive heating. 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 rocket system (Davis, 1984).

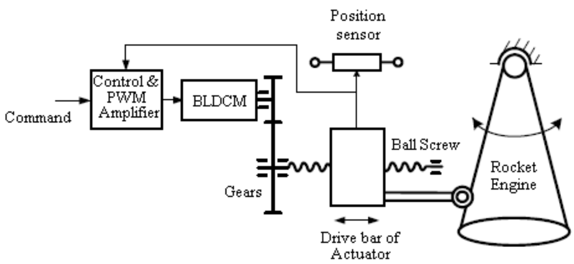


**Fig. 1:** Electromechanical Engine Gimbal Control System.

The rest of the paper investigating the mathematical model of the electromechanical engine gimbal control system. In the next section, the designing and simulation of hybrid fuzzy-PID controller and setpoint weighted PID controller is described. Later the discussions are done on the results. And the concluding work of the paper is presented in the last section.

***EM EGC system model:***

***BLDC torque motor current:***

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,

$$|R_m \, i_{mc} + K_b \omega_m| < V_s \tag{1}$$

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,

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

Where, $V_i$, $K_A$, $R_m$, $K_b$, $\omega_m$ 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,

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

***Rocket Engine:***

The mechanical portion of the EM EGC system is the rocket engine. Rocket stability is an important issue for rocket scientists. The success of a space launch depends upon pinpoint accuracy. 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 (Dale E. Schinstock *et al.*, 1998). The nozzle and thrust exhaust for gimbal angle control is illustrated in Fig. 2.

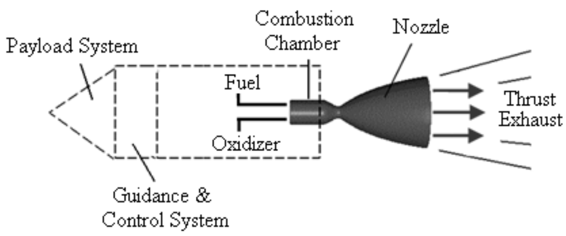


**Fig. 2:** Nozzle and thrust exhaust.

The roll angular rate, pitch angular rate, yaw angular rate, roll, pitch, yaw, forward velocity, lateral velocity and vertical velocity are the output parameters (Pei-zhi Liu, 2011) of a rocket. With the pitch angular rate and yaw angular rate, the properties of rocket should be described precisely with mathematical model before the design of rocket control system. The two common methods to build up the model are modeling with the equation of dynamics and with system identification. The two can be combined together for application. Primarily, the model structure is determined by linearizing the 2DoF motion equations of rocket system. Then the dynamics model of the rocket is identified based on the collected data of inputs and outputs. The state space model of the rocket engine is derived as (4),

$$A = \begin{bmatrix} 0 & 1 \\ -0.1908 & -1.9084 \end{bmatrix}$$

$$B = \begin{bmatrix} 0 \\ 0.0019 \end{bmatrix}$$

$$C = [1 \quad 0] \quad (4)$$

$$D = [0]$$

***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 (Hao Lu *et al.*, 2012). Brushless direct current motors have been proven to be the best (Praveen *et al.*, 2011; United States, 1999) 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

**Australian Journal of Basic and Applied Sciences,** 8(9) June 2014, Pages: 88-95

and heat considerations it is desirable to limit the voltage to the motor and thus voltage limiting is included.

***Matlab simulink model:***

In order to provide an effective and realistic analysis, a detailed model of the control loop must include all the significant parameters and constraints for each of the component. With the model of the rocket and BLDC motor, the open loop electromechanical actuator system is developed using matlab/simulink is presented in Fig. 3. The specifications used in the simulation are given in Table I. The duration of simulation is set as 5 sec. 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 route or sometimes tumbling. So, it is essential to design an intelligent control system for the attitude control of a rocket engine.

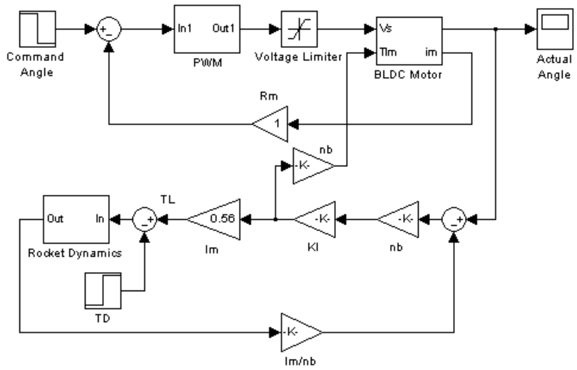


**Fig. 3:** Open Loop Electro Mechanical Actuator System.

**Table I: M**odel specifications.

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

***Design of controllers:***

***Fuzzy-PID controller:***

Fuzzy controllers are known for absorbing the non-linearities of the system and work well for the real system. They are very powerful techniques in the field of system control, especially when the systems have large uncertainties and strong non-linearities. Also the fuzzy controller does not rely on the precise mathematical model of the controlled object. It approximates the plant's unknown dynamics (Wuxi Shi *et al.*, 2011). PID controllers are often incorporated into the programmable logic controllers that are used to control many industrial processes. Unfortunately, the conventional PID loops that are incorporated in rocket control system are in continual need of monitoring and adjustment since they can easily become improperly tuned due to the rocket parameter variations and operating condition changes. There is a significant need to develop methods for the automatic tuning of PID controllers (Kevin M. Passino and Stephen Yurkovich, 1998). Hybridization of PID and fuzzy controller provides the beneficial sides of both categories.

The improved performances in both the transient and steady states have been achieved by the hybrid fuzzy-PID controller as compared to classical PID and fuzzy logic controller. It involves three main steps; Fuzzification, rule evaluation and defuzzification.

***Fuzzification:***

The first step in designing a fuzzy logic controller is to decide state variables that represent the system dynamic performance. These state variables are taken as the input signal to the controller. For this, the triangular shaped membership function is the most economic one. The inputs are error (e) in the angle deflection and corresponding change in error (ce). They are quantized into three fuzzy sets as negative (N), zero (Z) and positive (P). The chosen ranges for the membership functions are shown in Table II.

**Table II:** Input/Output Range of FLC.

| Parameter | Positive Angle Deflection | Negative Angle Deflection |
|---|---|---|
| Error | -8 to 8 | -8 to 8 |
| Change in Error | -2 to 2 | -2 to 2 |
| Output | -5.15 to 1 | -1 to 2 |

***Defuzzification:***

The computing unit utilizes mamdani type fuzzy processing and the centre of area method to 'de-fuzzify' the results. The Matlab/Simulink model of the proposed fuzzy-PID based rocket control system is shown in Fig. 4. Here, two fuzzy logic controllers are utilized to give better control performance. One is for positive angle deflection and another one is for negative angle deflection control. After numerous simulation experiments, the parameters of the fuzzy controller are selected as Ka = 8.2, Ker= 0.9 and Kc = 0.001. The PID controller parameters are preferred as Kp = 8, Ki = 13 and Kd = 1.

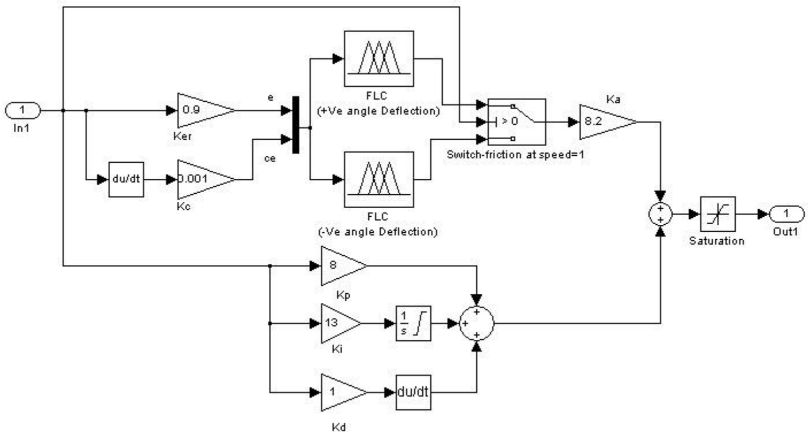


**Fig. 4:** Gimbal angle control by Hybrid Fuzzy-PID Controller.

***Rule Base:***

The relations of the inputs and the outputs of the fuzzy tuner are listed as fuzzy rules and it is presented as,
If (e is positive) and (ce is positive) then output is positive;
If (e is zero) and (ce is positive) then output is positive;
If (e is negative) and (ce is positive) then output is zero;
If (e is positive) and (ce is zero) then output is positive;
If (e is zero) and (ce is zero) then output is zero;
If (e is negative) and (ce is zero) then output is negative;
If (e is positive) and (ce is negative) then output is zero;
If (e is zero) and (ce is negative) then output is negative;
If (e is negative) and (ce is negative) then output is negative;

The drawbacks faced here is the time taken for tuning the fuzzy parameters are too high. Also it produces more steady state error and the settling time is high. So, it is necessary to design an effective controller for this sensitive application.

***Setpoint weighted 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 (Farrukh Nagi *et al*., 2010). 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,

$$G_{md}(s) = \frac{K_d s}{\frac{T_d}{N}s + 1} \quad (5)$$

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 (Rajinikanth and Latha, 2012). The setpoint weighted PID is 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 SPW-PID controller is equivalent to an error feedback PID controller with a PD controller in the inner loop.

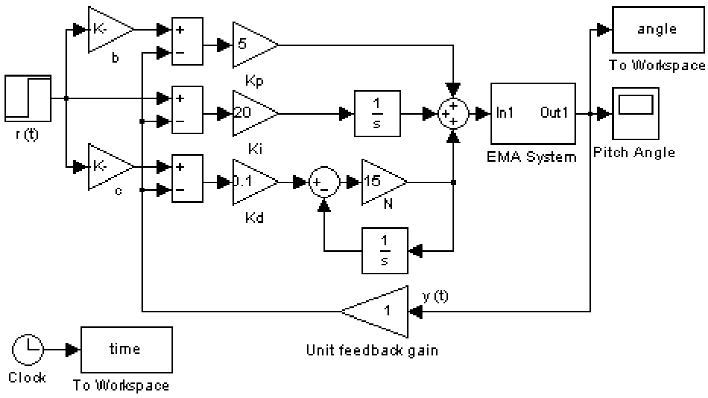


**Fig. 5:** Gimbal angle control by SW-PID Controller.

Fig. 5 depicts the rocket engine gimbal control system with SPW-PID controller. It has 2DOF structure and the parameters to be tuned are $K_p$, $K_i$, $K_d$, N, b and c. The SPW-PID controller with derivative filter is mathematically expressed as,

$$u(t) = K_p e_p(t) + K_i \int_0^t e_i(\tau)d\tau + K_d \frac{de_d(t)}{dt} \frac{1}{\frac{T_d}{N}s + 1} \quad (6)$$

Where,

$$e_p(t) = b\, r(t) - y(t) \quad (7)$$

$$e_i(\tau) = r(\tau) - y(\tau) \quad (8)$$

$$e_d(t) = c\, r(t) - y(t) \quad (9)$$

Where $K_p$, $K_i$, $K_d$ and N denote proportional gain, integral gain, derivative gain and derivative filter coefficient 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 (Chidambaram, 2007). When b ∈ (0,1)and c ∈ (0,1), the PID controller functions as a PID-PD controller (Chan-Cheng Chen *et al.*, 2008). 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.

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 Fuzzy-PID, SW-PID controller's settling time is very low.The setpoint weighted PID controller provides better results for the setpoint tracking and error minimization in an electromechanical actuator system in spacecraft.

Australian Journal of Basic and Applied Sciences, 8(9) June 2014, Pages: 88-95

## 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. 6 to Fig. 11. The value of time domain specifications such as settling time and the Integral Square Error (ISE), Integral Absolute Error (IAE) are summarized in Table III. The most required quality of any controller is to have less overshoot, settling time and error. From the table, it is observed that the Fuzzy-PID controllers have good static performance, while its response rate is not quick enough and produces more steady state error in their response and settling time is high.

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

**Table III:** Performance Analysis.

| Gimbal Angle (Degree) | | -5 | -4 | -3 | 3 | 4 | 5 |
|---|---|---|---|---|---|---|---|
| Settling Time | SPW-PID | 0.9609 | 0.9634 | 0.9547 | 0.9516 | 0.9491 | 0.9569 |
| | Fuzzy-PID | 3.1 | 3 | 2.9 | 2.7 | 2.5 | 2.1 |
| ISE | SPW-PID | 2.45 | 1.56 | 0.88 | 0.88 | 1.56 | 2.45 |
| | Fuzzy-PID | 3.238 | 2.462 | 1.943 | 1.938 | 2.46 | 3.237 |
| IAE | SPW-PID | 0.846 | 0.677 | 0.507 | 0.507 | 0.677 | 0.846 |
| | Fuzzy-PID | 1.322 | 1.322 | 1.322 | 1.312 | 1.312 | 1.312 |

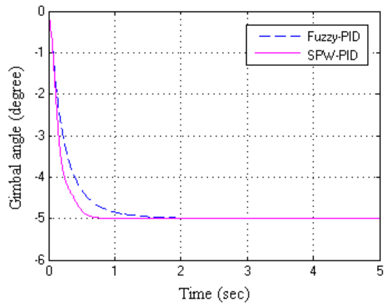


**Fig. 6:** Response for Deflection of -5$^{0}$.

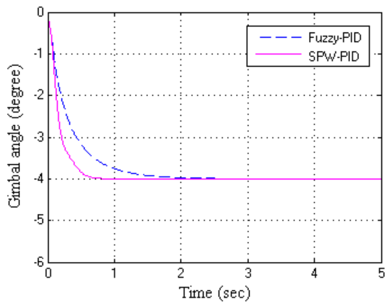


**Fig. 7:** Response for Deflection of -4$^{0}$.

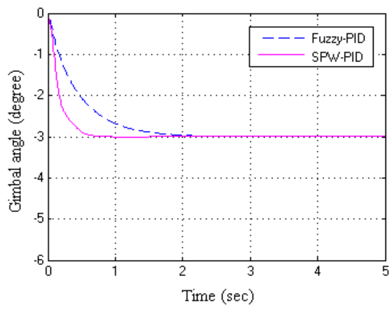


**Fig. 8:** Response for Deflection of -3$^{0}$.

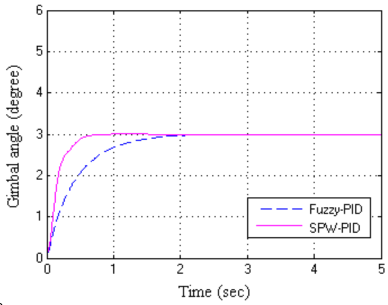


**Fig. 9:** Response for Deflection of +3$^{0.}$

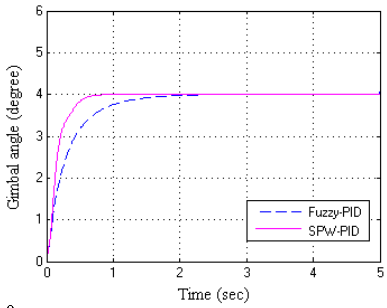


**Fig. 10:** Response for Deflection of +4$^{0.}$

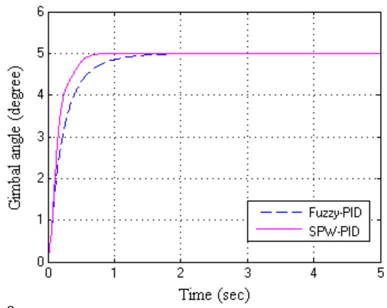


**Fig. 11:** Response for Deflection of +5$^{0.}$

***Conclusion***

The primary aim of this paper is to control the gimbal angle of rocket engine 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 a hybrid fuzzy-PID 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 fuzzy-PID controller designing, it requires more knowledge about the system and takes more time to design. It has high settling time and produces more error 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 SPW-PID controller is better than fuzzy-PID controller.

To conclude, the setpoint weighted PID controller designed present is having more advantages with respect to fuzzy-PID. Here it has less settling time and steady state error. As a result, the system exhibits a fast transient response with no 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.

## ACKNOWLEDGEMENT

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

Astrom, K.J. and T. Hhgglund, 2001. The future of PID control, Control Engineering Practice, 9(11): 1163-1175.

Beni Kusuma Atmaja and EndraJoelianto, 2011. Surface Control Design of Rocket using MIMO PID Robust Integral Backstepping, 2nd International Conference on Instrumentation Control and Automation, Bandung, Indonesia, pp: 162-169.

ChanchalDey, R.K. Mudi and T.T. Lee, 2006. A PID controller with dynamic set-point weighting, IEEE International conference on Industrial Technology, pp: 1071-1076.

Chan-Cheng Chen, Hsia-Ping Huang and Horng-Jang Liaw, 2008. Setpoint Weighted PID Controller tuning for time-delayed unstable processes, Industrial and Engineering Chemistry Research, 47(18): 6983-6990.

Chidambaram, M., 2007. Setpoint Weighted PI/PID Controllers", Chemical Engineering Communications, 179(1): 1-13.

Dale, E. Schinstock, Douglas A. Scott and Tim A. Haskew, 1998. Modeling and Estimation for Electromechanical Thrust Vector Control of Rocket Engines, Journal of Propulsion and Power, 14(4).

Davis, M.A., 1984. High Performance Electromechanical Servo Actuation Using Brushless DC Motor, Moog Technical Bulletin 150, Motor-Con'84 Conference Proceedings, Atlantic City, pp: 1-12.

Debabrata Roy, RagupatiGoswami, Sourish Sanyal and Amar Nath Sanyal, 2013. Pitch Attitude Control of a Booster rocket, International Journal of Engineering and Science, 2(7): 8-12.

Farrukh Nagi, Syed Khaleel Ahmed, A.A. Zainul Abidin and F.H. Nordin, 2010. Fuzzy bang-bang relay controller for satellite attitude control system, Fuzzy sets and systems, 161(15): 2104-2125.

Hao Lu, Yunhua Li and Chenglin Zhu, 2012. Robust synthesized control of electromechanical actuator for thrust vector system in spacecraft, Computers and Mathematics with Applications, 64(5): 699-708.

Kevin, M., Passino and Stephen Yurkovich, 1998. Fuzzy Control, Addison Wesley Longman, Inc., California.

La Civita, M., 2002. Integrated modeling and robust control forfull-envelope flight of robotic helicopters, PhD thesis,UMI Number: 3074895, Carnegie Mellon University.

Le Zhang, Shaojie Bi and Hong Yang, 2010. Fuzzy-PID Control Algorithm of the Helicopter Model Flight Attitude Control, Chinese Control and Decision Conference (CCDC), Chinese, pp: 1438-1443.

Pei-zhi Liu, Zhi-qiangBai and Jin-hua Wang, 2011. Robust controller design of small-scale unmannedhelicopter, International Journal of Modelling, Identification and Control, 12(1/2): 7-21.

Praveen, R.P. and M.H. Ravichandran *et al*., 2011. Design and Analysis of Zero Cogging Brushless DC Motor for Spacecraft Applications, ECTI Transactions on Electrical Eng., Electronics and Communications, 9(1):113-120.

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

Rashid, M.M. and Ahmad Wali, 2010. Fuzzy-PID Hybrid Controller for Point-to-Point (PTP) Positioning System, American Journal of Scientific Research, 9:72-80.

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

VenkataNarayana, E., Vidya Sagar Bonu and G. MallikarjunaRao, 2011. 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, 11(1): 190-195.

Wuxi Shi, Mu Zhang, Wencheng Guo and Lijin Guo, 2011. Stable adaptive fuzzy control for MIMO nonlinear systems, Computers and Mathematics with Applications, 62(7): 2843-2853.