

Adaptive Backstepping Control for Roll Channel of Launch Vehicle

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Abstract: Launch vehicles are those which are used to carry payloads from earth's surface to outer space. This paper describes the design of Backstepping and Adaptive Backstepping control on the roll dynamics of the launch vehicle in order to control the roll angle and roll rate. Backstepping is a recently developed design tool for constructing globally stabilizing control laws for a certain class of nonlinear dynamic systems. Backstepping is a recursive design methodology for the construction of both feedback control laws and associated Lyapunov functions in a systematic manner. While designing the backstepping control algorithm all the uncertainties are assumed to be constant which reduces the stability of the system. With Adaptive Backstepping, stabilization is achieved in the presence of unknown parameters. The comparison of the performance analysis of both Backstepping and Adaptive Backstepping is studied using MATLAB simulation. From the simulation results it is clear that Adaptive Backstepping Control Scheme gives better and satisfactory responses than the Backstepping Control.

Keywords: Backstepping Control (BS), Adaptive Backstepping Control (ABS), Launch Vehicle

1. Introduction

Non linear systems are more complex when compared to linear systems. Thus the control of nonlinear systems is very difficult. Launch vehicle is highly complex nonlinear system and thus the control of launch vehicle is a challenging task. A launch vehicle is used to carry payload to outer space. Generally Launch vehicles are classified into two: Expendable launch vehicles and Reusable launch vehicles. Expendable launch vehicles are those launch vehicles that are designed for one-time use while Reusable launch vehicle are those which can be used more than once, they are designed to perform many missions within their life cycle.

Over the past two decades the focus in control theory has shifted from linear to nonlinear system. The analysis of launch vehicle can be done using linear controllers and nonlinear controllers. Earlier the control design for the launch vehicle was restricted to linear controllers. Linear control designs reduce the stability of the system since some useful nonlinearities are neglected. Several control techniques, including Proportional-Integral-Derivative (PID) control law with gain scheduling [1], Trajectory Linearization Control (TLC) [2], adaptive Neural Network (NN) [3], have been developed under Advanced Guidance and Control (AG&C) project and is used for launch vehicle flight control. However, by means of these control techniques the robustness issues were not satisfactory.

Backstepping offers flexibilities which are not present in other nonlinear design, one of them is that it avoid the cancellation of useful nonlinearities. In [4] backstepping is applied to flight path angle control. Backstepping is recursive method based on Lyapunov theory. In backstepping the parameter uncertainties are assumed to be constant, thus fails in the presence of uncertainties. Adaptive Backstepping [5], [6], [7], [8] makes use of dynamic parameter update laws to deal with parametric uncertainties. Moreover the stability of a system may be affected by some bounded disturbances and

high rate of adaptation which can be overcome by incorporating a robust control.

In this paper Backstepping and Adaptive Backstepping Controls have been implemented on the roll channel to control the roll angle and roll rate of the launch vehicle. A comparative study on both these controllers has been done. The performance analysis of both these controllers is studied using MATLAB simulations. The Paper has been organized as follows: Section II deals with the modelling of roll dynamics. Section III deals with the Backstepping Controller design. Section IV deals with the design of Adaptive Backstepping Control. In Section V the Simulation results are shown with some discussions on it. Section VI is the Conclusion.

2. Modelling roll dynamics

Fig. 1 shows the roll dynamics of a launch vehicle. It shows that there are two thrusters. By varying the thruster angle launch vehicle direction in roll channel is controlled. The tilting force to cause roll is in the direction shown as $T \sin \delta$. The total torque is due to thrusts of both the thrusters. Then the torque equation can be written as:

$$I\ddot{\theta} = 2Tl_c \sin \delta$$

$$\ddot{\theta} = \frac{2Tl_c}{I} \sin \delta = \mu_c \sin \delta \quad (1)$$

where T = force due to each thruster, l_c = length between the main motor and each thruster, δ = thruster angle, I = moment of inertia of the vehicle, θ = roll angle.

$$V_2(x, z) = \frac{1}{2}x_1^2 + \frac{1}{2}z^2 \quad (10)$$

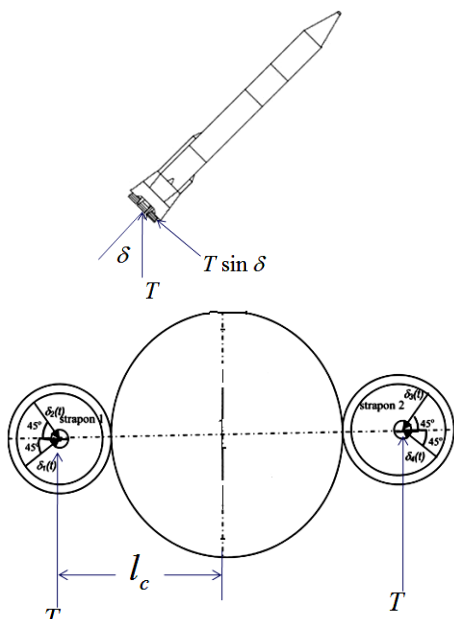


Figure 1: Launch vehicle roll control

3. Backstepping Control Design

Backstepping is a recursive procedure which breaks a design problem for the full system into sequence of design problems for lower order systems. Backstepping designs by breaking down complex nonlinear systems into smaller subsystems. Then designing control Lyapunov functions and virtual controls for these systems and finally integrating these individual controllers into an actual controller, by stepping back through the subsystem and reassembling it from its component subsystems.

In this paper Backstepping Control is designed for the roll channel control of the system (1). In order to adopt the backstepping control design, the model (1) can be transformed into the following:

$$x_1 = \theta, x_2 = \dot{x}_1 = \dot{\theta}, \delta = u \quad (2)$$

$$\dot{x}_1 = x_2; \dot{x}_2 = \mu_c \sin \delta \quad (3)$$

A.Step 1

The first subsystem is $\dot{x}_1 = x_2$. Let the Lyapunov function be

$$V_1(x) = \frac{1}{2}x_1^2 \quad (4)$$

$$\dot{V}_1 = x_1 \dot{x}_1 = x_1 x_2 \quad (5)$$

$$x_{2des} = -c_1 x_1, c_1 > 0 \quad (6)$$

$$\dot{V}_1 = -c_1 x_1^2 \quad (7)$$

Where the scalar c_1 is always greater than zero so that \dot{V}_1 is always negative definite.

B.Step 2

$$\text{Error variable, } z = x_2 - x_{2des} = x_2 + c_1 x_1 \quad (8)$$

$$\begin{aligned} \dot{z} &= \dot{x}_2 + c_1 \dot{x}_1 \\ &= \mu_c \sin u + c_1 (z - c_1 x_1) \end{aligned} \quad (9)$$

Augmented Lyapunov function,

$$\begin{aligned} \dot{V}_2 &= x_1 \dot{x}_1 + z \dot{z} \\ &= -c_1 x_1^2 + z [\mu_c \sin u + c_1 (z - c_1 x_1)] \end{aligned} \quad (11)$$

The desired value of u , u_{des} is given by

$$u_{des} = \sin^{-1} \frac{1}{\mu_c} [-c_2 z - c_1 (z - c_1 x_1)] \quad (12)$$

4. Adaptive Backstepping Control Design

Adaptive backstepping control is a recursive, Lyapunov based nonlinear design method, which makes use of dynamic parameter update laws to deal with parametric uncertainties. For applying adaptive backstepping control design on roll channel of system (1) the equations are modified as:

$$\begin{aligned} \dot{x}_1 &= x_2; \\ \dot{x}_2 &= \mu_c \sin \delta = \phi \sin \delta \end{aligned} \quad (13)$$

where $\phi = \mu_c$ is the unknown parameter.

A.Step 1

The first error variable is defined as

$$e = x_1 - \theta_{sp} \quad (14)$$

where θ_{sp} is the desired set point.

Using the Lyapunov function

$$V_1 = \frac{1}{2}e^2 \quad (15)$$

$$\dot{V}_1 = e \dot{e}$$

$$= e(x_2 - \dot{\theta}_{sp}) \quad (16)$$

Using the derivative of the Lyapunov function, the virtual control law can be formulated as

$$x_{2des} = -k_1 e + \dot{\theta}_{sp} \quad (17)$$

where $k_1 > 0$ and is a design parameter which guarantees $\dot{V}_1 < 0$.

B.Step 2

The second error variable ξ is defined as

$$\xi = x_2 - x_{2des} \quad (18)$$

By augmenting the Lyapunov function V_1 with the error variable ξ and the unknown parameters in the system, we get

$$V_2 = \frac{1}{2}e^2 + \frac{1}{2}\xi^2 + \frac{1}{2\gamma}\tilde{\phi}^2 \quad (19)$$

where $\tilde{\phi}$, is the parameter estimation error of ϕ , and γ is the adaptation gain.

$$\begin{aligned} \dot{V}_2 &= e \dot{e} + \xi \dot{\xi} + \frac{1}{\gamma} \tilde{\phi} \dot{\tilde{\phi}} \\ &= -k_1 e^2 + \xi (\dot{x}_2 - \dot{x}_{2des}) + \frac{1}{\gamma} \tilde{\phi} (\dot{\phi} - \dot{\hat{\phi}}) \\ &= -k_1 e^2 + \xi (\hat{\phi} \sin u - \dot{\theta}_{sp} + k_1 \dot{x}_1 - k_1 \dot{\theta}_{sp}) \\ &\quad + \tilde{\phi} (\xi \sin u - \frac{1}{\gamma} \dot{\hat{\phi}}) \end{aligned} \quad (20)$$

The parameter adaptation law is obtained by setting:

$$\xi \sin u - \frac{1}{\gamma} \dot{\hat{\phi}} = 0 \quad (21)$$

Thus the adaptation law is given by:

$$\dot{\phi} = \gamma \xi \sin u \tag{22}$$

The control law is obtained by setting:

$$\dot{\phi} \sin u - \ddot{\theta}_{sp} + k_1 \dot{x}_1 - k_1 \dot{\theta}_{sp} = -k_2 \xi \tag{23}$$

where k_2 is the design parameter, such that $k_2 > 0$.

Thus control law is given by:

$$u = \sin^{-1} \left[\frac{1}{\gamma} [-k_2 \xi + \ddot{\theta}_{sp} - k_1 \dot{x}_2 + k_1 \dot{\theta}_{sp}] \right] \tag{24}$$

5. Simulation Results and Discussions

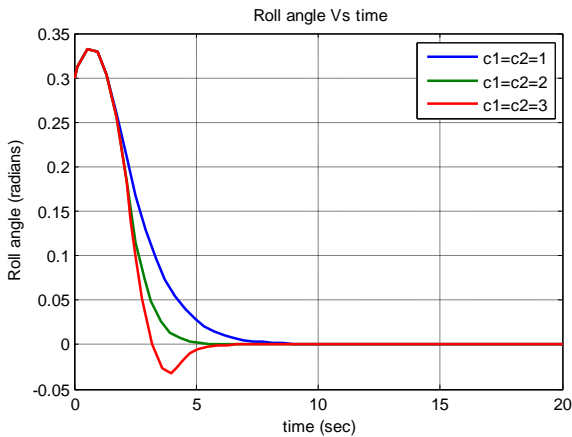


Figure 2: Regulation of Roll angle using Backstepping

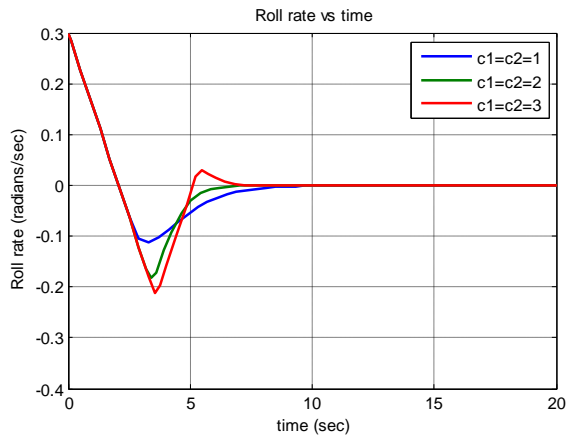


Figure 3: Regulation of Roll rate using Backstepping

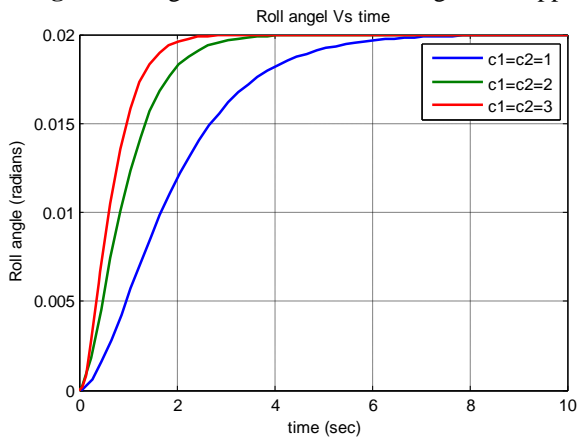


Figure 4: Tracking of Roll angle using Backstepping

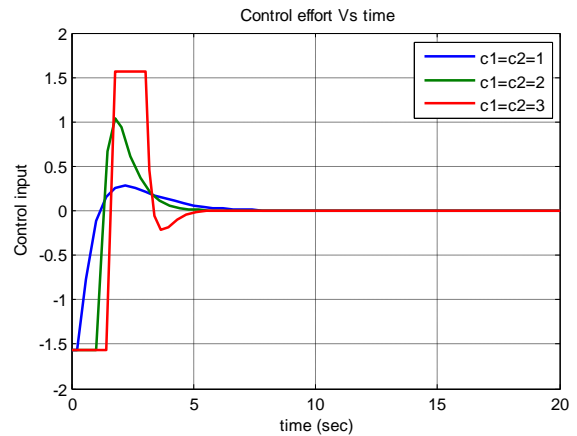


Figure 5: Variation of Control effort using Backstepping

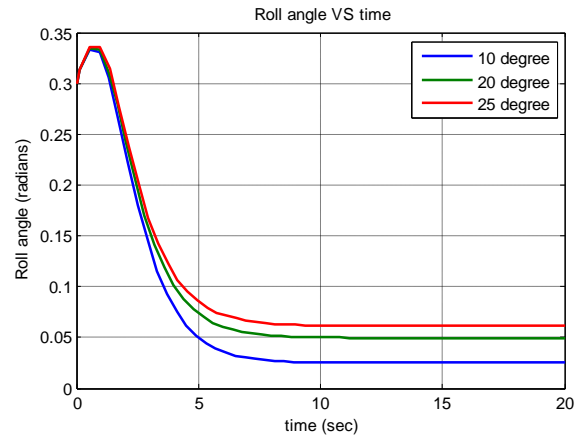


Figure 6: Disturbance Analysis using Backstepping

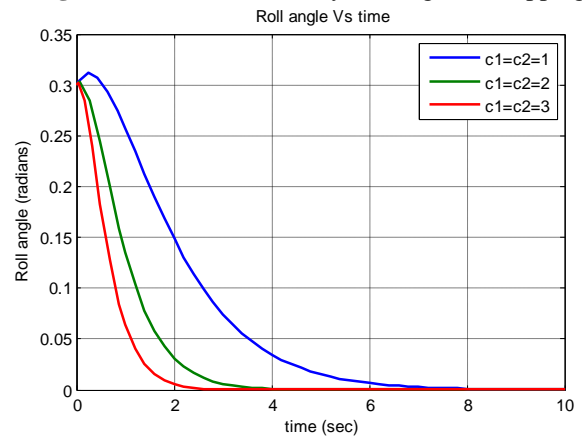


Figure 7: Regulation of Roll angle using Adaptive Backstepping

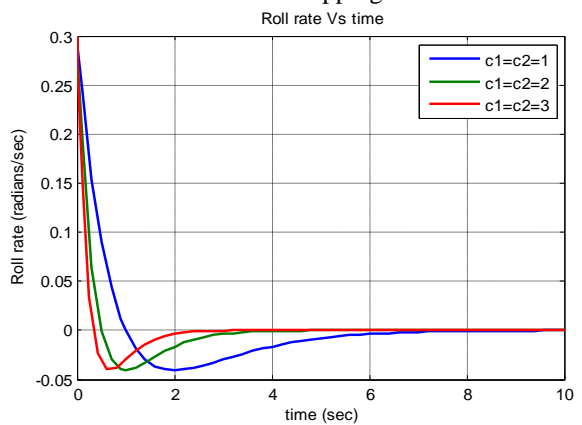


Figure 8: Regulation of Roll rate using Adaptive Backstepping

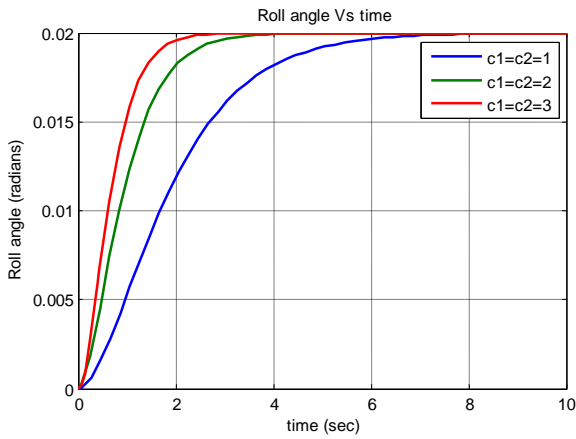


Figure 9: Tracking of Roll angle using Adaptive Backstepping

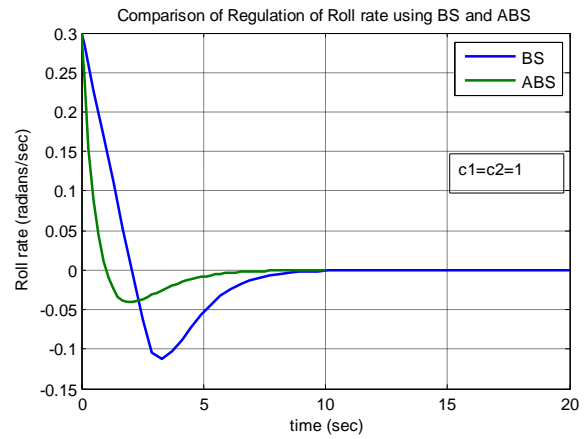


Figure 13: Comparison of regulation of Roll rate using BS and ABS

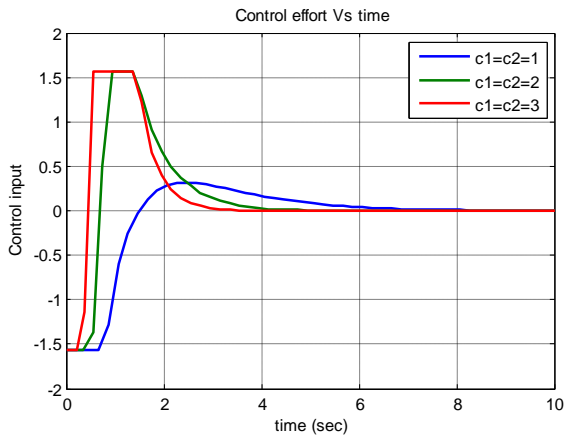


Figure 10: Variation of Control effort using Adaptive Backstepping

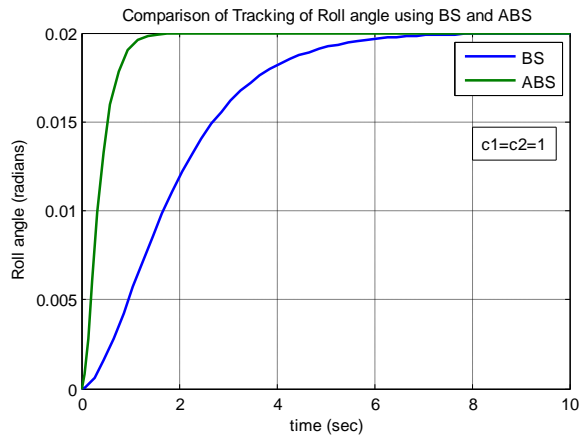


Figure 14: Comparison of tracking of Roll angle using BS and ABS

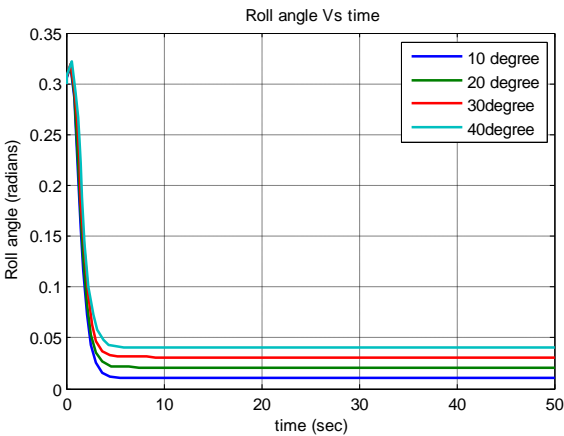


Figure 11: Disturbance Analysis using Backstepping

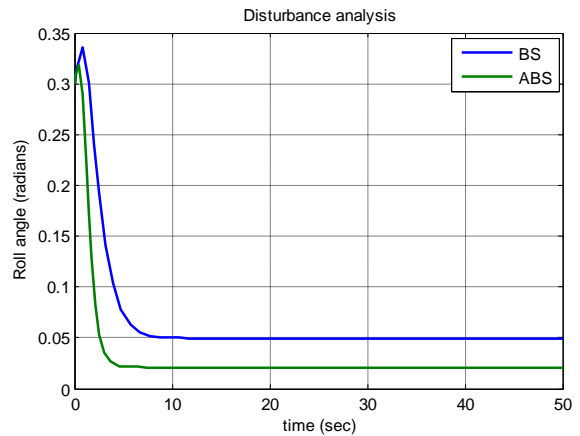


Figure 15: Comparison of disturbance analysis

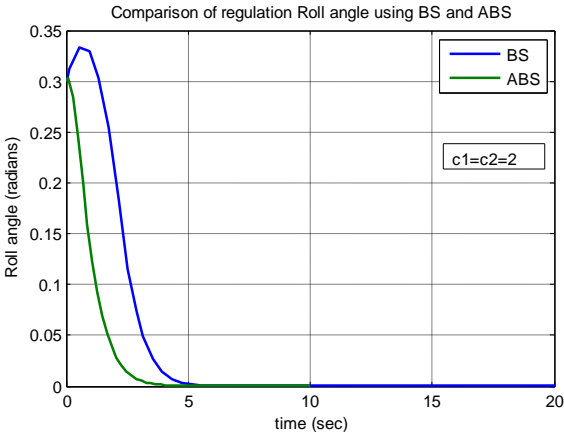


Figure 12: Comparison of regulation of Roll angle using BS and ABS

Figure 2 shows the regulation of the roll angle using BS for different values of C_1 and C_2 , with an initial condition of 20 degree. Figure 3 shows the variation of roll rate with time for the same initial condition. Figure 4 shows the tracking of roll angle using BS. Figure 5 shows the variation of control effort with time using BS. Figure 6 shows the disturbance analysis of roll angle using BS. Figure 7 shows the regulation of roll angle using ABS with 20 degree initial condition and for different values of C_1 and C_2 . As the value of C_1 and C_2 is increased the settling time decreases but for each case there is a small overshoot. Figure 8 shows the variation of roll angle for different values of C_1 and C_2 using ABS. Figure 9 shows the tracking of roll angle using ABS. Figure 10 shows the variation of control effort using ABS. Figure 11 shows the disturbance analysis of ABS on the roll angle for different

disturbance conditions. Figure 12 shows the comparison of regulation of roll angle using BS and ABS with $C_1 = C_2 = 1$. Figure 13 shows the comparison of regulation of roll rate using BS and ABS with $C_1 = C_2 = 1$. Figure 14 shows the comparison of tracking of roll angle using all the two controllers with $C_1 = C_2 = 1$. Figure 15 shows the disturbance analysis of the two controllers when they are subjected to a disturbance of 20 degree. From the simulation results, it is clear that the Adaptive Backstepping Controller gives a better response than Backstepping Controller.

6. Conclusion

In this paper Backstepping and Adaptive Backstepping Control schemes has been designed for the roll channel of launch vehicle in order to control the roll angle and the roll rate of launch vehicle. In the Backstepping control design all the non linearities affecting the system were considered as constant where as in Adaptive Backstepping design uncertainties associated with the system is considered while designing the control law and the parameter adaptation law. Simulation results shows that Adaptive Backstepping Control design gives comparatively better and satisfactory responses in comparison with the Backstepping Control design. Thus Adaptive Backstepping Controller displays good adaptability.

References

- [1] C.E.Hall, A.S.Hodel, J.Y.Hung, "Variable structure PID control to prevent integral windup", in: *Proceedings of the IEEE 31st Southeastern Symposium on System Theory*, 1999, pp.169-173.
- [2] J.Zhu, A.ScottHodel, K.Funston, C.E.Hall, "X-33 entry flight controller design by trajectory linearization—a singular perturbation approach", in: *Proceedings of American Astronautical Society Guidance and Control Conference, Breckenridge, CO, January 2001*, pp.151–170.
- [3] E. Johnson, T. Calise, H. El-Shirbiny, "Feedback linearization with neural network augmentation applied to X-33 attitude control", in: *Proceedings of AIAA Guidance, Navigation and Control Conference, 2000*.
- [4] Ola Harkegard and S. Torkel Glad, "A backstepping design for flight path angle control" *IEEE Conference on Decision and Control, Sidney, Australia, December 2000*, pp.3570-3575.
- [5] M. Kritic and I. Kanellakopoulos and P. Kokotovic, "Nonlinear and adaptive control design", John Wiley and sons, United States of America, 1995.
- [6] Arbin Ebrahim and Gregory V Murphy "Adaptive Backstepping Controller Design of an Inverted Pendulum", *Proceedings of IEEE Thirty-Seventh Symposium on System Theory*, 2002, pp. 172-174.
- [7] Baohua Lian, Hyochoog Bang, "Adaptive Backstepping Control based Autopilot design for Reentry Vehicle", in *proceedings of AIAA Guidance, Navigation and Control Conference, Providence, Rhode Island, August 2004*.
- [8] Ashima. C. R, Dr. S. Ushakumari, S. Geetha," Application of adaptive backstepping for the control of a Reusable Launch Vehicle", *National conference on technological trends, 2014*.

Author Profile

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