ISSN (Online): 2230-7893
www.IJCEM.org

VLSI Hardware Design of Generic MIMO Controller with Application in Satellite Orbit Control

Megha Kataria[1], Adarsh Srivastava[2]
[1]Research Scholar, Department of Electronics & Communication Engineering, Delhi College of Technology & Management, Delhi.
[2]Asst. Prof., Department of Electronics & Communication Engineering, Delhi College of Technology & Management, Delhi.

Abstract

This paper deals with the attitude and orbit control of a satellite by applying MIMO quantitative feedback approach. The objective is to design a set of proper controllers in presence of unknown disturbances and parametric uncertainties for a nonlinear MIMO system. The controller goal is to control the rotational speed of reaction wheels to adjust the satellite in desired course. In the present work, we have followed a different and convenient approach to design a generic MIMO controller that can be used for any applications. The design strategy relies on system parameters that can be encoded in the form of digital bit patterns and further control schemes can be easily designed based on that information. We further show how this generic MIMO controller can be used to control the satellite in its orbit which is considered to be a difficult problem. We solve various kinematic equations of motion of the satellite to arrive at control laws and then find the desired control scheme for our MIMO controller. The complete implementation of the design is achieved using VHDL and targeted for Virtex 6 FPGA using Xilinx ISE Design Suite.

***Keywords*: -** MIMO Controller, Digital Control, VLSI, VHDL, FPGA, Orbit Control

1. **INTRODUCTION-** The path of the satellite through space is called its orbit; the orientation of the satellite in space is called its attitude. Control of the orbital path is required to ensure that the satellite is in the correct location in space to provide the services required of it. Attitude control is essential on the spacecraft to prevent the satellite from tumbling in

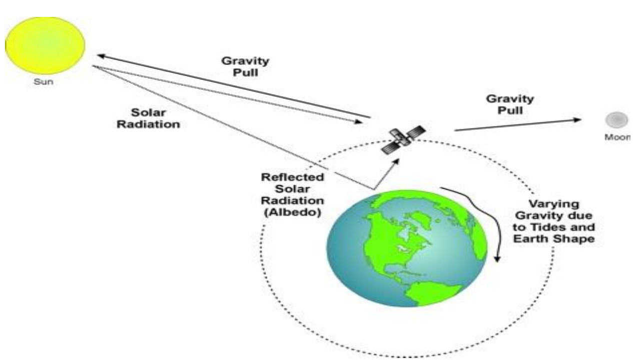


Fig 1.1 Satellite orbit diagram

space and to ensure that the antennas remain pointed at a fixed point on the Earth's surface. These functions are the responsibility of the Attitude and Orbit Control Subsystem (AOCS)[1]. A common problem in the operation of satellites is to guide them and position them at a desired orbit. During its motion however, it is influenced by numerous forces of diverse intensities and directions, emanating from different sources. These forces tend to disturb the satellite and put it into other than the desired orbit. In this thesis an analysis of the problems encountered in modeling and estimating the forces acting on a satellite will be made. The relative motion of satellites is defined as a space track or trajectory of one satellite with respect to another satellite in a gravitational field. The dynamics and control problems of satellite relative motion in a central gravitational field are highly challenging, compared to the problems associated with a single satellite system. Although it is possible to have an infinite number of satellites in a system, so it is require that the satellite remains in its orbits .One of the main difficulties encountered when designing adaptive controllers dealing with orbit and attitude control is that controller has to control the non-linear as well as well as the linear condition. A lot of research i.e. satellite control include linear and nonlinear $H\infty$[2] control, spacecraft attitude control[3], small satellite attitude control and simulation[4] and satellite attitude control using three reaction wheels[5] has been devoted in order to control the angular position in all the direction. But the better conclusion was not found therefore such a MIMO controller required that can control both the linear and non-linear conditions. So in this thesis a Generic MIMO Controller is designed that can control both the conditions and this MIMO controller is used for any other industrial application because this is Generic. The main objective of the work is to simulate a geostationary orbit of a satellite and apply suitable control schemes in order to keep it in the desired orbit, irrespective of external influences and resulting perturbations, using a generic PID MIMO controller (by keeping the kinetic, potential energy and momentum of satellite as the reference input of digital PID MIMO controller.

2 KINEMATIC EQUATIONS OF MOTION

Occasionally satellites will orbit in paths that can be described as ellipses [6]. In such cases, the central body is located at one of the foci of the ellipse. Similar motion characteristics apply for satellites moving in elliptical paths. The velocity of the satellite is directed tangent to the ellipse. The acceleration of the satellite is directed towards the focus of the ellipse. And in accord with Newton's second law of motion, the net force acting upon the satellite is directed in the same direction as the acceleration - towards the focus of the ellipse. Once more, this net force is supplied by the force of gravitational attraction between the central body and the orbiting satellite. In the case of elliptical paths, there is a component of force in the same direction as (or opposite direction as) the motion of the object, such a component of force can cause the satellite to either speed up or slow down in addition to changing directions. So unlike uniform circular motion, the elliptical motion of satellites is not characterized by a constant speed.

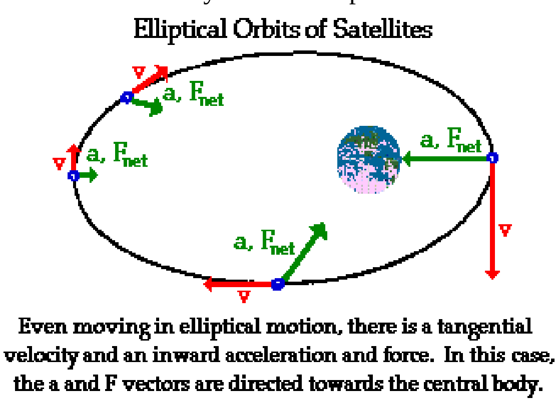


Fig 5.2 Elliptical orbit of Satellite

In summary, satellites are projectiles that orbit around a central massive body instead of falling into it. Being projectiles, they are acted upon by the force of gravity - a universal force that acts over even large distances between any two masses. The motion of satellites, like any projectile, is governed by Newton's laws of motion. For this reason, the mathematics of these satellites emerges from an application of Newton's universal law of gravitation to the mathematics of circular motion. Consider a satellite with mass M_{sat} orbiting a central body with a mass of mass $M_{Central}$. The central body could be a planet, the sun or some other large mass capable of causing sufficient acceleration on a less massive nearby object. If the satellite moves in circular motion, then the net centripetal force acting upon this orbiting satellite is given by the relationship

$$\mathbf{F_{net} = (M_{sat} \bullet v^2) / R}$$

This net centripetal force is the result of the gravitational force that attracts the satellite towards the central body and can be represented as

$$\mathbf{F_{grav} = (G \bullet M_{sat} \bullet M_{Central}) / R^2}$$

Since $F_{grav} = F_{net}$, the above expressions for centripetal force and gravitational force can be set equal to each other. Thus,

$$\mathbf{(M_{sat} \bullet v^2) / R = (G \bullet M_{sat} \bullet M_{Central}) / R^2}$$

Observe that the mass of the satellite is present on both sides of the equation; thus it can be canceled by dividing through by $\mathbf{M_{sat}}$. Then both sides of the equation can be multiplied by **R**, leaving the following equation.

$$\mathbf{v^2 = (G \bullet M_{Central}) / R}$$

Taking the square root of each side, leaves the following equation for the velocity of a satellite moving about a central body in circular motion.

$$v = \sqrt{\frac{G * M_{central}}{R}}$$

where **G** is 6.673 x 10^{-11} N•m^2/kg^2, $\mathbf{M_{central}}$ is the mass of the central body about which the satellite orbits, and **R** is the radius of orbit for the satellite.

2.1Energy-Momentum Analysis

A satellite orbiting the earth in elliptical motion will experience a component of force in the same or the opposite direction as its motion. This force is capable of doing work upon the satellite. Thus, the force is capable of slowing down and speeding up the satellite. When the satellite moves away from the earth, there is a component of force in the opposite direction as its motion. During this portion of the satellite's trajectory, the force does negative work upon the satellite and slows it down. When the satellite moves towards the earth, there is a component of force in the same direction as its motion. During this portion of the satellite's trajectory, the force does positive work upon the satellite and speeds it up. Subsequently, the speed of a satellite in elliptical motion is constantly changing - increasing as it moves closer to the earth and decreasing as it moves further from the earth. These principles are depicted in the diagram below.

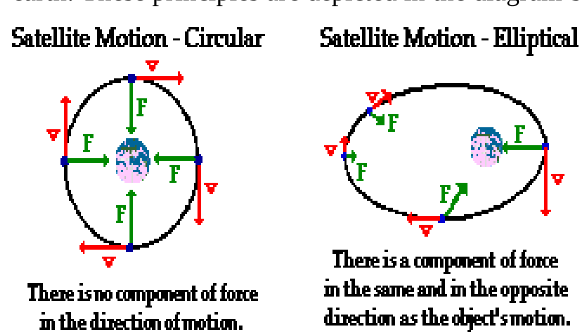


Fig 5.2.1Satellite Motion

In motion was analyzed from an energy perspective. The governing principle that directed our analysis of motion was the **work-energy theorem**. Simply put, the theorem states that the initial amount of total mechanical energy (TME_i) of a system plus the work done by external forces (W_{ext}) on that system is equal to the final amount of total mechanical energy (TME_f) of the system. The mechanical energy can be either in the form of potential energy (energy of position - usually vertical height) or kinetic energy (energy of motion). The work-energy theorem is expressed in equation form as

1.1 $KE_i + PE_i + W_{ext} = KE_f + PE_f$

The W_{ext} term in this equation is representative of the amount of work done by external forces. For satellites, the only force is gravity. Since gravity is considered an internal (conservative) force, the W_{ext} term is zero. The equation can then be simplified to the following form.

$\mathbf{KE_i + PE_i = KE_f + PE_f}$ In such a situation as this, we often say that the total mechanical energy of the system is conserved. That is, the sum of kinetic and potential energies is unchanging. While energy can be transformed from kinetic energy into potential energy, the total amount remains the same - mechanical energy is *conserved*. As a satellite orbits earth, its total mechanical energy remains the same. Whether in circular or elliptical motion, there are no external forces capable of altering its total energy.

$$\mathbf{E_T = KE + PE}$$
$$\mathbf{=1/2M_2V^2 + M_2\,gR}$$

By considering the velocity of satellite from above equation

$$\mathbf{=(G \bullet M_{Central})M_2 / R + M_2gR}$$
$$E_T= \frac{\mathbf{(G \bullet M_{Central})M_2 + M_2gR^2}}{\mathbf{R}}$$

2.2 Momentum

Momentum can be defined as "mass in motion." All objects have mass; so if an object is moving, then it has momentum - it has its mass in motion. The amount of momentum that an object has is dependent upon two variables: how much *stuff* is moving and how fast the *stuff* is moving. Momentum depends upon the variables mass and velocity. In terms of an equation, the momentum of an object is equal to the mass of the object times the velocity of the object.

1.1.1 Momentum = mass • velocity

In physics, the symbol for the quantity momentum is the lower case "p". Thus, the above equation can be rewritten as

$$\mathbf{p = m \bullet v}$$

where **m** is the mass and **v** is the velocity. The equation illustrates that momentum is directly proportional to an object's mass and directly proportional to the object's velocity.

$$\mathbf{dp/dt=d(mv)/dt}$$
$$\mathbf{=(dv/dt)*m}$$

Acceleration is the rate at which the velocity of a body changes with time.

$$\mathbf{dv/dt=a}$$
$$\mathbf{p=m*a \text{ although } p=F=m*a=m*g}$$
$$\mathbf{E_{T=} =\frac{(G \bullet M_{Central})M_2 + FR^2}{R}}$$

Hence by controlling the momentum and energy the attitude and orbit of satellite can be easily controlled.

3. Block diagram of MIMO controller to control the attitude of satellite:-

The MIMO control designs would utilize robust and modern control theories to synthesize attitude control designs which can take better advantage of the control system hardware to provide higher authority controllers, i.e., phase or gain stabilized. This paper presents an application of the intelligent PID generic MIMO controller in the attitude stabilization of flexible satellite.

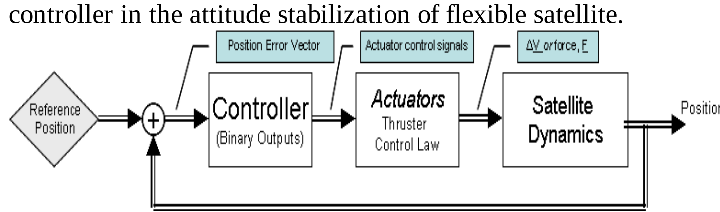


Fig .3 Block diagram of controller

3.1 Controller Description

A block diagram of the control loop is given in Fig. In practice the controller would be discrete, however, to simplify the design our controller is continuous and analog output is transformed in discrete form.

3.2Input and Output Signals

Signal	Type	Description
Position Reference	Reference	Angles defining satellite attitude in Euclidean Angles
U	Plant Input	Thruster input imparted on frame along Euclidean Angle
Δwd	Disturbanc e	Represented as acceleration imparted on body

Table 1 Input signal of Controller

3.3Actuators

In real attitude control systems, a blend of actuator systems such as gas thrusters, gyroscopic reaction wheels, and magnetoroquers are typically used. This project only uses gas jet thrusters for the attitude determination and control system (ADCS)[7]. The thrusters actuate the plant by imparting a torque about each axis of the spacecraft coordinate system. For a fully actuated system, a minimum of four opposing thrusters are required for each degree of freedom. This requirement allows the satellite to move in a bidirectional sense about each axis.

Signal	Type	Description
Thruster Control	Controller Output	Message command of optimal thrust output
U	Actuator Output	Thrust vector
Position	Plant Output	pitch, and yaw angles (Euclidean Angles)

Table 2 Output signal of Controller

3.4 Control Goals

The control goals [9] for our control problem can be deduced from considering the operational requirements of real satellites. Regardless of application, all satellites uplink and downlink information with ground based control stations. If the satellite attitude is disturbed, communication with the ground may be permanently lost since new control parameters cannot be uploaded with misaligned antennas. A similar control requirement seeks to keep the solar panels aligned with the sun. While large platforms like military and weather satellites usually have adjustable solar panels, smaller communication satellites can have fixed panels. If the solar cell alignment is lost for extended periods, the power cells may die and result in loss of the spacecraft. Additionally, some satellites observe features of the earth, atmosphere or celestial bodies. These sensor are usually very sensitive and require precise positioning. All of these situations lead to general stability requirements for the satellite. While some of the antennas and sensors may have their own stability control system.

For this model, our initial controller design goals will be to reposition the satellite according to a commanded reference input and to compensate for disturbances introduced [8] as rates imposed on platform. We are seeking feedback on our choice of controller requirements. Our metrics are somewhat arbitrary since the true constraints are based upon actual hardware flying on the spacecraft.

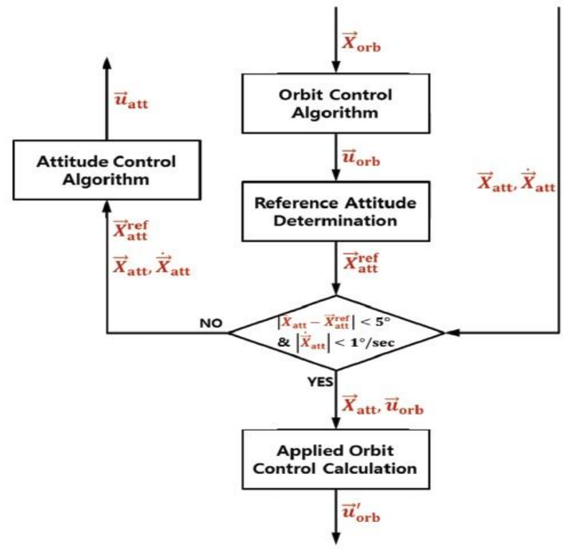
3.5 Algorithm for Controller

The same steps that have explained in block diagram is followed by flow chart.

1. Calculate the satellite attitude if it is not equal to reference attitude then error is generated and reduced by using attitude control algorithm.

2. Similarly calculate the satellite orbit if it is not equal to reference orbit then error is generated and reduced by using orbit control algorithm.

3.6Flow Chart of design



4. RESULT AND SIMULATION

The designing of PID based generic MIMO controller is achieved by using VHDL.The VHSIC Hardware Description Language VHDL is an industry standard language used within the design of digital circuits and systems. Toolsets based on the language allow the designer to model, simulate and ultimately synthesize into hardware logic complex digital designs commonly encountered in modern electronic devices. Figure identifies how VHDL is utilized in a typical approach to the design process. The design of the system at the gate level is more time consuming since the integrated circuit technology is more complex. Therefore the use of VHDL (Very High Speed Integrated circuit hardware Description Language) is preferred. VHDL can be used to describe and simulate the operation of digital circuits ranging from few gate to more complex gates[10]. VHDL can be used for the behavioral level design implementation of a controller and it offers several advantages. These are the advantages of VHDL :

1. VHDL allows us to describe the function of the controller in a more behavioral manner rather than focus on its actual implementation at the gate level .

2. VHDL makes the design implementation easier to read and understand.

4.1 Algorithm for designing a stable MIMO controller for satellite's orbit and attitude control using VHDL

1. Set the reference input pattern (by taking the power and momentum)

2. Initialize the all the input port and delay register

3.Execute the master gain Km, Proportionality gain, derivative gain and integral gain.

4. if (reset=1) all the outputs are zero.

5. Else t_div_late= value of Kd plus the delay between adjacent sample.
6.V_div= difference between the two samples.
7.V_acu= integration of errors.
8. V_acu_earl= sum of N - 1 samples of error
9. V_sum= V_acu + V_div (first adder)
10.Correct_O = Kp error + V_sum
11. if sum of all the three errors pattern i.e (Km > input pattern) then all the errors pattern become zero so that the system always remain stable.

4.2 RTL Schematic Of digital PID MIMO Controller

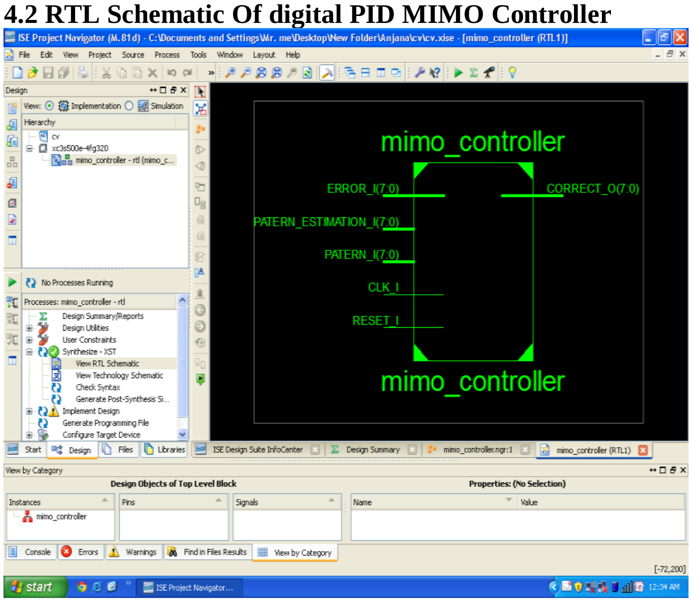


Fig 4.2 RTL view of PID Controller

4.3 Design object of top level block

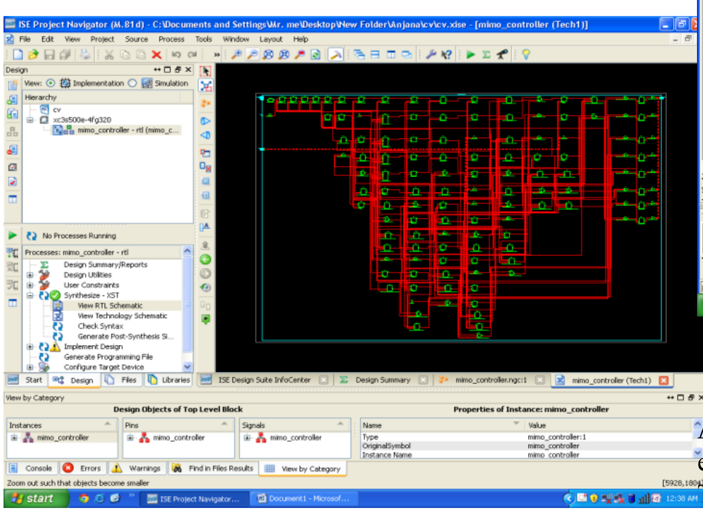


Fig 4.3 Design object of top level block

4.4Simulation results using Modelsim after 100 ns

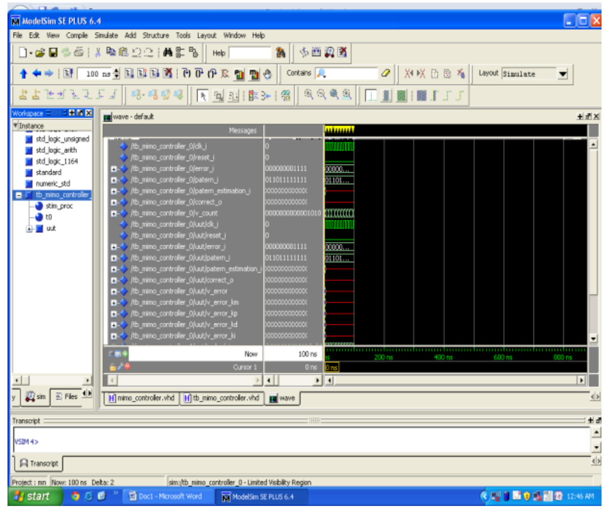


Fig4.4 Simulation results after 100 ns

At the time of 100 ns the value of Kp, Ki and Kd error is undefined.

4.5 Simulation results using Modelsim after 505 ns

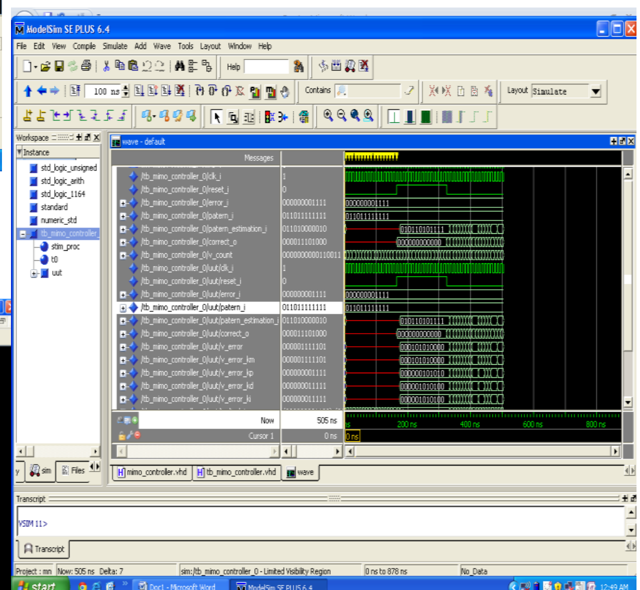


Fig 4.5 Simulation results after 505 ns

At the time of 505 ns the value of error_kp="000000001111".
The value of error_kd="000000011111"
The value of error_ki="000000011111"
And the sum of error error_km="000001111101"
Hence the system is going to be unstable.

4.6 Simulation results using Modelsim after 1100 ns

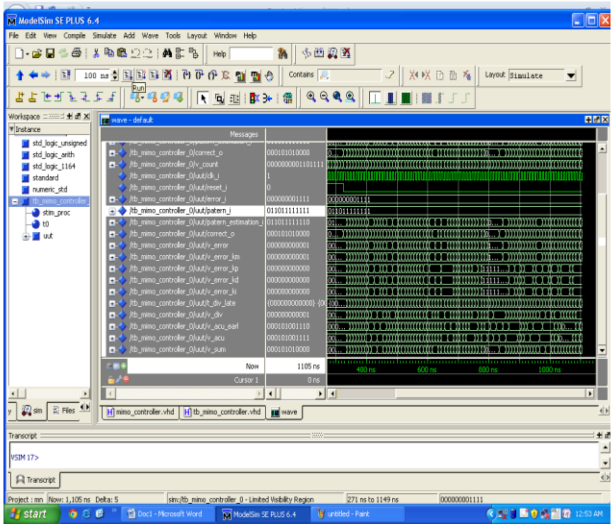


Fig 4.6 Simulation results after 1100 ns

The value of error_kp=”00000000000”
The value of error_kd=”00000000000”
The value of error_ki=”000000000000”
And the sum of error error_km=”000000000001”
Hence the system become stable because all the errors and sum of the error is zero and below the max. overshoot time. This is the Generic MIMO Controller, because by changing the reference input pattern this MIMO Controller can be used for any other application i.e. controlling the parameters of plant and industrial application etc.

Conclusion and Future Scope

As per the results shown and demonstrated, we have successfully implemented a generic MIMO controller and have shown how it can be effectively used to control a satellite in its orbit through controlling its energy and momentum parameters. The use of Field Programmable Gate Array (FPGA) for hardware implementation of the controller further allows us to reconfigure system parameters as and when needed and hence it can be used for a number of controlling needs.
Simulation results show the superiority of the control strategy and its capabilities. Our focus on simplified design approach yielded us better results in lesser time-frame than otherwise more complex routing solutions that need more time-complexity for execution. Also, our design based on generating error pattern is much better suitable for hardware based control systems rather than relying on estimation of error signal as in traditional control schemes which is more reliable for software based solution. This work can also be extended in several possible ways. One way would be to prove its BIBO stability mathematically for any system whatsoever for sake of convergence of theoretical result. At present, we can only show that the control strategy is finite and BIBO stable experimentally.

REFERENCES

[1] Regina M. Evans, ‘‘Satellite Orbital Control” December 12, 2008
[2] A. Umut Gen,‘‘ A State-Space Algorithm for Designing H1 Loop Shaping PID controller’’ October 12, 2000
[3] Hyungjoo Yoon and Panagiotis Tsiotras,‘‘Adaptive Spacecraft Attitude Tracking Control with Actuator Uncertainties Georgia 30332-0150, USA
[4] M.R. Ajir, ‘‘Small satellite attitude control and simulation,” Journal Mekanikal, Jun 2004
[5] Shahin S. Nudehi, Umar Farooq, Aria Alasty and Jimmy Issa,‘‘ Satellite attitude control using three reaction wheels’’ 2008 American Control Conference
[6] Louis J. Ippolito, Jr., ‘‘A book on Satellite Communications System Engineering, Atmospheric Effects”
[7] Ying-Wen Jan , Lee H. Ting , ‘‘Attitude determination and control system for a small LEO satellite” Spacecraft Project, National Space Program Office, Hsinchu 300, Taiwan, ROC
[8] Kleanthis Neokleous, ‘‘Modeling and Control of a Satellite’s Geostationary Orbit Department of Department of Space Science”, Kiruna 2006
[9] Robert Kohl, James Morton and Mike Roddewig, ‘‘Satellite On-station Orbital Control May 6, 2010
[10] A. Grout and K. Keane, ‘‘A matlab to VHDL conversion toolbox for digital control” University of Limerick, Limerick, Ireland
[11] P. Samundiswary1, K. Anitha, ‘‘Design and Analysis of CMOS Based DADDA Multiplier” International Journal of Computational Engineering and Management IJCEM, Vol. 16 issue 6, November 2013.