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PID COMPENSATOR DESIGN FOR LOW EARTH ORBIT SATELITE YAW-AXIS ALTITUDE STABILIZATION

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ABSTRACT:

There is still need to improve the tracking error and robustness of the control system in the presence of disturbance because the existing systems or technique doesn't meet the performance criteria for the system with regards to settling time and overshoot as high-precision satellite attitude control system (SACS) is critically demanded. In order to achieve this, the transfer function models of amplifier, actuator, and satellite structure for determining the transfer function a LEO satellite yaw-axis attitude were obtained. This work presented a yaw-axis ACS for LEO satellite using Proportional Integral and Derivative Tuned Compensator (PID-TC). The compensator was designed using the control system toolbox of MATLAB/Simulink based on PID Tuning design method using response time tuning technique with interactive (adjustable performance and robustness) design mode at a bandwidth of 44.5 rad/s. The compensator was added to position control loop of yaw-axis. Simulations were carried out in MATLAB environment for four separate cases (uncontrolled, PID-D, PID-TC-D, and LQR-D) by applying unit forced input to examine the various step responses. Initial simulation without the inclusion of the compensator (PID-TC) in the control loop resulting in rise time of 2.16 s, settling time of 22.14 s and 38.63% overshoot. Thus, in terms of the performance criteria defined for the system, all conditions were not met specifically the settling time and the overshoot. Hence, a PID-TC controller was designed and introduced into the system, which resulted in transient and steady-state performances of the system being characterized by rise time of 3.82, settling time of 7.30 s, overshoot of 3.88%, and steady-state error (0). The robustness of the designed PID-TC was examined by introducing a unit disturbance load torque and the step response simulation plot indicated that the achieved reduced rise time (1.82 s) and settling time (6.90 s) but with slight deterioration in smoothness and stability (as the overshoot was increased to 4.14%).

KEYWORDS: satellite, yaw-axis altitude control, tuned compensator, orbit.

INTRODUCTION

Background to the Study

The satellite attitude is regarded as the orientation in space considering the different coordinate system [1]; [2]nbbbv. The flight attitude of the satellite changes to different degrees during the on-orbit flight of a satellite because of external disturbances of and gravitational perturbation [17p.5]). These disturbances acting on the satellite can cause it to shift over time and the resulting effect can be angular (or degree) variation in pitch, yaw, and roll [4;17]. Considering the fact that a satellite is exposed to varying disturbances, it is important to keep it at a preset attitude and a specified attitude so as to realize desired function and performance criteria [5]. In this work, a PID-tuned control system that requires a LEO satellite yaw-axis attitude control system (ACS) to achieve improved transient and stable performance in the presence of disturbance is presented. This way, the system will be able to maintain reliable adjustment and stability in the presence of disturbance during its on-orbit flight operation.

Statement of the Problem

A high-precision satellite attitude control system (SACS) is critically demanded. Besides, the rapid development in aerospace industry has made the need for reliable, stable and accurate satellite control system to become ever more stringent. When a satellite is in an on-orbit flight, its flight attitude will change due to varying angular variations in pitch, yaw, and roll caused by gravitational perturbation and external disturbance [5].

Aim and Objectives

This work aims to enhance the stabilization of a low Earth orbit satellite's yaw-axis attitude control system using a robust proportional-integral-derivative-tuned compensator (PID-TC).

The specific objectives are to:

Determine the mathematical model of a satellite yaw-axis attitude control system.

Design a PID-tuned compensator for the satellite yaw-axis attitude control system.

Develop a simulation model for a satellite attitude control system (SACS) using MATLAB/Simulink control system toolbox.

Scope of the Study

In this work, the mathematical model representing the dynamics of the LEO satellite yaw-axis is presented. A robust control scheme is designed. A MATLAB/Simulink model of the satellite yaw-axis control system is developed.

LITERATURE REVIEW

The environment in which satellites must operate and energy conservation will be discussed in this chapter. Geosynchronous earth orbit (GEO), Medium Earth Orbit (MEO), and Low Earth Orbit (LEO) are useful orbits that will be presented.

Satellite Environment and Energy Conservation

Above the Earth's atmosphere are conditions generally called space environment. The edge of space cannot be described by any predetermined condition since increase in attitude results in gradual dissipation of the atmosphere [4,p6]. Conventionally, 100 km above the surface of the earth that marks the beginning of space is defined as the edge of atmosphere [4]. Once the satellite is out of the atmosphere, it operates in a vacuum (i.e. empty space). Satellite, while operating in the vacuum environment experiences many challenges such as lack of convention heat transfer process, out gassing, and cold welding[6]. Risks of micro-meteors are also faced by satellite in the absence of atmospheric protection. The earth's magnetosphere protects satellite from charged particles and electromagnetic radiation. There are many advantages to staying in the atmosphere. However, for satellites to reach their missions' attitude, they have to leave somewhat safety or comfort provided by the atmosphere. The structure of a spacecraft or satellite with reference body coordinate frames with respect to pitch, roll and yaw-axis is shown in Figure 1.1.

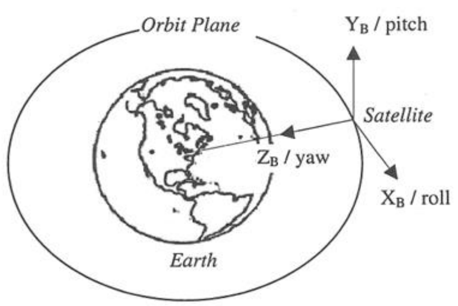

Figure 1.1 Satellite reference coordinate frames [7]

Satellite Orbits

The various earth's orbits associated with satellite operation are described in this section. These orbits have been successfully used for space mission. Each of the orbits has its own peculiar advantages and disadvantages. Hence, choosing any of these orbits for space mission depends on the advantages that are critical and the disadvantages that can be overlooked. The inclined orbit representation of on board satellite called OBITO and its open view are shown in Figures 1.2 and 1.3.

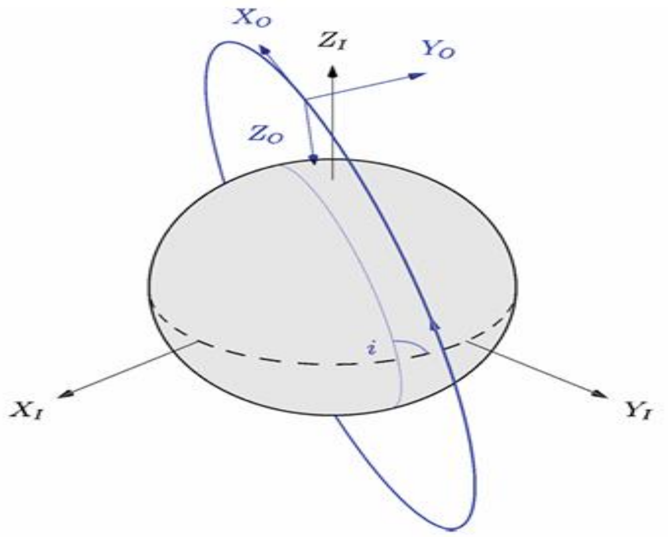

Figure 1.2 Inclined orbit representation of QBITO satellite together with orbit (X_o, Y_o, Z_o) del Castañedo *et al*. (2019)

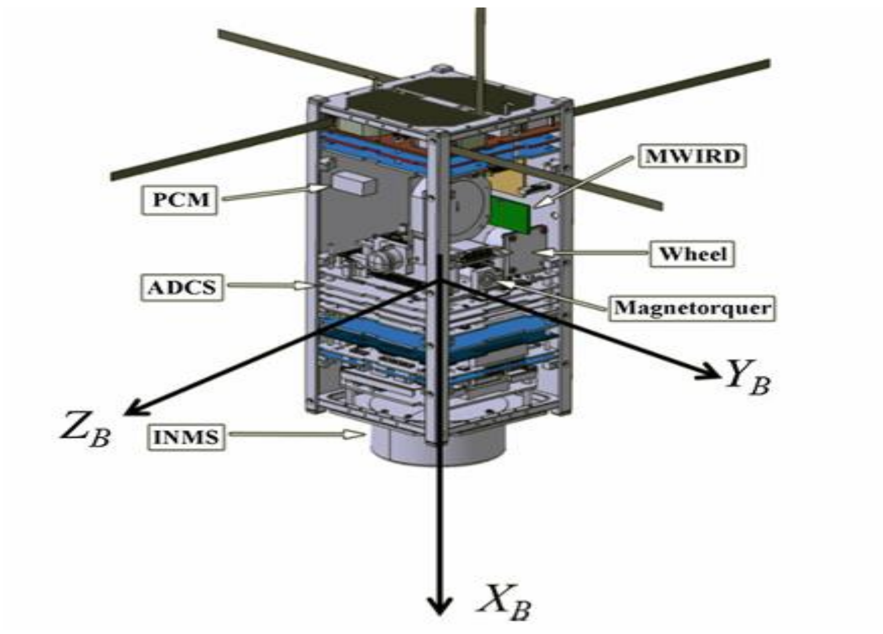

Figure 1.3 Open view QBITO with all payloads[8]

Low Earth Orbit

Low earth orbit (LEO) is of described by an altitude between 160 to 6000 km. It can be elliptical or circular orbits. LEO is useful for several reasons because of its relative closeness to the earth's surface[4]. Compare to other orbits, putting the LEO satellite into orbit requires least amount of energy (smaller rocket) because it has the smallest size. In staying in LEO orbit, there are some compromises required. This because staying in such low orbit will result in limited view. This can be addressed using multiple satellites in slightly orbits at the same altitude, but at significant cost [4,p9].

Medium Earth Orbit

The medium earth orbit (MEO) tends to be circular and with an altitude of nearly 20,000 km. Over a given area of the earth, the revisit times of the satellite are consistent and predictable because the altitude equates to a period of 12 hours [4]. Putting satellites in this orbit, which is a higher altitude than LEO, provides larger footprint or coverage across the earth surface. This means that unlike in LEO were 60 + satellites may be required to cover the entirety of the earth's surface, few satellites (say 24) can be used to offer continuous coverage such as in Global Positioning System satellite[4,p9].

Torque Rods (or Magnetic Torquers)

As electromagnets, torque rods or magnetic torquers are designed for asymmetric magnetic field production [9]. The desired magnetic field is created together with desired magnetic dipole by controlling current through the coils of electromagnets. The magnetic field of the torque rod interacts with the ambient magnetic field of the earth[9,p5]. An effective torque needed in achieving attitude control is produced from this interaction. The magnetic torquers generate a control torque, which is the product of the earth's magnetic field and torque rod magnetic dipole's moment. Additionally, the produced control torque for the correction of attitude also depends on angle between the torque rod and magnetic field line[9p5]. When the torque rod's dipole moment and the magnet field of the earth are perpendicular to each other, the maximum torque is produced. The satellite attitude can be controlled within 0.87 to 8.7 mrad pointing precision by the torque produced, or the torque produced together with the reaction wheels can be used to achieve improved control and offer desaturation (Ju, 2017). For de-tumbling and corrections of attitude with low pointing precision, magnetic torquers are relied upon by most satellite [9,p3]. There is no torque generated when the magnetic field of the earth and the dipole moment are parallel. Hence, no rotational movement is produced about magnetic field line of the earth by a satellite with a single torque rod. Regarding attitude control, two-axis control can be provided by a satellite fitted with a single torque rod when one of the torque rods line up with the earth's magnetic field line [9]. However, this control problem can be addressed by accurate model of the earth's magnetic field line and predictive control techniques. Generally, the magnetic torquers can be simply explained as a compass needle[11]. It operates by creating a magnetic field that interacts with the magnetic field of the earth. Hence, the operation is such that a local magnetic field is created when current is applied through a coil. The local magnetic field created tends to align with the magnetic field of the earth. This way, the satellite attitude is allowed to change and is a very common strategy for small spacecraft such as cubesats [11p7]. Figure 1.4 shows torque rods of iron core wound copper wire.

Figure 1.4 Torque rod of iron core wound copper wire[12]

Thus, because of the fact that the magnetic field of the earth moves from the North Pole to the South Pole as illustrated in Figure 1.5 lies one of the problems with magnetic torquers. This is because there will be mostly a downward magnetic field component that reduces the actuation operation of the magnetic torquer to only two axes, and also along the equator, when the satellite crosses the North Pole[12]. Also, very slow or passive attitude control is offered by magnetic torquers, but when used together with reaction wheel, they aid in momentum dumping that can prolong the ACS lifespan. Figure 1.6 shows the arrangement of three orthogonal magnetic torquers in a HiNCub satellite.

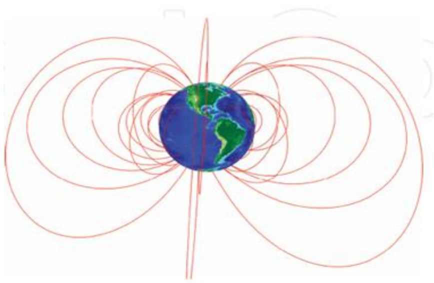

Figure 1.5 Illustration of the magnetic field of the earth[12]

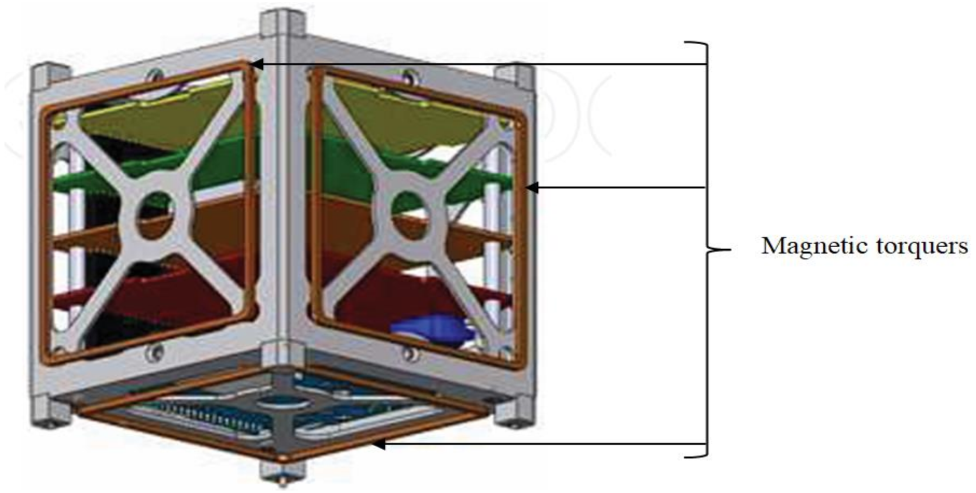

Figure 1.6 Illustration of magnetic torquers on the HiNCube satellite [12]

Momentum Wheel

Both reaction wheels and momentum wheels are similar. However, the rotation of the flywheel in the case of the reaction wheels occurs at a constant speed. The spinning of the momentum wheel is usually at high speed. Momentum wheel has angular momentum that is large. As the disturbance torques are absorbed by the momentum wheel, its speed decreases. However, through feedback law enabled by small deviation in applied voltage to the momentum wheel's motor, the speed and angular momentum is restored. The satellite's orientation is controlled by adjusting each flywheel's rotation speed. Equation (2.2) is a mathematical expression for three momentum wheel system that is used to achieve orientation control of satellite based on adjusting each flywheel rotational speed [9]:

$$\left.\begin{aligned} I_x^{mw}\dot{\omega}_x^{mw} + (I_Z^{mw} - I_y^{mw})\dot{\omega}_z^{mw}\dot{\omega}_y^{mw} &= I_x^{sa}\dot{\omega}_x^{sa} \\ I_y^{mw}\dot{\omega}_y^{mw} + (I_x^{mw} - I_z^{mw})\dot{\omega}_x^{mw}\dot{\omega}_z^{mw} &= I_y^{sa}\dot{\omega}_y^{Sa} \\ I_z^{mw}\dot{\omega}_z^{mw} + (I_y^{mw} - I_x^{mw})\dot{\omega}_y^{mw}\dot{\omega}_x^{mw} &= I_z^{sa}\dot{\omega}_z^{sa} \end{aligned}\right\} \quad (2.2)$$

The expression in Equation (2.2) describes the momentum wheel's torque and the total satellite's torque relationship. where I_i^{mw} is the momentum wheel inertia, I_i^{sa} is the satellite inertia, $\dot{\omega}_i^{mw}$ is the moment wheel angular acceleration, $\dot{\omega}_i^{sa}$ is the desired satellite angular acceleration, and all resolved in reference to ith axis of the ACS frame.

Attitude Control Methods

The inclusion of a potential detector in performing attitude control is quite an important method. This involves the addition of infrared sensors that facilitate the earth's circumference detection with respect to the space background. The method is carried out by integrating four sensors with each covering a quadrant and the reference point being the center of the earth. Thus, by detecting change in the orientation of the satellite, a restoring torque is generated that corresponds to the change detected. The ways by which the torque that controls the attitude is generated are as follows: active and passive attitude control respectively.

Similar to open loop control system, the passive attitude control enables a referenced attitude to be maintained by the satellite in a way that its position sustained utilizing little or no torque. In this method, the stabilization of the satellite is achieved without the energy supplies impeded. This method of satellite attitude control includes dampers, spin stabilization, and gravity gradient stabilization.

The active attitude control is regarded as a closed-loop control technique in which a feedback mechanism is required to make sure that needed fine-tuning are performed. This is in contrast to passive attitude control in which the whole torque needed for stabilization is not provided in order to pay off for perturbation torque. Whereas for the active control, the whole corrective torques needed to properly solve disturbance torque effect is provided[13].

Control System Concept

Open-loop Control System

In open-loop control system, the output and the control action are independent. Figure 1.7 is a block diagram description of open-loop control system's elements. These elements can be considered in two parts namely, the controller and the controlled process.

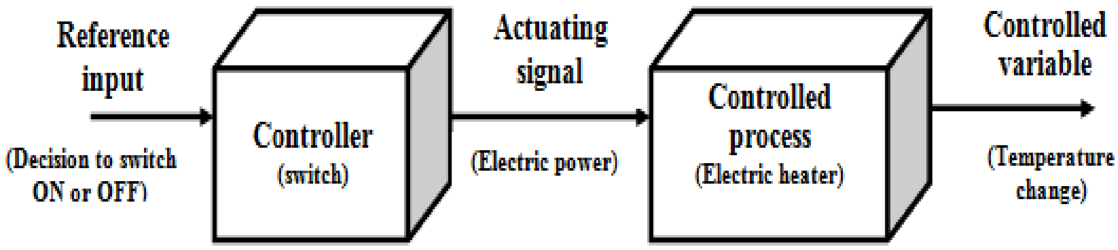

Figure 1.7 Illustration of open- loop control system[14]

With a reference signal applied to the controller, it generates a control action called actuating signal. This signal so generated is fed to the controlled process, which output a response signal called controlled variable. The resulting control variable performs according to defined standards. The illustration of open-loop control shown in Figure 1.7 considers an electric room heater operated by a switch. When the switch is turned ON, the room heats up and attains a predetermined temperature which is determined by the electric heater wattage rating. Output of the electric heater cannot be regulated and thus remains the same despite changes in the condition of the room temperature since no information is sent back via a feedback mechanism to the heating element. This is the basic concept of open loop control system.

There are associated advantages and disadvantages to open-loop control system. Its advantages are that the only parameter responsible for the provision control signal, performance accuracy is a measure of calibration, simple to design and implement, and it is not prone to instability. However, the disadvantages include absence of feedback, and it malfunction due to presence of nonlinearities.

Closed-loop Control System

A closed-loop control system is generally characterized by a feedback from that provides fraction of the output to be compared with the reference input. The feedback mechanism is missing in open-loop control system, which forms the main difference between two control systems. With the presence of feedback mechanism, accurate control is sure to be achieved. This involves feeding back the controlled variable into a summing circuit together with the reference input. Both the controlled variable and the reference input are compared in the summing circuit and the resulting effect is a variable called actuating error or simply error. The error from the summing circuit is proportional to the difference between the controlled variable and the reference input. The controller uses this error to provide correctional or control command to adjust the control system as shown in Figure 1.8.

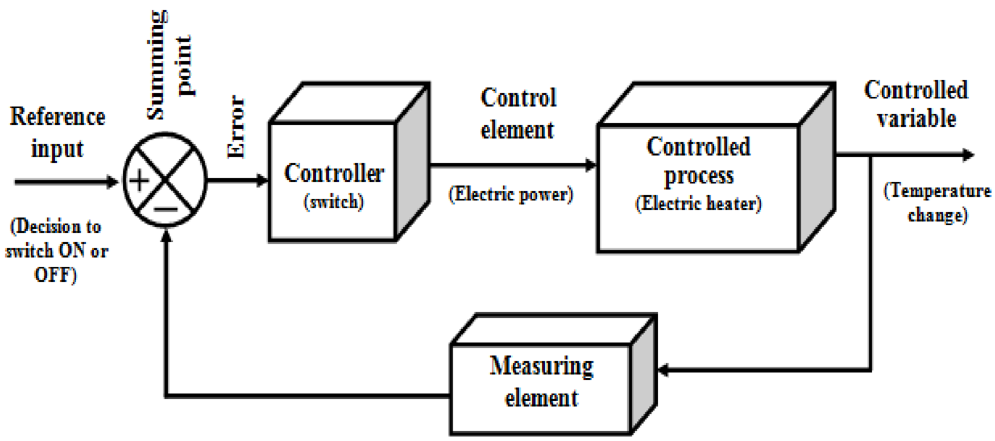

Figure 1.8 Closed-loop control system [14]

There are basically five elements in closed-loop control system

Comparison element: Comparison element is the summing point in Figure 1.8 and gives the difference between the reference Input and feedback signal. Error signal is equal to reference value signal-Measured value signal.

Correction element: The correction element (controller) produces a change in the process to correct or change the controlled condition. Thus it might be a switch which switches on a heater and so increase the temperature of the process or a valve which opens and allow more liquid to enter the process. The term actuator is for the element of a correction unit that provides the power to carry out the control action.

Control element: Control element (actuating signal) decides what action to take (for example, switch on or off when it receives an error signal).

Process element: The process being controlled could be a room in a house with its temperature being control or a tank of the water with its level being controlled.

Measuring element: The measuring element produces a signal related to the control variable (output). For example, it might be a Thermocouple which gives an EMF proportional to the output temperature.

Description of PID Control System

A Proportional Integral Derivative (PID) controller is a generic control loop feedback mechanism widely used in industrial control systems and regarded as the standard control structures. A PID controller, sometimes called three-term control, calculates an error value as the difference between a measured process variable and a desired set point. The controller attempts to minimize the error by adjusting the process through use of a manipulated variable.

The PID controller has the optimum control dynamics including zero steady state error, fast response (short rise time), no oscillations and higher stability. The necessity of using a derivative gain component in addition to the PI controller is to eliminate the overshoot and the oscillations occurring in the output response of the system. One of the main advantages of the PID controller is that it can be used with higher order processes including more than single energy storage. Figure 1.9 shows the control system of schematic model with general PID controller.

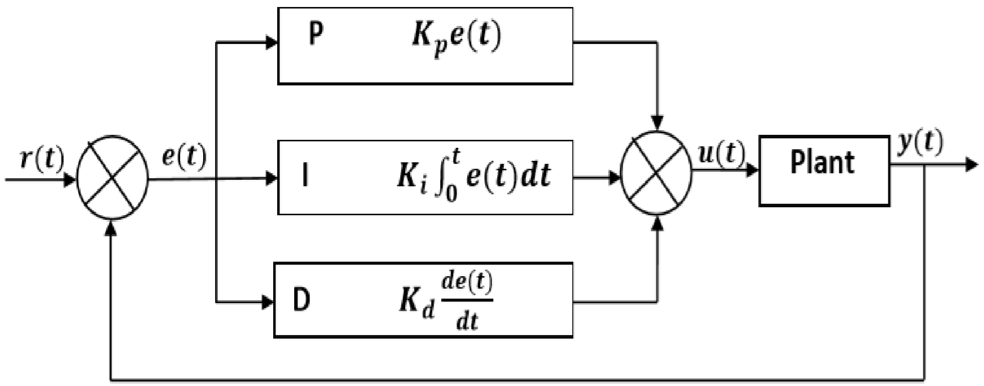

Figure 1.9 The Schematic Model of a PID Controller Configuration [15]

Proportional Controller (P): In a Proportional controller, there is a continuous relationship between the output of the controller (Controlled Variable) and the actuating error signal e(t) (deviation). Basically, proportional controller is an amplifier with adjustable gain. The action of this controller depends on the present error. The main usage of the P controller is to decrease the steady state error of the system. As the proportional gain factor K increases, the steady state error of the system decreases but not completely eliminated. The equation for proportional controller is given by:

$$u(t) = K_p e(t) \quad (1.1)$$

where $u(t)$ = controller output, K_p = proportional gain/sensitivity, and e(t) = actuating error signal

Integral Controller (I): In the integral controller action (also known as Reset Control), the output of the controller changes at a rate proportional to the actuating accumulation of past error signal, $e(t)$.

$$u(t) = K_i \int e(t)dt \quad (1.2)$$

where K_i = Integral gain, $u(t)$ = Control output.

Derivative Controller (D): In a controller with derivative control action, the output of the controller depends on the rate of change of the actuating prediction of future error signal e(t). This type of controller cannot be used alone because when the error is zero or constant, the output of the controller will be zero. The equation for D is written as

$$u(t) = K_d \frac{de(t)}{dt} \quad (1.3)$$

where K_d = Derivative gain constant.

Table 2.1 summarizes the functions of the three elements that make up a PID controller. Figure 2.15 is block diagram representation of a PID controller.

Table 1.1: A summary of the elements of PID controller.

Control Action	Symbol	Function
Proportional Control	P	It implements the typical operation of increasing the control variable when the control error is large
Integral Control	I	It momentarily tracks the control error. It does this by relating to the past values of the control error and allows the reduction to zero of the steady state error when desired step input is applied
Derivative Control	D	It predicts the future values of the control error and has a great potential in improving the control performance as it can anticipate an incorrect trend of the control error and counteract for it.

Review of Related Works

The demand for satellite attitude control (SAC) system with high precision has become critical and the desire to have a satellite controller that will provide stability, accuracy and reliability has become increasingly stringent looking at the fast growth in aerospace business [3; 16]. When a satellite is in its on-orbit flight, it experiences variations in yaw, roll, and pitch due to external disturbances and effect of gravitation. Displacement of the satellite over time can occur due to the influenced of these disturbances and the result could be angular change in yaw, roll and pitch[4]. Therefore, having a subsystem (Controller) that ensures that the required maneuvering is provided to keep an on-orbit flight satellite at a specified position and a given attitude is of the essence. This is to ensure that expected task and design criteria are achieved. Based on this, a controller is integrated with a satellite attitude control system (SACS) to serve as the subsystem offering the required maneuvering ability to maintain defined orientation for the satellite for efficient fight action. Nevertheless, it is important to examine the subsystem of the SACS so as to find the proper controller that provides improvement to the dynamic or transient characteristics and steady state performance for the adjustment of the flight attitude and stability. This ensures that the needed on-orbit flight is effectively accomplished.

Considering the fact that attitude angles of a satellite can be put out of place due to various sources of usual perturbation like pressure from solar radiation, earth’s gravitational force, and the earth’s magnetic field; and because successful mission of a satellite depends on its ability to maintain a predetermined orientation with respect to the earth [18], many methods of control have been developed stabilization of attitude motion.

Software-in-the loop (SIL) was used for the design and implementation of microsatellite attitude determination and control subsystem by [19].In the study, a description of the development of a microsatellite attitude and control subsystem (ADCS) including its functionality verification using SIL method was presented. Attitude control functions were provided by the ADCS together with de-tumbling and satellite angular velocity stabilization and in addition to the orbit and attitude information estimation during the operation of the satellite using unscented Kalman filter (UKF). There are three modes of operation carried out by the ADCS, which included initialization mode, de-tumbling mode, and normal mode. Early orbit measurement data are collected by ADCS from various sensors during the initialization mode so as to downlink the data to the ground station for more analysis. In order to minimize the satellite angular velocity, the thrusters are implemented in pulse-wide modulation (PWM) control method by the ADCS during the de-tumbling mode. During normal mode, the attitude determination function for satellite state estimation was provided by the ADCS. The UKF algorithm was adopted by the three modes of microsatellite for attitude estimation. The attitude estimation errors were shown from the results of SIL to be 3 degree and the UKF error was reported to converge after 240 s despite large initial attitude error. An attitude determination error of less than 5 degree was achieved by the ADCS so as to meet the design requirement.

Linear control techniques that largely depend on feedback from output such as the classical Proportional Integral and Derivative (PID) controllers have been well implemented as subsystem for SAC. For instance, classical PID controller was used to meet performance specifications in yaw angle control of satellite system [1]. The PID controller was designed using the Ziegler-Nichols tuning method and it was introduced into the closed loop of satellite model for the determination and control of yaw-axis. The results of the simulation conducted in MATLAB indicated that the PID controller provided settling time of 1.09 s and overshoot of 4.55% for the satellite attitude control system (SACS). Similarly, [20] used PID controller in satellite attitude control system to achieve rapid settling time, reduced overshoot and zero steady-state error.

Summary and Research Gap

In most of the control systems for satellite attitude stabilization, conventional PID models have largely been used. This can be attributed to their ease of design and the ability to offer control solution to system with dynamic complexity usually in many process control operations in the industry due to its simplified structure. Similarly, the classical PD control algorithm is commonly implemented in ADCS [21]. For instance, PID has been advantageously considered for satellite yaw-axis ACS because of its rapid transient response and steady-state error (Hassan, 2009). Notwithstanding the benefits offer by PID models, the problem of mismatch or parameter changes due to nonlinear effect caused by disturbance during operation still impact on its performance because this is not considered during system modelling. Therefore, this work is designed to meet performance criteria of a LEO satellite yaw-axis ACS as in [22; 19; 1]; with improved stability in the presence of disturbance.

MATERIALS AND METHODS

Material

This section presents the basic tools used in carrying out this work. The tools are enumerated as follows: MATLAB m-file environment, LTI Viewer, MATLAB Control System tool manager, Graphical user interface (GUI) of PID-Tuning Compensator, Simulink

3.2Method

The existing type of control loop for yaw-axis ACS in some of the recently published literature such as in [23, 5, 13, and24] is shown Figure 2.0. This control model does not take into consideration the effect of disturbance. The approach taken in terms of modelling of yaw-axis attitude control system, which comprises a controller, an amplifier, a DC motor, and a satellite system with a feedback sensor whose gain is considered to be unity with torque disturbance is presented in Figure 2.1.

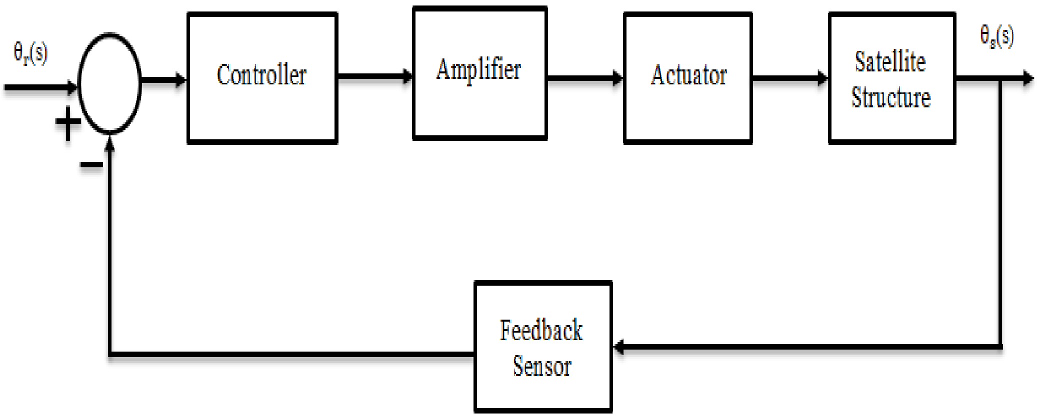

Figure 2.0 Closed loop of satellite yaw-axis ACS without torque disturbance.

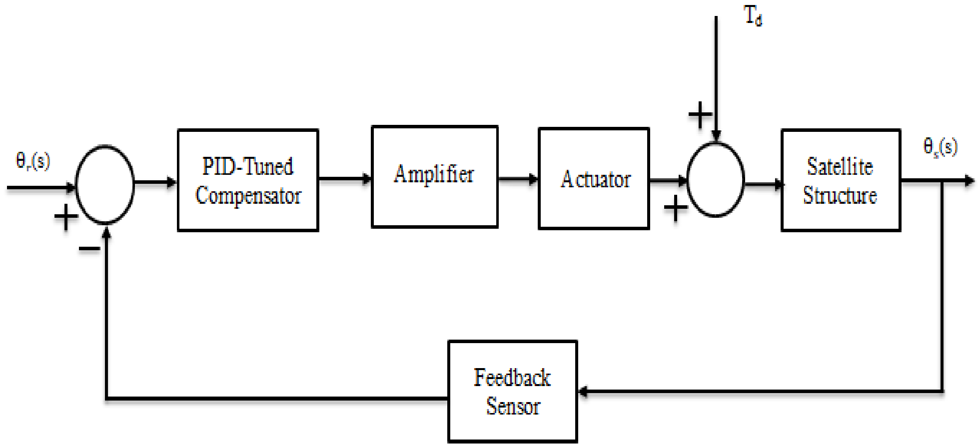

Figure 2.1 Closed loop of satellite yaw-axis ACS with torque disturbance.

For the yaw-axis ACS shown in Figure 3.1, the objective of the design is to ensure that the yaw-axis attitude or angle is stabilized by providing a suitable control maneuvering that returns and keep the satellite on its referenced or target attitude. In the figure, $\theta_r(s)$ is the reference or target attitude while $\theta_o(s)$ is the actual attitude. Hence, for stabilized and effective control of yaw-axis attitude at any instant, $\theta_r(s) = \theta_o(s)$. In meeting the design objective the proposed system is expected to achieve the following design criteria for a typical LEO satellite system: overshoot of $\leq 5\%$, settling time of ≤ 10 s and zero steady-error [22., 2023; 14.1]

Mathematical Modelling

Mathematical Model of Satellite System

The load torque T_L due to the torque delivered by the DC motor T_m and the disturbance torque T_d as shown Figure 3.2 is given by:

$$T_L = T_m + T_d \tag{1.4}$$

The moment of inertia J of the entire system consists of the motor moment of inertia J_a and the moment of inertia of the satellite structure or body J_I about axis of rotation at the center of mass [1] . Given the associated vicious friction B of the satellite structure (i.e. the load) and its actual angular position $\theta_o(t)$ about the yaw-axis, the load (satellite) torque assuming $T_d = 0$ is given by:

$$T_L = T_m = J\frac{d^2\theta_o(t)}{dt} + B\frac{d\theta_o(t)}{dt} \tag{1.5}$$

The Laplace transform of Equation (1.5) assuming zero initial condition is given by:

$$T_m(s) = Js^2\theta_0(s) + Bs\theta_0(s) \quad (1.6)$$

The transfer function of the satellite body dynamic in terms of the ration the actual angular position or attitude of the yaw-axis and input motor torque T_m (s) is given by:

$$\frac{\theta_o(s)}{T_m(s)} = \frac{1}{s(Js+B)} \quad (1.7)$$

Substituting the values for the parameters in Table 3.1 into Equations (1.1), (3.11) and (1.5) yields the numerical expressions for amplifier transfer function gain, the DC motor transfer function, and the satellite body transfer function as follows:

$$G_a(s) = \frac{V_a(s)}{V_i(s)} = 10 \quad (1.8)$$

$$G_m(s) = \frac{\theta(s)}{V_a(s)} = \frac{0.01}{0.05s^3 + 0.105s^2 + 0.0101s} = \frac{0.2}{s^3 + 2.1s^2 + 0.202s} \quad (1.9)$$

$$G_s(s) = \frac{\theta_o(s)}{T_m(s)} = \frac{1}{2.5s^2 + 1.17s} \quad (2.0)$$

The yaw-axis ACS is represented with a block diagram in terms of the transfer function of amplifier, DC motor, satellite body and unity gain feedback sensor assuming zero torque disturbance is shown in Figure 3.4 and the resulting transfer functions for open loop and closed control configuration of the yaw-axis ACS neglecting the PID-tuned compensator are given in Equations (3.19) and (3.20). Further modelling is considered assuming that unit torque disturbance enters the system as shown in Figure 2.2. The dynamic of the yaw-axis ACS with unit torque disturbance is divided into two parts as presented in Equation (2.0) without the compensator.

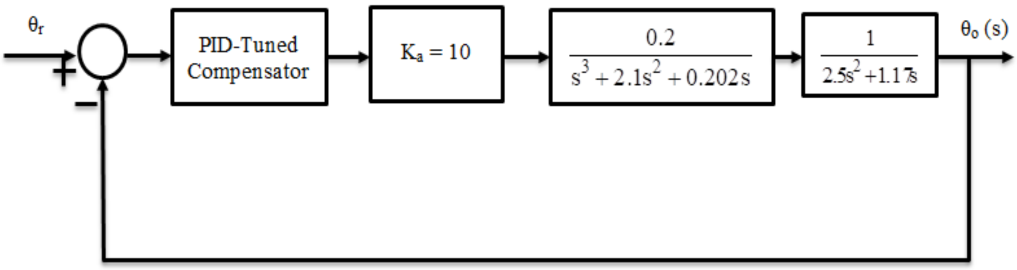

Figure 2.2 Closed loop network of satellite yaw-axis ACS with zero torque disturbance

$$G_{op}(s) = G_a(s) \times G_m(s) \times G_s(s) = \frac{2}{2.5\,s^5 + 6.42\,s^4 + 2.962\,s^3 + 0.2363\,s^2} \quad 2.1)$$

$$G_{cl}(s) = \frac{G_a(s)\times G_m(s)\times G_s(s)}{1+G_a(s)\times G_m(s)\times G_s(s)} = \frac{2}{2.5\,s^5 + 6.42\,s^4 + 2.962\,s^3 + 0.2363\,s^2 + 2} \quad 2.2)$$

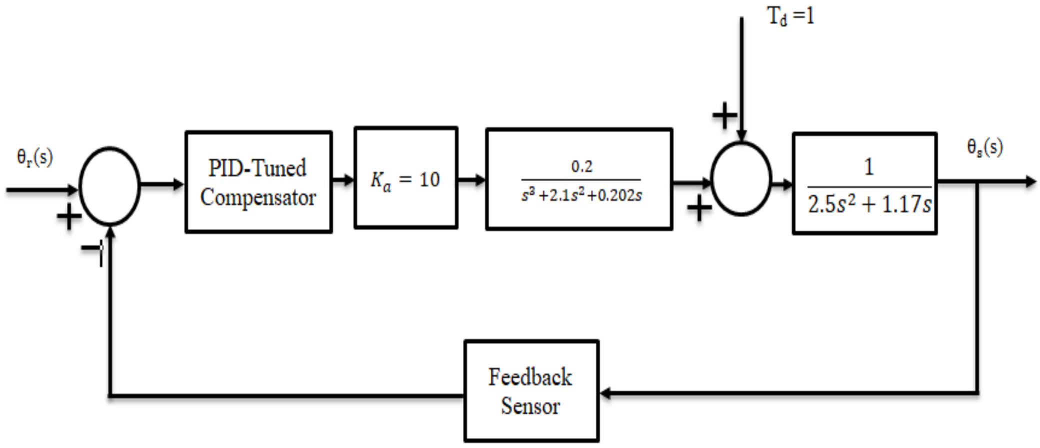

Figure 2.3 losed loop network of satellite yaw-axis ACS with unit torque disturbance

$$G_L(s) = \frac{[G_a(s)\times G_m(s)+T_d(s)]G_s(s)}{1+[G_a(s)\times G_m(s)+T_d(s)]G_s(s)} = \frac{s^3+2.1s^2+0.202s+2}{2.5s^5+6.42s^4+3.962s^3+2.336s^2+0.202s+2} \quad 2.3)$$

Design of PID-Tuned Compensator

Symmetrical analysis, design, and tuning of linear control systems is provided by the control system designer (CSD) of the MATLAB/Simulink for industrial algorithms and applications [25; 26]. Designing a compensator using CSD, can be achieved via PID tuning. Therefore, this section presents the design of PID-tuned compensator (PID-TC) for yaw-satellite ACS in CSD environment. The flowchart for the designing the PID-TC is shown in Figure 2.4.

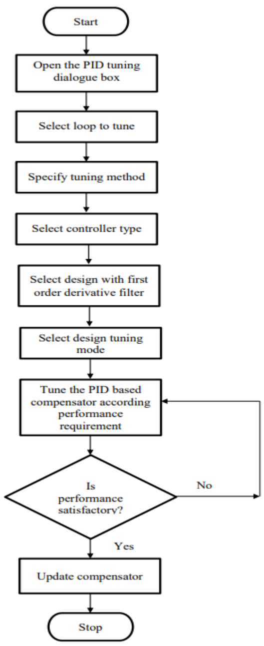

Figure 2.4 Design flowchart for the PID-TC

In designing the compensator, the tuning method chosen is the robust response time. The mode of design used is the frequency domain with a frequency bandwidth of 44.5 rad/s. The resulting PID-TC, G_C, is given by:

$$G_c(s) = 7.2402 \times \left[\frac{(1+0.33s)(1+2.8s)}{s(1+0.0024s)}\right] \quad 2.4)$$

Considering PID-TC in the closed loop control models in Figures 2.2 and 2.3, Equations (3.20) and (3.21) can be redefined by Equations (3.23) and (3.24), respectively.

$$G_{clc}(s) = \frac{G_c G_a(s) \times G_m(s) \times G_s(s)}{1 + G_c G_a(s) \times G_m(s) \times G_s(s)} \quad (2.5)$$

$$G_L(s) = \frac{[G_c G_a(s) \times G_m(s) + T_d(s)]G_s(s)}{1 + [G_c G_a(s) \times G_m(s) + T_d(s)]G_s(s)} \quad (2.6$$

Thus, Equation (3.23) represents the mathematical model of the PID-TC based yaw-axis ACS without torque disturbance. Equation (2.6) is the mathematical model of the PID-TC based yaw-axis ACS with torque disturbance.

Simulation Parameters

Table 2.1 shows the description of the values of the physical parameters for amplifier, DC motor, and satellite structure of Low Earth Satellite (LEO).

Table 1.2 Parameters of the of yaw-axis ACS (27; 28; 1)

Definition	Symbol	Value
Amplifier	K_a	10
motor a constant	K	0.01 Nm/A
Resistance of motor	R_a	1 Ω
Inductance of motor	L_a	0.5 H
Damping ratio of motor	B_a	0.01 Kgm^2
Moment of inertia of motor	J_a	0.1 Nms
Moment of inertia of satellite	J	2.5 Kg m^2
Damping ratio of satellite	B	1.17 Nms

RESULTS ANALYSIS.

Uncontrolled System Analysis

This section presents the simulation analysis of the LEO satellite yaw-axis attitude dynamic when it is uncontrolled. In this scenario, it is assumed that no controller was introduced as a subsystem in the attitude control system (ACS). The essence of controller is to make sure that the satellite yaw angle (or attitude) is stabilized and tracked (or maintained) within the reference value while ensuring that the system performance criteria which include rapid convergence to stable and steady-state with little or no cycling, and zero or minimum deviation is attained. This analysis was performed using the system model in Figure 2.5 without the developed PID-TC controller. The resulting step response performance parameters of the uncontrolled system are listed in Table 1.2.

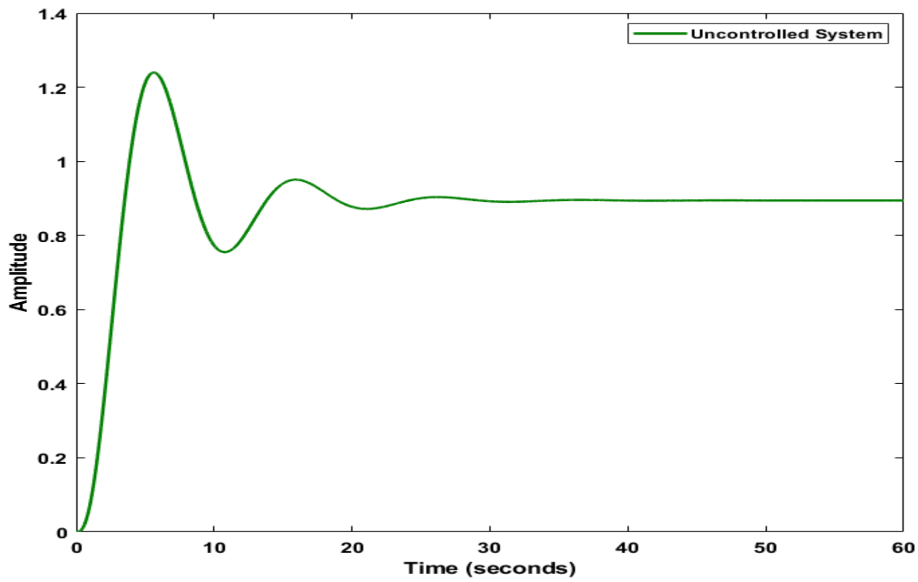

Figure 2.5 Step response of system without controller

Table 1.3 Step response performance characteristics of uncontrolled system.

Step response parameter	Value
Rise time	2.16 s
Settling time	22.14 s
Peak time	5.62 s
Peak value	1.24
Overshoot	38.63%
Final value	0.89
Steady state error	0.11

From the step response shown in Figure 1.3, the dynamic response of the uncontrolled system to unit forcing input command revealed that it is characterized by rise time of 2.16 s, settling time of 22.14 s, peak time of 5.62 s, peak value of 1.24, overshoot of 38.63%, final value of 0.89 degree, and steady state error of 0.11. These performance parameters show that in uncontrolled state, the yaw-attitude of the satellite will take a long time (measured in terms of settling time) to settle or reach a stable state during on orbit flight operation. Even when it reach a steady-state, it does so at undesired or expected attitude (i.e. 0.89), which is less than the reference (or desired attitude taken as unit magnitude. This resulted in a steady-state error of 0.11, which is very much larger than the minimum value required of a control system usually 2% criterion in order to achieve stable and reliable operation. Generally, as shown in

Figure 4.1, the curve revealed that the uncontrolled system was not able to achieve the desired attitude and suffers high instability as it overshoots the desired attitude by 38.63% (which is very much larger than the required 10%) at peak time of 5.62 s and reaching a peak value of 1.24 before settling at an attitude (0.89) very much less than the desired value (i.e. $0.89 \ll 1$). 4.2

Simulation Analysis of PID Tuned Compensator

This section presents the simulation scenario regarding the step response of the system when the PID tuned compensator (PID-TC) was introduced as a subsystem into the yaw-axis ACS. The simulation plot is shown in Figure 4.2 and the numerical analysis is shown in Table 4.2.

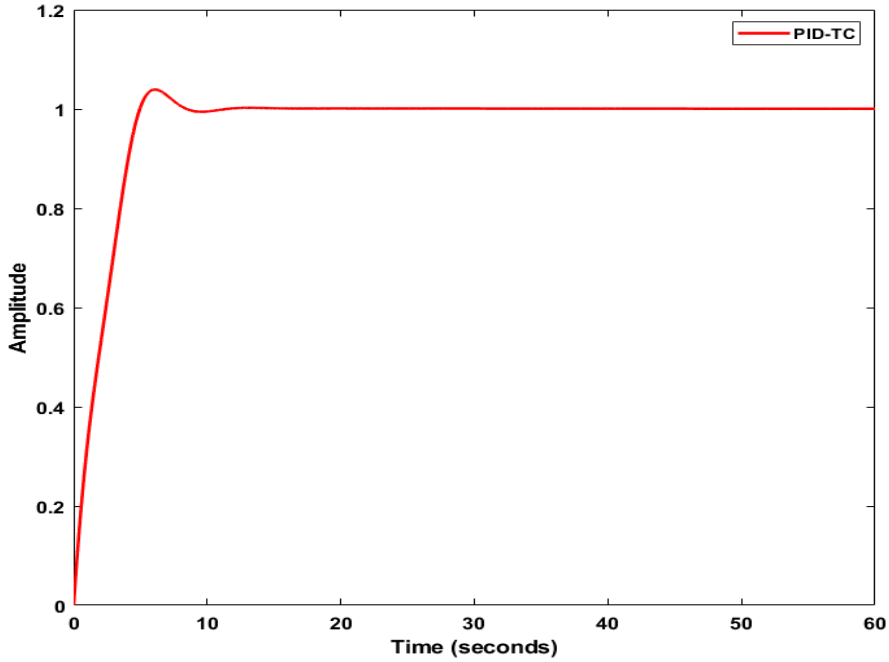

Figure 2.5 Step response of PID-TC yaw-axis ACS.

Table 1.4 Step response performance characteristics of PID-TC system.

Step response parameter	Value
Rise time	3.82 s
Settling time	7.30 s
Peak time	6.1 s
Peak value	1.04
Overshoot	3.88%
Final value	1.00
Steady state error	0.00

Looking at Figure 2.5, it can be observed that step response of the PID-TC control system overshoots or peaks the referenced unit attitude by 3.88% reaching a peak value of 1.04 at 6.1

s before settling at the referenced attitude at 7.30 s as shown in Table 1.4. The obtained dynamic response performance offered by the developed PID-TC is obviously within the acceptable required overshoot and settling time in terms of the performance specifications. It also represents an improvement over the uncontrolled system in settling time and overshoot.

Robustness Test of PID-TC with Unit Load Torque Disturbance

The robustness of the developed PID-TC was examined in this section by considering the presence of load torque disturbance on the dynamic response characteristics of the yaw-axis ACS. The step responses of the PID-TC based ACS and that with unit input load torque disturbance are shown in Figure 4.3. The resulting step response of the PID-TC with disturbance introduced in the control loop is tagged PID-TC-D. The parameters of the step response are listed in Table 1.5.

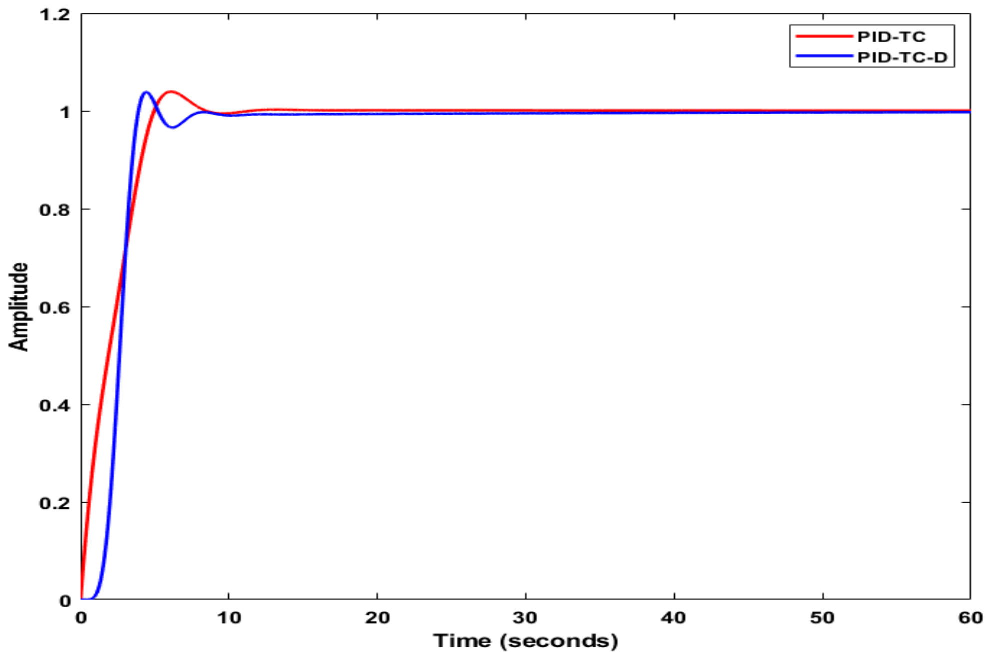

Figure 2.6 Step response of PID-TC ACS with and with disturbance

Table 1.5 Step response performance characteristics of PID-TC/PID-TC-D system.

Step response parameter	PID-TC	PID-TC-D
Rise time	3.82 s	1.82 s
Settling time	7.30 s	6.90 s
Peak time	6.1 s	4.42 s
Peak value	1.04	1.05
Overshoot	3.88%	4.14%
Final value	1.00	0.997
Steady state error	0.00	0.003

Looking at Table 1.5, it can be seen that with the introduction of unit step load torque disturbance, PID-TC-D exhibited reduced rise (or response) time and settling time compared with PID-TC. This can be attributed to the fact that the presence of disturbance caused the controller (PID-TC) to rapidly response to applied input command in order to cancel the effect and converges or settles faster in order to restore the satellite at the appropriate yaw-axis attitude. However, the presence of the disturbance caused the system to further overshoot above the referenced attitude by 4.14% and reaching a slight increased peak value of 1.05 at time 4.42 s before it eventually settles at final attitude of 0.997. The resulting steady-state error is 0.003 (or 0.3%), which is very much less than the usually 2% (0.02) or 5% (0.05) criterion required of a control system. Thus, the steady-state error is approximately equal to zero. From this performance looking at Table 4.3, it is obvious that the developed system met the design specifications (i.e. overshoot of $\leq 5\%$, settling time of ≤ 10 s, and zero steady-error) in both control conditions behaviour.

Performance Comparison of Controllers

In this section, the developed yaw-axis ACS based on PID-TC is compared with other control techniques based implemented previously for LEO satellite as in Enerjor *et al*. (2023); Eze *et al.* (2016); and Mbocha *et al.* (2016), where PID and LQR have been applied. Simulation analysis was carried out initially when the ACS was without load torque disturbance as shown in Figure 2.7 and then with load disturbance as shown in Figure 2.8.

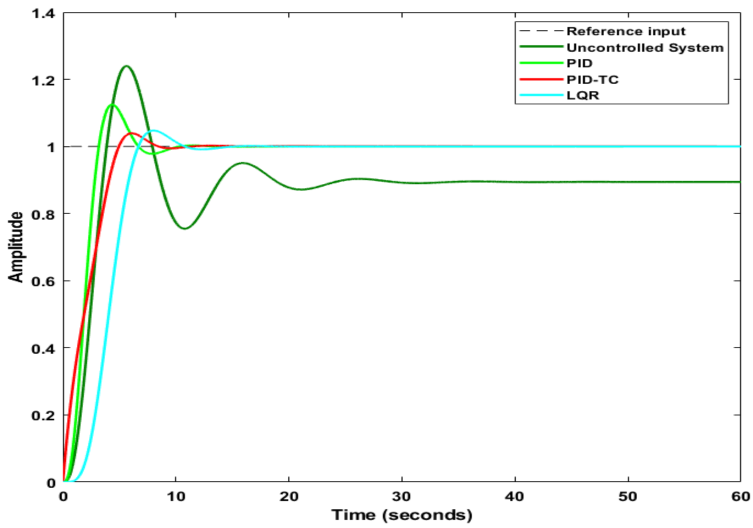

Figure 2.7 Comparison of ACS with different controllers (no disturbance)

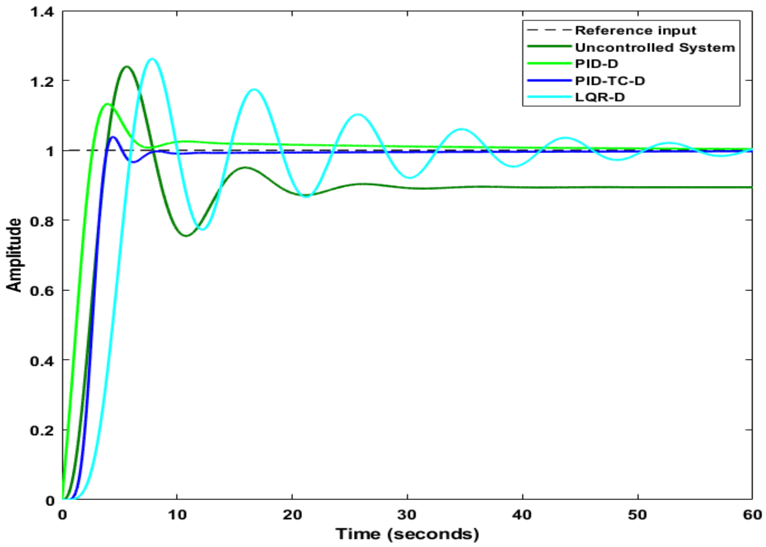

Figure 2.8 Comparison of ACS with different controllers (disturbance)

Table 1.7 Comparison of performance characteristics (no disturbance)

Step response parameter	Uncontrolled	PID	PID-TC	LQR
Rise time	2.16 s	1.95 s	3.82 s	3.53 s
Settling time	22.14 s	8.31 s	7.30 s	9.67 s
Peak time	5.62 s	4.35 s	6.1 s	8.02
Peak value	1.24	1.13	1.04	1.05
Overshoot	38.63%	12.51%	3.88%	4.74
Final value	0.89	1.00	1.00	1.00
Steady state error	0.11	0.00	0.00	0.00

Table 1.8 Comparison of performance characteristics (with disturbance).

Step response parameter	Uncontrolled	PID-D	PID-TC-D	LQR-D
Rise time	2.16 s	2.02 s	1.82 s	2.97 s
Settling time	22.14 s	11.9 s	6.90 s	57.32 s
Peak time	5.62 s	3.95 s	4.42 s	7.83 s
Peak value	1.24	1.13	1.05	1.26
Overshoot	38.63%	12.84%	4.14%	25.72%
Final value	0.89	1.00	0.997	1.00
Steady state error	0.11	0.00	0.003	0.00

From Figure 2.7 and Table 2.8, it can be seen that the introduction of the only the developed PID-TC and the LQR controllers met the specifications for the dynamic response of the yaw-axis ACS. Though, the PID met the specified settling time, its overshoot was 12.51% above the desired or referenced attitude. Also, the PID-TC provided the best performance in terms of in terms of settling time and overshoot. This means that the developed system offered faster convergence, smoother and stable torque control performance than the other controllers. Further comparison in terms of the ability to offer robustness in the presence disturbance with respect Figure 4.5 and Table 4.5, revealed that the PID-TC outperformed the PID and LQR. The LQR showed the worst performance in the presence of disturbance. Therefore, it suffices to say that the developed PID-TC outperformed the existing PID and LQR controllers.

CONCLUSION AND RECOMMENDATION

Summary of Discussion

This work has presented enhancing the stabilization of low earth orbit satellite yaw-axis attitude control system using robust proportional-integral-derivative-tuned compensator (PID-TC). In order to realize the aim of this work, the dynamic equations representing the behaviour of a microsatellite yaw-axis in attitude control system were determined. The dynamic equations were then modelled using Simulink embedded blocks in MATLAB. A PID-TC was developed to provide command action for LEO satellite yaw-axis ACS. The developed control system was modelled and simulated in MATLAB/Simulink environment. The results from the simulation revealed that the developed system met the performance specifications of the LEO satellite yaw-axis ACS particularly yielding very much reduced oscillation in terms of overshoot and zero steady-state error. This indicates improved stabilization of the satellite compared to its overshoot (38.63%) when the PID-TC has not been introduced. The system performance was measured in terms of time domain transient characteristics such as rise time, transient time, settling time, maximum overshoot, peak time, final value and steady state error.

Recommendations/Future Work

The PID-Tuned Compensator (PID-TC) for satellite yaw-axis attitude control can be applied in various contexts, benefiting a range of stakeholders as follows:

PID-TC can be applied to Low Earth Orbit (LEO) Satellites and be used in satellites for accurate orientation control to maintain data quality and communication reliability.

It can be applied in telecommunications and be used in communication satellites to ensure stable transmission and reception of signals.

Recommendation/Future Work

There are quite a number of research areas that require further attention such as the pitch and the roll dynamics; and are not considered in this work. These have both theoretical and practical aspects. The proposed controller was developed and examined using

MATLAB/Simulink. Since the pitch and the roll dynamics were not considered in this work, recommendations are made as follows for further work:

The effect of disturbance on the plant can be examined to further ascertain robustness of the PID-TC controller by varying the load torque for a given simulation time. This will help to further ascertain its robustness to varying disturbance and in providing effective control for the satellite structure in the presence environmental perturbations.

Contribution to Knowledge

Control technique that uses PID-TC controller for LEO satellite yaw-axis attitude control system (ACS) has been designed.

It has been shown by simulation analysis that PID-TC can provide robust and improved tracking performance for LEO satellite yaw-axis attitude in the presence of load torque disturbance.

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