

Attitude Determination and Control of Thinsat System Using Adaptive Control Technique

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Abstract: This paper presents attitude determination and control of ThinSat system using an adaptive control technique. This study aims to reduce the impact of dynamic torque on the angular velocity and orientation of spacecraft while maintaining a steady position in the axes. This was achieved by collecting the data of Nigeria Sat-2 which was trained with a multi-layered neural network algorithm employed to generate an adaptive control system which was implemented on the satellite using Simulink software. The training performance of the adaptive controller was evaluated and validated using Mean Square Error (MSE) and regression. The result showed that the average MSE is 0.045394 and 0.97271 for regression. The implication is that the neural network correctly learns the spacecraft data collected and was able to detect changes in the angular velocity. The step response of the adaptive controller was evaluated with the characterized Proportional Integral Derivative (PID) control system and the result showed that the total time of the attitude determination and control of the spacecraft is 111.24ms as against 465ms with PID which gives 76% reduction in decision time to control error due to dynamics. The comparative analysis with the characterized in the rate of error minimization on the pitch angular velocity showed that the angle was reduced from 13.46mm with the adaptive controller to 9.55mm which gives a percentage improvement of 29%.

Keywords: ThinSat, Adaptive Control, Spacecraft, Nigeria Sat-2, Neural Network

1. Introduction

Since the beginning of the 21st century, the use of low-orbit satellites has increased with great development in the research of space science and technology. These satellites vary from micro to mini types and are mostly used for weather forecasting, telecommunication, ship movement surveillance, taking images of the earth, obtaining digital elevation maps of disaster areas and environmental tracking of some animals for scientific research [12]. The satellite system is classified into three types which are low earth orbit (LEO), medium earth and geostationary earth orbit satellite system [5].

Nigeria as the giant of Africa for instance launched the NigeriaSat-2, NigeriaSat-X (earth Observation satellites) and NigComSat-1R (a communication satellite) to space in August and December 2011 respectively. Nigeria Sat-2 was

launched in August 2011. It has high-resolution satellite spatial resolutions of 2.5m panchromatic, 5m multispectral and with area coverage (swath width) of 20 by 20km and the capacity to rapidly produce accurate mapping to update the existing information and acquire new mapping information. The Nigeria Sat-2 allows for environmental and disaster management, infrastructure mapping, settlement classification, development of urban green spaces, service provision maps, access control mechanisms regional planning, and security [11]. However, the capacity to take precise readings due to the impact of aerodynamic and magnetic parameters has hindered the effective performance of the system and hence presents the need for Attitude Determination and Control System (ADCS) [15].

ADCS was developed for monitoring the navigation behaviour of spacecraft as they orbit the earth. The ADCS is divided into three main areas which are the dynamic modelling, controller, filtering and estimation of attitude [17]. The dynamics

of the system include the environmental models and attitude mechanics which describe the translational and rotational behaviour of the satellite. The filtering and estimation models account for the different hardware properties of the system sensors [16]. Lastly, the controller design brings the control algorithms together with the dynamics and estimation to ensure mission performance requirements are met.

Various controllers have been proposed to achieve this aim such as the Linear Quadratic Regulator, Proportional Integral Derivative, pitch yaw adjustment controller, etc., [10]. However, despite their success, the high level of dynamic electromagnetic torque which is present in the inner actuators of the spacecraft presents the need for a control system which is adaptive to ensure better and faster control response [13-14]. This when achieved will reduce the error of angular velocity on the momentum of the spacecraft and hence provide a better attitude.

2. Literature Review

Alexandre et al presented Assurance and Control Framework for a Global Navigation Satellite System-Reflectometry (GNSS-R) Earth Perception 6U CubeSat Mission [1]. This work portrays the demeanour assurance and control framework Attitude Determination and Control System (ADCS) of Feline 2 which is a six-unit CubeSat. This target controls the satellite in a circle and satisfies the prerequisites fundamental for the satellite framework. Feline 2 is utilized to guide the receiving wires towards the earth to perform tests and afterwards situate the sun-oriented boards towards the sun to expand the force input when the battery level is low.

Assaad et al showed the Mentality Assurance and Control Framework for CubeSat [2]. This work centers around the equipment determination in the space of sensors, actuators and processors of the Shape satellite framework which is driven by NASA Goddard Space Flight mission. This examination showed the Disposition Assurance and Control Framework (ADCS) utilizing the mathematical codes written in MATLAB. This examination was produced for exploratory tests and confirmation of ADCS. This work builds the viability of the control by 12.5%, taking it from 76% to 88.5%. Subsequently, an improvement in the adequacy of this framework will be fundamental.

Cullen demonstrated an exploration work on Direction, Route and Control of Little Satellite Demeanor Utilizing Miniature Engines [8]. This work manages the plan, improvement and combination of a Guidance Navigation and Control (GNC) subsystem into a unique system that can be executed on-board progressively to perform satellite demeanour controls by telling the precise speed increase dependent on a fourth-order polynomial regarding time. The rate blunder rate distinguished for this examination was recorded to be 15% overall. Thusly, future attempts to diminish these mistake rates are vital for a more solid framework.

3. Methodology

The procedure of design for this system involves the development of the model of the attitude control system and the data of the spacecraft dynamics collected considering the attributes of navigation such as position and speed. The data was trained with an adaptive control system to get a reference point for adjustment and control instability. The system developed was implemented with a high-level programming language and integrated into the testbed/test facility for optimization.

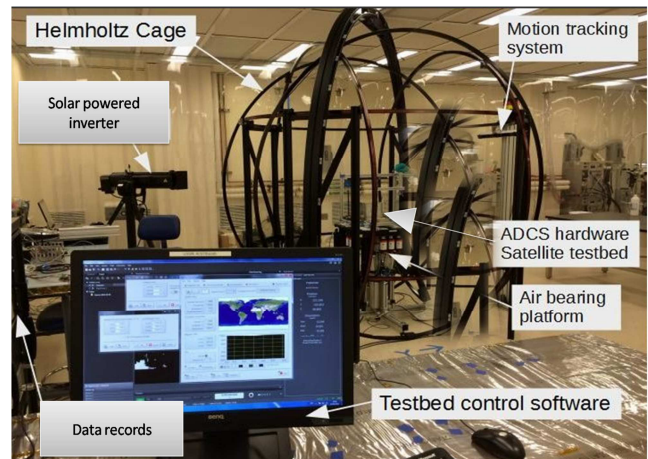


Figure 1. Image of the Test facility (Courtesy: NIGCOMSTAT).

From the test facility in figure 1, the Helmholtz cage was used to provide a three-axis dynamic magnetic field which will cancel the earth's magnetic field and create a geomagnetic field-based environment similar to space for satellite habitation. The ADCS hardware is the satellite control system developed with a Proportional Integral Differentiator (PID) control system which was used to control the attitude parameters of the spacecraft towards desired orientation. The test control system software used is the space mission control software which can monitor the dynamic behaviour of satellites and report to a monitoring laptop. The motion tracking system is a horn antenna which is specialized in tracking the torque, and angular velocity of a satellite, while the sun simulator is used to provide up to 50,000lux illumination and can be adjusted from 30 to 100 per cent. The air-bearing platform is used to introduce nonlinearity in the environment and then test the controlling attitude of the satellite system.

3.1. Model of the Attitude Determination and Control System (ADCS)

This section presents the modelling diagram of the ADCS under study with the various sections such as the earth electromagnetic field model, attitude determination algorithm control algorithm, spacecraft dynamics, and attitude.

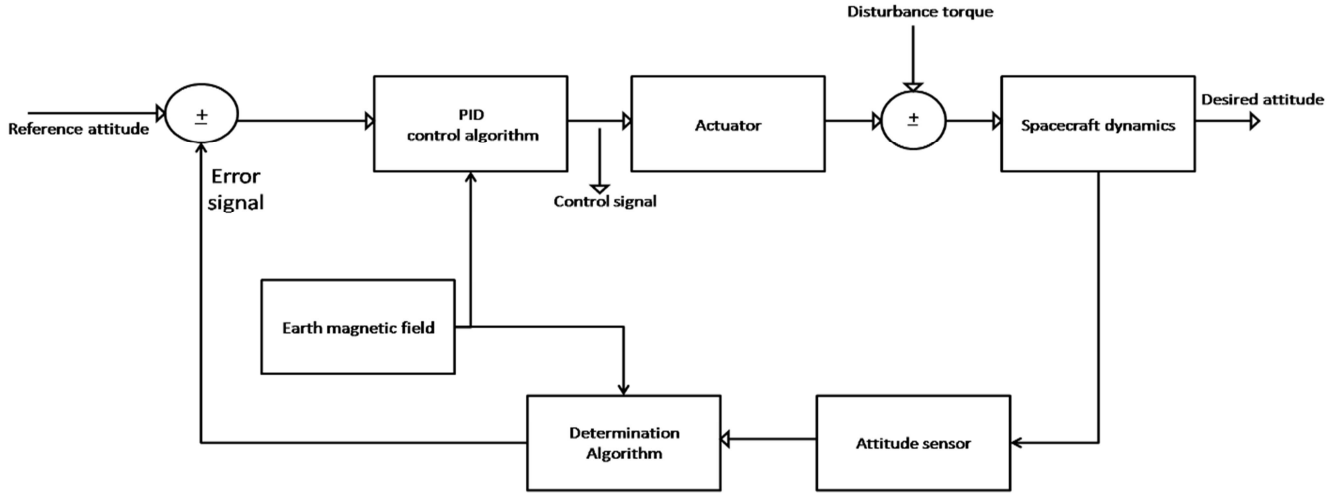


Figure 2. Architecture of the ADCS.

In figure 2, the ADCS sensors composed of absolute and relative sensors collect data on the spacecraft's attitude such as the speed, sun position, temperature, position, and orientation; then forward to the Tri-Axial Attitude Determination (TRAID) determination algorithm [7] which collected data about the dynamic nature of the input and feed to the control algorithm which adjusts the position of the actuator to reject disturbance and ensure better navigation performance.

3.2. Model of the Problem Formulation for ADCS

Based on Euler's model [4], the angular momentum of a static body in the body frame is presented as;

$$h^b = Jw_{i,b}^b \quad (1)$$

Where $J \in R^{3 \times 3}$ is the matrix of inertia and angular velocity is $w_{i,b}^b \in R^3$ which is relative to the frame of inertia. The angular momentum is determined by the frame of inertia [9]. It is represented;

$$h^i = R_b^i h^b \quad (2)$$

The rate of change of angular momentum is equal to torque such as $\dot{r}^i = \dot{h}^i$ and differentiating the frame of inertia in equations 1 and 2 gives [9];

$$\dot{r}^i = \dot{h}^i = R_b^i S(w_{i,b}^b) h^b + R_b^i \dot{h}^b \quad (3)$$

Equation 3 can be written as [4];

$$\dot{r}^b = S(w_{i,b}^b) J w_{i,b}^b + J \dot{w}_{i,b}^b \quad (4)$$

Where the inertia matrix is kept constant, the torque decomposition into the actual component is $r^b = r_a^b + r_p^b$, while the dynamics induces on the spacecraft due to perturbed torque is presented [4];

$$J \dot{w}_{i,b}^b = -S(w_{i,b}^b) J w_{i,b}^b + r_a^b + r_p^b \quad (5)$$

Where $r_a^b \in R^3$ presents the actuator torques and $r_p^b \in R^3$ is the dynamic torque from gravity. The application of quaternion presentation of the satellite attitude relative to the

inertial frame is presented [4];

$$q_{i,b} = \frac{1}{2} T(q_{i,b}) \begin{bmatrix} 0 \\ w_{i,b}^b \end{bmatrix} \quad (6)$$

Equations 5 and 6 presented the attitude behaviour of the spacecraft under dynamics due to the perturbed torque.

3.3. Error Dynamics Models

From Euler's model, the angular acceleration presents the relationship to the inertia frames. For control of the dynamics, the angular velocity relative to the orbit frame has to be approximated and it is presented as $w_{o,b}^b = w_{i,b}^b - R_i^b w_{i,o}^i$ and differentiated as equation 7;

$$J \dot{w}_{o,b}^b = -S(w_{i,b}^b) w_{i,b}^b + r_a^b + r_p^b + JS(w_{i,b}^b) R_i^b w_{i,o}^i - JR_i^b w_{i,o}^i \quad (7)$$

Figure 7 presented the attitude dynamics relative to the orbit frame. The relative dynamic error to enable tracking a desired attitude and angular velocity can be represented as $q_{o,d}, w_{o,d}^d, \dot{w}_{o,d}^d \in \infty$ using the quaternion and angular velocity error [9]. This can be determined as;

$$q_{o,d} = q_{o,d} \otimes q_{o,d} \quad (8)$$

$$\dot{w}_{d,b}^b = w_{o,b}^b - R_d^b w_{o,d}^d \quad (9)$$

With kinematics as;

$$\dot{n}_{d,b} = -\frac{1}{2} \epsilon_{d,b}^T w_{d,b}^b \quad (10)$$

$$\dot{\epsilon}_{d,b} = (n_{d,b} I + S(\epsilon_{d,b})) w_{d,b}^b \quad (11)$$

The angular acceleration error in equation 9 can be differentiated as;

$$J \dot{w}_{d,b}^b = -S(w_{i,b}^b) J w_{i,b}^b + r_a^b + r_p^b + JS(w_{i,b}^b) R_i^b w_{i,o}^i - JR_i^b w_{i,o}^i + JS(w_{o,b}^b) R_d^b w_{o,d}^d - JR_d^b w_{o,d}^d \quad (12)$$

Hence the control objectives can be defined as the making of $(q_{d,b}, w_{d,b}^d) \rightarrow (0,0)$ which is the desired position the spacecraft is meant to follow.

3.4. Attitude Determination Algorithm (TRIAD)

The TRIAD algorithm provides a fast and simple deterministic solution for the attitude of spacecraft systems based on two vector observations generated from two different coordinate systems. TRIAD only accommodates two vector observations at any one-time instance [3]. Initially, TRIAD assumes that one of the vector measurements is more exact than the other. The vector measurements in the spacecraft body frame are named (b_1 and b_2), and the vectors in the reference frame (r_1 and r_2). It is assumed that the first vector measurement b_1 is the most reliable. Based on this, three TRIAD are set up respectively [7].

$$t_{1b} = \frac{b_1}{|b_1|} t_{1r} = \frac{r_1}{|r_1|} \quad (13)$$

$$t_{2b} = \frac{b_1 \times b_2}{|b_1 \times b_2|} t_{2r} = \frac{r_1 \times r_2}{|r_1 \times r_2|} \quad (14)$$

$$t_{3b} = t_{1b} \times t_{2b} t_{3r} = t_{1r} \times t_{2r} \quad (15)$$

Finally, equations 13 – 15 were used to develop the TRIAD as;

$$A_{triad} = [t_{1b} \times t_{2b} \times t_{3b}] [t_{1r} \times t_{2r} \times t_{3r}]^T \quad (16)$$

3.5. Development of an Adaptive Control System (ACS)

The development of an adaptive control system was proposed to solve the dynamics problems experienced by the spacecraft. The adaptive control strategy in focus employed an artificial neural network solution which uses the acquired data about the spacecraft dynamics to train and adjust the orientation of the system to the desired point.

The data was collected for the training of the adaptive control system developed with a Multi-Layered Neural Network (MLNN). The MLNN algorithm by [6] was used. The MLNN is made of weight, bias, activation function and training algorithm. The architectural model of the MLNN was presented in figure 3.

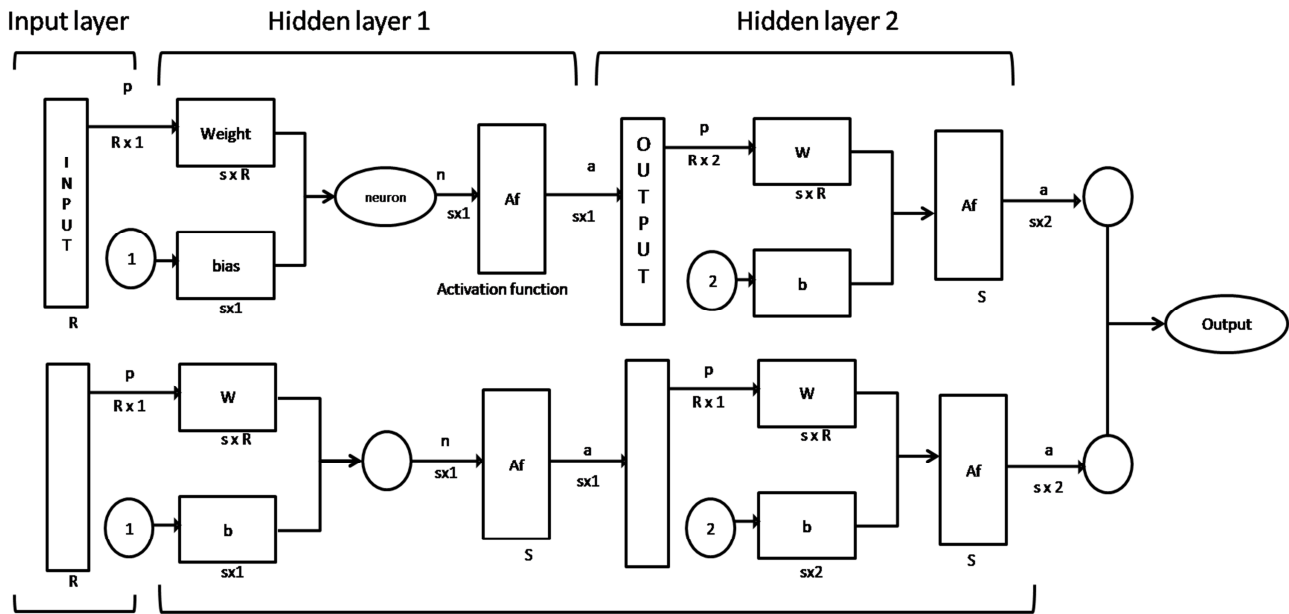


Figure 3. Architectural model of the Neural Network algorithm.

The architectural diagram of the MLNN comprises two-layered neural network models used to train the data collected. The number of inputs of the neural network is determined using the attributes of the dataset collected, while the activation function used is the tansig type.

PSEUDOCODE OF THE ACS

1. Start
2. Load training set
3. Divide into training and test set
4. Configure the MLNN
5. Activation MLNN
6. Select training algorithm
7. Set epoch parameters and intervals
8. Set performance evaluation metrics (Mean Square

Error (LSE) and regression)

9. Train neural network
10. If
11. LSE is true
12. Then
13. Generate ACS
14. Else
15. Back-propagation
16. Adjust neurons
17. Apply (step 9)
18. Do
19. Until (Step 11 is true)
20. Apply step 13
21. End

3.6. Development of the Adaptive ADCS

The ADCS was developed using the ACS algorithm

generated in the previous section to model an improved ADCS for optimal satellite navigation. The ADCS was developed using the flow chart in figure 3;

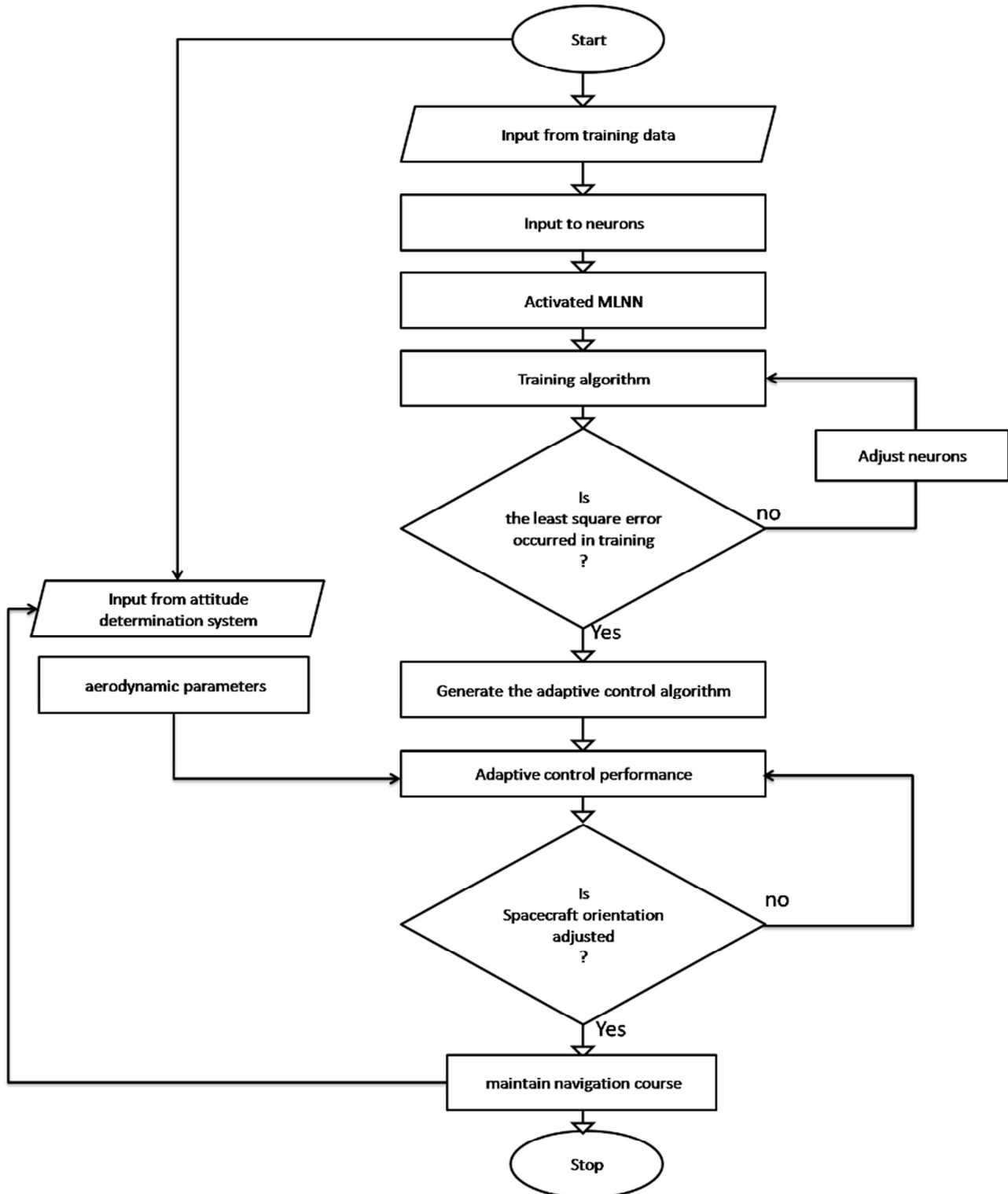


Figure 4. The flow chart of the adaptive ADCS.

The flow chart was used to show the workflow of the adaptive ADCS developed. The trained algorithm was used to adjust intelligently the dynamic attitude of the spacecraft to achieve the desired attitude as shown in the architectural model in figure 5;

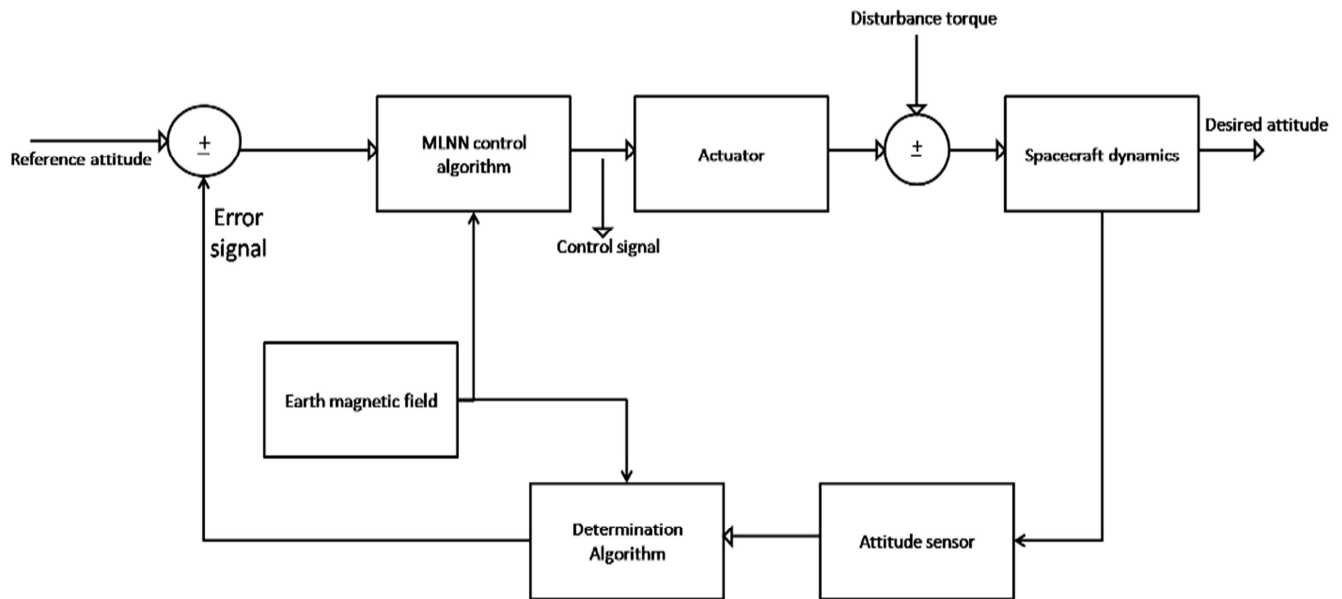


Figure 5. Architectural diagram of the adaptive ADCS.

Figure 5 presents the architectural diagram of the ADCS developed with the MLNN control algorithm developed. The ADCS sensors collected data of the spacecraft dynamics introduced due to torque disturbance and fed to the MLNN algorithm via the attitude determination system for training and correction of the error to ensure controlled navigation.

4. System Implementation

The adaptive ADCS was implemented with Simulink. This

was achieved with the aerospace toolbox, control system toolbox and neural network toolbox. The neural network toolbox was used to train the data collected to generate the ACS and then used to configure the control system toolbox to develop the Simulink block of the ACS. The aerospace toolbox was used to implement the NigeriaSat-2 model and then control the dynamics with the adaptive ACS model developed. The simulation parameters are all reported in table 1.

Table 1. NigeriaSat-2 Simulation parameters.

Parameters	Values
Spacecraft mass, size	1960 kg (launch mass), 2.6 m x 1.5 m x 1.5 m
Spacecraft dry mass	968.5 kg
Power	1164 W, two 18 Ah Ni-Cd batteries
Propulsion	440 N LAM (Liquid Apogee Motor) and twelve 22 N thrusters with MMH (Mono Methyl Hydrazine) as fuel and MON-3 (Mixed Oxides of Nitrogen) as the oxidizer
Antenna size	0.9 m and 1.0 m
Mission design life	7.7 years
Distance covered	35786km
Uplink frequency	0.1± 402.75
Downlink	0.1± 4506.05

5. Results

This section presents the result of the attitude determination using the neural network and the result of the satellite navigation from the system implementation.

5.1. Result of the Attitude Determination

To evaluate the attitude of the ACS developed with a neural network, the MSE and Regression were used respectively. The idea was to measure the training error achieved in the neurons during the learning process and also

determine the ability of the adaptive ADC algorithm to classify changes in the angular momentum and approximate to minimize the impact on the angular velocity. The MSE attitude is presented in figure 6 and the regression results are in figure 7;

Figures 6 and 7 present the MSE and regression performance of the neural network-based ADC algorithm developed. From the result the MSE recorded is 0.056845Mu which is very good as it is approximately zero. The Regression also showed that the average R recorded from the training, test and validation set is 0.99999 which is approximately 1 and also very good.

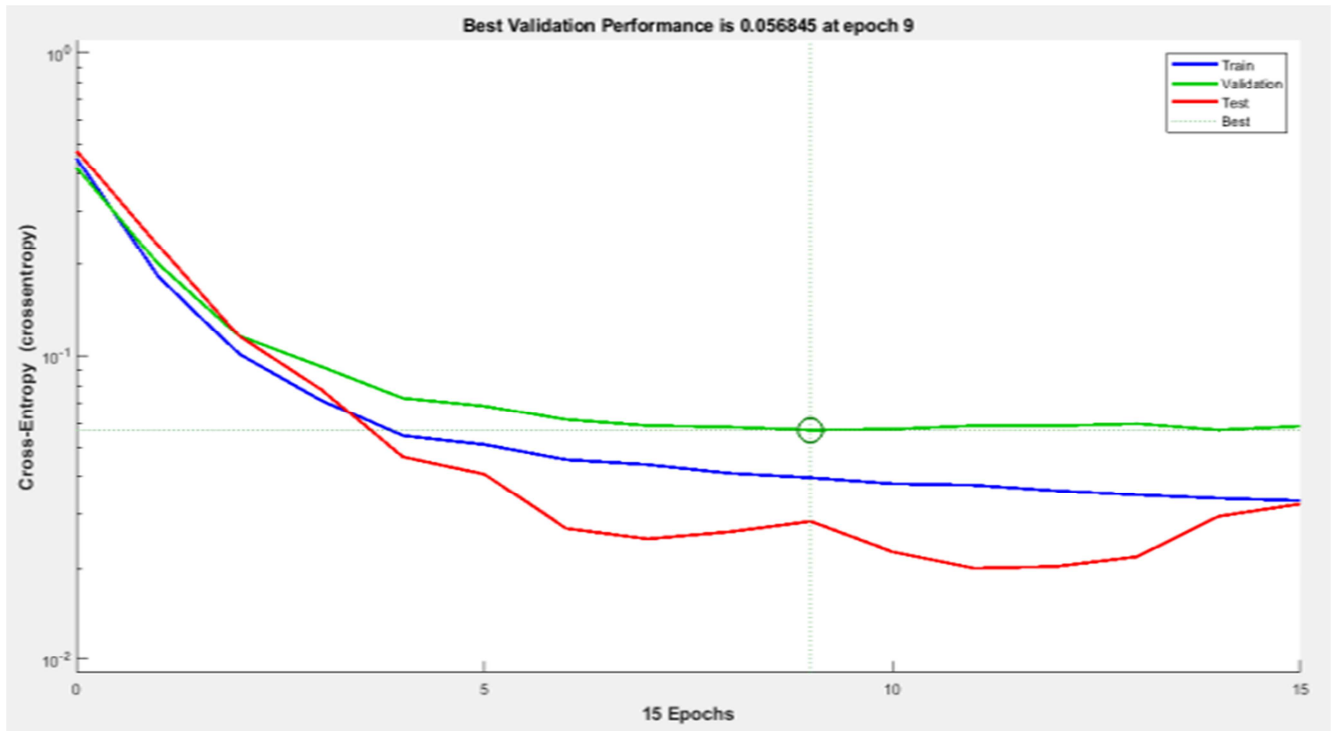


Figure 6. MSE result of the ADC.

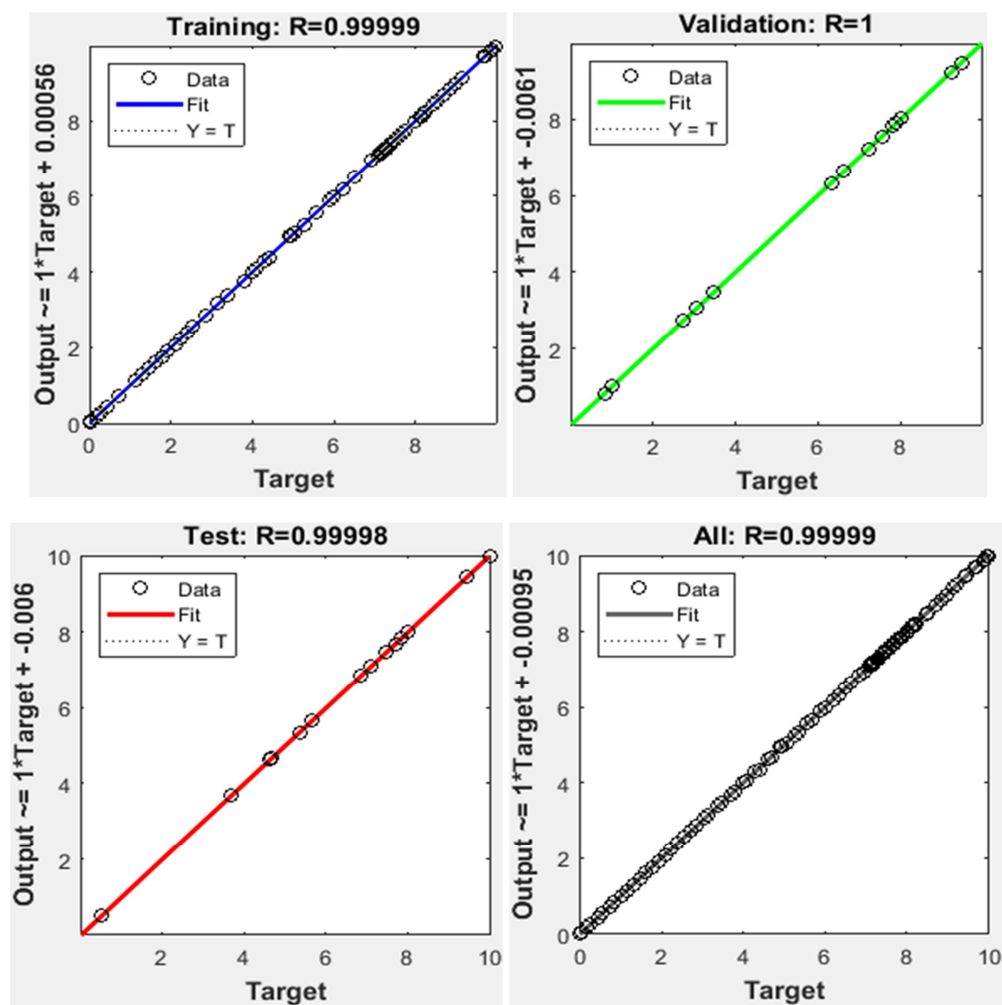


Figure 7. Regression Result.

5.2. Result of the Satellite Navigation

This section discussed the attitude of the satellite when simulated with the adaptive control system developed as the attitude control system. The impact of dynamics due to electromagnetic torque acting on the wheels momentum and the quaternion representation modelled in equations 5 and 6 is presented in figure 8.

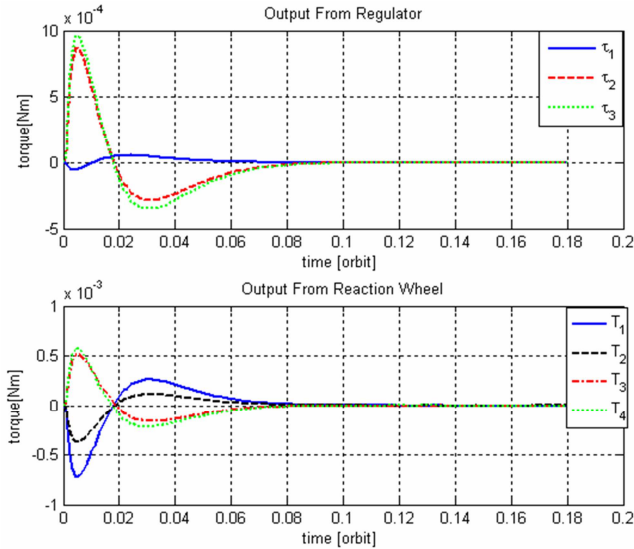


Figure 8. Impact of torque on the satellite.

From the result in figure 8, it was observed that nonlinear torque affected the momentum of the spacecraft orientation which was reflected in the unstable orientation of the wheels based on the Euler rotational theorem but was controlled at three orbits. This was due to the impact of the adaptive control system developed which was able to approximate the impact of the torque dynamics and stabilize the angular velocity as shown in figure 9.

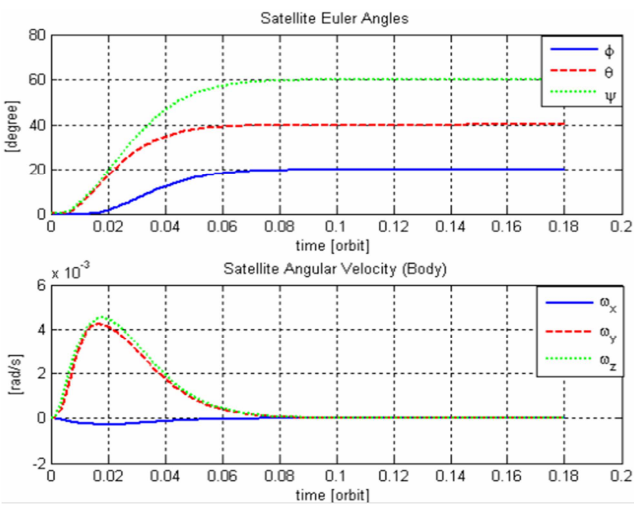


Figure 9. Result of the angular velocity.

From the result, it was observed that the impact of the dynamics torque affected the Euler angle position as in

equation 7 which results in an error in the angular velocity as modelled in equation 12. However, this error was controlled by the adaptive control system developed and maintained stable orientation at 0.08orbit respectively. The implication of the result showed that the dynamic torque which affects the stable orientation of the spacecraft was controlled by the adaptive control system developed and was able to maintain a stable satellite attitude.

6. Conclusion And Recommendation

This section presents the conclusion of the work and the recommendations for future research and improvements satellite navigation system.

6.1. Conclusion

This paper presents attitude determination and control of a satellite system using an adaptive controller. The aim was to control the orientation of the spacecraft during navigation and mitigate the impact of dynamic electromagnetic torque which resulted in an error in the angular velocity for the axes. This problem was solved using an artificial neural network which was trained with the data collected from the spacecraft and developed an adaptive control which adjusts the orientation of the satellite to the reference position. The result when implemented showed that the adaptive controller was able to reduce the error in the angular velocity of the spacecraft and achieve better control performance.

6.2. Recommendation

This control system developed is recommended to be integrated with other Nigerian satellites like the NigariaSat-3 system for optimized navigation performance. For future works, this paper can serve as a valuable reference for researchers and engineers who are interested in the development and implementation of adaptive control systems for spacecraft. Based on the findings of this study, it may be beneficial for future research to investigate the effectiveness of the developed adaptive control system in different scenarios or under varying conditions. Additionally, further studies could focus on the integration of other control techniques or algorithms to further improve the performance of the adaptive control system. Furthermore, the results of this study may provide insights into the development of more efficient and effective control systems for spacecraft in the future.

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