Extended Kalman Filter Based Estimations for Satellite Attitude Control System

D. Y. Dube, S. N. Sharma, H. G. Patel

***Abstract**:This paper mainly focuses on the maneuver of the satellite in orbit. A non-linear multi-inputs multi-outputs model has been derived from Newton-Euler equations of motion. The dynamics is presented with control methodologies allowing the Extended Kalman Filter (EKF) to iteratively provide improved data sets with zero errors. As the system is distracted from the atmospheric swings which are random hence the problem of stochastic disturbance is furnished. A set of differential equations of two dimensional Ito stochastic type is used for modeling the said disturbances (before t = 4s is recorded). The attitude parameters are recorded in RT-LAB setup with the Extended Kalman Filter (EKF) providing adequately superior estimation outcome which thereby makes the filter more appealing. With the presence of Gaussian noise in both dimension and system, Extended Kalman Filter gives the correct estimates. It's collaboration with hardware setup RT-LAB is commendable. Hence, an Extended Kalman Filter which deals with such non-linear models proves to be a higher choice for achieving best online results. A comparison reflecting the tracking and stable control of the satellite for the designed advanced adaptive robust controller (AARC) for two situations is plotted. The priority of making the system stable in the presence of stochastic disturbance is also visited. Also, the use of three different values of the confounding variables revealed that the control weighting line is completely diminished thereby boosting the tracking when the satellite is in orbit. Moreover, the previous research involves methods to improve satellite communication on ground station, this paper deals with exact positioning of concerned satellite attitude parameters and its validation tested experimentally on OPAL-RT hardware. To sum up, the development of advanced adaptive robust controllers have encouraged the stability and accuracy of systems considering the varying atmospheric conditions. The simulation results predict perfect tracking of output with respect to the desired set-point in the presence of stochastic disturbance for the proposed controller.*

***Keywords**: Advance Adaptive Robust Controller, Extended Kalman Filter, Ito Stochastic Differential Equation.*

I. INTRODUCTION

Inthis contemporary world, it is so much simpler to realize precisely where you are and find out your exact position and direction.The Global Navigational Satellite Systems (GNSS) contributes navigational data to airborne transit and varied demands. GPS devices are casted off for diverse reasons like road navigation, tracing, surveillance and so on. Specific satellites assist to forecast the weather, whilst others collect statistics about our universe for NASA and other bodies. To overcome issues when the satellite is in orbit (such as those related to satellite parameters behavior with external disturbances which cannot be avoided), this paper suggests a better strategy.

A nonlinear adaptive control law for the attitude control of satellites using gyroscope was presented by Iyer et al., (1990). A simplified control law for spinning satellites was derived which required only attitude tracking error and its derivative for feedback. Also, the design of the controller does not ought to any information on the dynamics of the satellite.

Even Monk et al., (1995) considered an adaptive power control (APC) scheme to combat large scale shadowing and distance losses. Due to lengthy round-trip delay on a satellite link, the most marginal beneficial ones are the closed loop power control systems. To quantify the performance of the APC, the standard deviation of the power control error in decibels is analyzed as a function of the specular power-to-scatter power ratio, the measurement time and the vehicle velocity.

The attitude control of a satellite is often characterized by a limit cycle, studied by Buijtenen et al., (1998). To reduce the limit cycle, a nonlinear fuzzy controller was introduced. The tuning of the controller was done by means of reinforcement learning without using any model of the sensors or the satellite. Thereby improving by computing the temporal difference error over several time steps and adapting the critic and the controller at a lower sampling rate. The main idea being the optimal mapping between system states and controls through exploration and evaluation of possible control commands.

A new two-step automatic frequency control (AFC) (A. Wannasammaytha et al., 2000) suited for direct conversion-type receivers to counteract large frequency offset with time variation in low earth orbit (LEO) was discussed. This research provided a two step frequency estimation scheme, i.e., coarse and fine. An adaptive open loop power control (OLPC) method for DS/CDMA satellite communication systems based on a Markov chain channel model was introduced by Zihua et al., (2000). He analyzed the derivation of Erlang capacity of the satellite DS/CDMA system with the PC scheme and demonstrated that Power Control Error (PCE) affects this capacity.

Manuscript received on May 06, 2021.
Revised Manuscript received on May 13, 2021.
Manuscript published on June 30, 2021.
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Li et al., (2001) discussed the LEO satellite CDMA systems which called for the different considerations on power control algorithms. The algorithm was based on the criteria of fast response, small over-compensation, oscillation-avoiding and minimum power control error, the transient behaviors of the fixed step, adaptive step and multistep power control algorithms which were investigated and compared. A kalman-Bucy Filter was presented by Asif (2004) for combining satellite altimetry data with the nonlinear ocean circulation models. A typical Input-Output (I/O) linearization control method in the nonlinear multi-input multi-output (MIMO) system was developed by Guan et al., (2004). An adaptive fuzzy control was combined to constitute the hybrid controller for attitude maneuver control of the flexible satellite, which is a complex nonlinear system. Certainly, the controller compensates for the plant's uncertainties.

The problem of disturbance caused by the reaction wheel with a current controller which profoundly influences the accuracy and stability of the satellite attitude control system was addressed by Ge et al., (2006). The idea of a speed feedback compensation control reaction wheel was put forward which controlled the interior disturbance and therefore improved the stability and pointing accuracy. An application of Minimal Controller Synthesis (MCS) by Arif (2006) achieved an excellent closed-loop control despite the presence of system parameter variations, external disturbances, dynamic coupling within the system and system nonlinearities. It was implemented to the problem of decentralized adaptive schemes and also enhanced the stability and robustness of the decentralized adaptive control systems.

Derivation of a satellite attitude estimation algorithm using vector observation from the star-sensor, in gyro-less or gyro-disable mode was accorded by Li et al.,(2006). The development and testing of a detection, isolation and diagnosis algorithm based on interacting multiple model (IMM) filters for both partial and total reaction wheel faults in a spacecraft was highlighted by Tudoroiu and Khorasani, 2007. Various operating and faulty conditions due to changes are considered in each reaction wheel associated with the three axes of the satellite. In addition, a bank of interacting multiple Kalman filters for detection and diagnosis of anticipated reaction wheel failures in the ACS was described and developed. The problem of attitude tracking control of rigid satellites subject to external disturbance and parametric uncertainty is analyzed by Lv et al., (2009). This scheme implemented the real time identification for inertia parameters and auto-tuning control parameters. Another adaptive variable structure control system design method for large scale satellite antenna and full physical simulation results was bestowed by Jia et al., (2009).

Guang and Wei (2009) furnished the multi-input multi-output indirect adaptive fuzzy tracking control method for satellite attitude systems with parametric uncertainty and external disturbance. The controller was able to track satellites at their location and force the tracking error to converge to a small neighborhood of the origin. In this process, the controller would also boycott the influence of uncertainties effectively. An Extended Kalman Filter (EKF) to trace a single road until a stopping criterion is satisfied was evolved by Movaghati et al., (2010). They have combined EKF with a particle filter (PF) to regain the trace of the road beyond obstacles, as well as to find and follow different road branches once arriving at the road junction. A robust dynamic control for a DSP-based satellite reaction wheel driven by a surface-mounted permanent-magnet synchronous motor and its friction estimation from the observed disturbance is monitored by Chou et al., (2011). A proportional plus integral feedback controller is augmented with a resonant-based feedback controller and a robust tracking error cancellation controller to yield an excellent sinusoidal winding current command tracking.

Based on the hierarchical fuzzy systems (HFS), the tracking control of satellite attitude with uncertain dynamical model was investigated, and a direct adaptive fuzzy predictive control method was provided by Sun and Huo (2010). Adaptive fuzzy control was implemented for attitude stabilization as well where the proposed control law can resist the perturbation effectively (Guan et al., 2011). An investigation regarding the integrated attitude control algorithm and steering law for agile small satellites configured with control moment gyroscope (CMG) was examined by Qin et al., (2011). Another decentralized adaptive fuzzy approximation design was projected by attitude tracking control for formation flying in the existence of external disturbances and actuator faults by Li and Dev Kumar (2012). However, in a multiple satellite formation control system an adaptive compensation scheme proved to be helpful in suppressing the effect of the uncertainties (Deb 2011). The tracking and stable control of a typical ship mounted mobile satellite communication system (MSCS) was studied by Jiang et al., (2012). A tri-axis nonlinear model including the kinematic and dynamic was used as the control object.

A brief of an X-Y pedestal using the feedback error learning (FEL) controller with adaptive neural network for low earth orbit (LEO) satellite tracking application was insisted by Taheri et al., (2014). The derivation of inverse dynamical model of the X-Y pedestal being the aim of this research minimized backlash and reduced the tracking error. Also, formation control of satellites for remote sensing applications has received considerable attention during the past decade. The research involves development of a formation strategy with sliding mode control and an adaptive tuning algorithm to tune the fuzzy parameter (Nair et al., 2015). A Simultaneous Perturbation Stochastic Approximation (SPSA) method was chosen by T. Oktay and F. Sal (2015) which augmented an adaptive algorithm considering the requirement of optimization variables. The algorithm also solves the passive and active morphing helicopter (T. Oktay and F. Sal 2016). The mind-set dynamics of geostationary satellite tv for pc is controlled with the collaboration of two-optimal robust fuzzy proportional-quintessential-derivative (FPID) and linear quadratic regulator (LQR).

Retrieval Number: 100.1/ijeat.E25920610521
DOI:10.35940/ijeat.E2592.0610521
Journal Website: www.ijeat.org

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Sari et al. had designed the matrices R and Q in such a way to balance the manage efforts and settling time of the device. A type of mismatched uncertainties and external disturbances found in a high-order nonlinear had been minimized by means of the design of a finite time adaptive manager (Abadi et al., 2019). Moreover, a performance criterion became established (indispensable of the rectangular value), to offer a numerical contrast among the proposed adaptive and non-adaptive controller. Alba et al., 2015 focused on the want for robustness, reliability and flexibility of relative navigation structures. These systems have been imposed through the cutting-edge and future self sufficient formation flying missions, and consequently calls for the implementation of solutions using an alternative method to single-sensor systems. An extended presentation of the Euresis-filter, a multi model-based totally FDI technique suitable for small satellite's thruster faults turned into discussion with the aid of Tantouris et al., (2017). The foremost Scope of the proposed multi model-based FDI function is to keep the spacecraft operation and protection as per requirements by means of the mission. Aboelaze et al., (2018) proposed a hardware inside the loop simulation platform to capture real-time system behavior. A satellite model with jitter and noise brought to the signal uses an emulator to look at the effect of constant point implementation on the controller performance. The principal highlight being the 50 percent electricity saving the usage of constant factor implementation with almost no overall performance degradation.

The concern of this paper will be to make the attitude angles as stable as possible with minor errors in the presence of random walks (Gaussian noise). A brief description about the hardware setup and the discussion of their dynamics for validation of the said techniques is presented successfully. This encourages the reader to use these models with a blend of conventional and uncommon approach. It also reveals the results which are justified with the performance. The main objectives of this paper include:

- To develop a more stable and accurate system,
- To model the attitude dynamics with extended kalman filter and analyze in RT-Lab,
- To produce exact positioning of concerned satellite attitude parameters,
- To promote the tracking of the satellite system.

The brief outline of this paper is as follows: In Section II, the problem statement is elaborated which follows a mathematical representation of the system model in Section III. An Extended Kalman Filter (EKF) with an illustration is discussed in Section IV and V. Furthermore, the proposed controller is focused in Section VI. While the Simulation results presented in Section VII, one may find the reflected conclusion in Section VIII.

II. PROBLEM STATEMENT

Satellite evolution and instigate actions are complex. An apparently innocuous delusion can communicate through the system. For instance, one of the early Pegasus XL missions broke-down because designers depended only on numerical modeling of vehicle aerodynamics rather than actual wind tunnel tests. It was found that there were meteoric swings on earth's atmospheric density with distractions. It is convenient to consider them as if they enter the system in the same way as the control signal. Hence, these are taken into consideration when modeling the rigid body dynamics. The equation for the system is developed from Newtonian mechanics of securing the satellite in circular orbit [11,21].

$$\ddot{x} + b(1+a\xi_t)\dot{x} + (1+a\xi_t)\sin x - c\sin 2x = 0 \quad (1)$$

here x is radial perturbation about the given orbit, ξ_t is Gaussian white noise and a, b, c are constants. The above equation is modeled as a 2-dimensional Ito stochastic differential equation.

$$d\begin{pmatrix} X_t^1 \\ X_t^2 \end{pmatrix} = \begin{pmatrix} X_t^2 \\ -bX_t^2 - \sin X_t^1 + c\sin 2X_t^1 \end{pmatrix} dt + \begin{pmatrix} 0 \\ -abX_t^2 - a\sin X_t^1 \end{pmatrix} dW_t \quad (2)$$

The problem due to the atmospheric distractions or swings are modeled in (3- 5). Above equations are evolved virtually in MATLAB with a 2-dimensional Ito Stochastic differential equation. The Wiener process *W(x)* being analysed with randomness in the vector (Brownian motion). This concluded a different output each time the system is manipulated. Atmospheric chaos is necessary for the design of both - the inlet and engine flight controls. It also supports for studying link between the propulsion and the structural dynamics for supersonic vehicles. In the referred paper, a more accurate model was developed to represent fractional order of atmospheric disturbances. Atmospheric model was accomplished by first ascending the kolmogorov spectral to convert them into finite energy von-karman forms. Hence, the objective lies for given parameters and the atmospheric conditions with all prior information, (the poles and zeros describing disturbances for respective acoustic velocity, temperature, pressure and density) the appropriate time domain simulations are evaluated. These disturbances also contribute to the problems cited in this paper. Their respective transfer functions as in [12]:

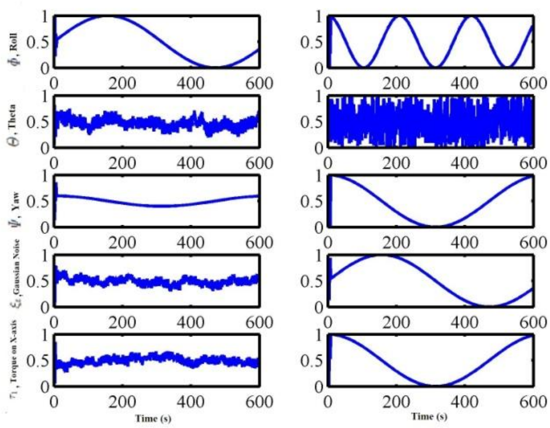

Fig. 1 The affect of stochastic disturbance at the output (Right hand side) via input (left hand side) of the satellite system

$$G_{LA}(s)=\frac{(s/9.2+1)(s/55+1)(s/335.5+1)}{(s/1.46+1)(s/30.1+1)(s/85.7+1)(s/1593.1+1)} \quad (3)$$

$$G_T(s)=\frac{(s/33+1)(s/45.6+1)(s/602.4+1)}{(s/1.1+1)(s/25.1+1)(s/109.8+1)(s/816.3+1)} \quad (4)$$

$$G_P(s)=\frac{(s/33+1)(s/45.6+1)(s/602.4+1)}{(s/1.1+1)(s/25.1+1)(s/109.8+1)(s/816.3+1)} \quad (5)$$

here G_{LA}, $G_T$and G_P are the atmospheric disturbance transfer function for longitudinal, temperature and pressure. They also exhibit behavioral changes in a particular pattern when they enter the system. This causes large instability in the satellite's control system operation. As shown in Fig. 1, the response is completely unwanted and unhealthy. It reflects that the disturbance is more inclined in the right half plane. A specific scaling will allow the satellite to hover at an altitude for executing a spinning maneuver and also communicate the required messages through sensing.

III. SATELLITE DYNAMICS

This section concentrates on building the attitude model of the rigid body. For a perceptible exploration of the satellite dynamics, an imaginary satellite is examined. To gain clarity, the actuators employed are only reviewed to be reaction wheels. The torques required are generated by the three reaction wheels denoted by $T_{\omega x}$, $T_{\omega y}$, $T_{\omega z}$in each of the three axes respectively. The first-order nonlinear differential equations resembling the attitude dynamics is given by:

$$I_{sat}\dot{\omega}+\omega\times(I_{sat}\omega+I_w\omega_w)+\tau_w=\tau_{sat} \quad (6)$$

here I_{sat}, I_ω, ω, ω_w, τ_w, τ_{sat} represent the satellite inertial matrix, the reaction wheels inertia matrix, the satellite and the reaction wheel angular speed with the torques respectively. Further, for reference the following values are assumed

$$I_{sat}=\begin{bmatrix}22&0&0\\0&15&0\\0&0&22\end{bmatrix},I_w=\begin{bmatrix}J&0&0\\0&J&0\\0&0&J\end{bmatrix} \quad (7)$$

$$\omega=\begin{bmatrix}\omega_x\\\omega_y\\\omega_z\end{bmatrix},\omega_w=\begin{bmatrix}\omega_{wx}\\\omega_{wy}\\\omega_{wz}\end{bmatrix} \quad (8)$$

$$\tau_w=\begin{bmatrix}\tau_{wx}\\\tau_{wy}\\\tau_{wz}\end{bmatrix},\tau_{sat}=\begin{bmatrix}\tau_x\\\tau_y\\\tau_z\end{bmatrix} \quad (9)$$

Placing above model and facets in league, the state-space representation for a single axis reaction wheel could be expressed as :

1. when $\omega_\omega \geq \omega_s$, then

$$\dot{x}_1=\frac{1}{J}[K_tD_a(x_1-x_2)-0.0049-0.0002(T+30)x_1-\tau_a-\tau_n+K_tD_a(1+u)+K_tD_a\tau_e] \quad (10)$$

2. and when $0 \leq \omega_\omega \leq \omega_s$

$$\dot{x}_1=\frac{1}{J}[-0.0049-0.0002(T+30)x_1-\tau_a-\tau_n+K_tD_a(1+u)+K_tD_a\tau_e] \quad (11)$$

The subsequent loops play an exceptional contribution in the dynamics of the reaction wheel. The motor torque is restricted by the negative feedback where an emf limiting loop τ_{emf} owes to a low voltage. In this case, the motor torque is demarcated at high speed resulting in the surged back-emf voltage gain K_v. The key aspect of the motor driver is a voltage headed current source with a dc gain of D_c. The motor torque control τ_c along with the constant K_τ entrusts torque analogous to the current. Finally, the torque noise disturbance τ_n is the repercussion of a torque diversification from the bearings which may be due to the lubricant linked dynamics. The insertion of torque noise (which is a disturbance is shown in Fig. 4) is constituted by a sinusoidal signal having a high pass filter frequency ω_m:

$$\tau_{noise}=J\theta_{noise}\omega_m^2\sin(\omega_m t) \quad (12)$$

for the spacecraft inertia given by

$$\theta_{sat}=\theta_{noise}\frac{J}{I_{sat}} \quad (13)$$

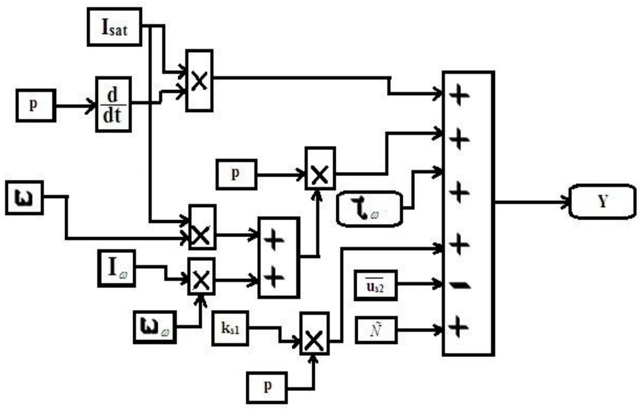

Fig. 2 Simulink block for implementing Satellite dynamics as mentioned in eq. (6).

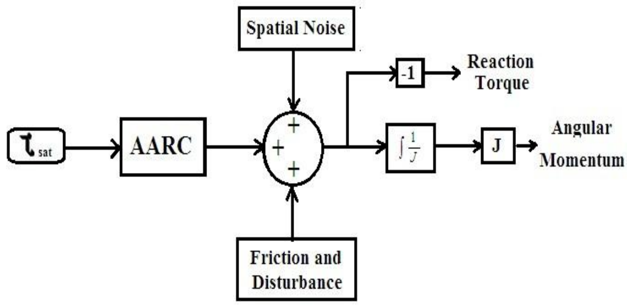

Fig. 3 Basic schematic block-diagram with advance control and perturbations in concern

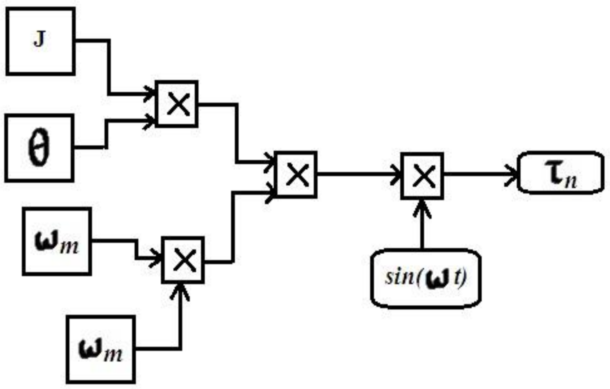

Fig. 4 The torque noise in satellite system with insertion of high pass filter frequency ω_m.

The visual implementation of satellite dynamics in MATLAB simulink for eq. (6) is suggested in Fig. 2 while Fig. 3 generates a short brief regarding the augmentation of AARC with external disturbance. Further, the attitude model given in eq. (14-16) is augmented to collaborate in realtime to an extended kalman filter. The results of which can be analyzed in the following section.

$$\ddot{\psi} + \frac{p_1}{I_x}\dot{\psi} + \left(1 + \frac{\dot{h}}{I_x}\xi\right)\sin x + \frac{1}{2}\frac{h\dot{\alpha}}{I_x}\sin 2x - \frac{T_x}{I_x} = 0 \tag{14}$$

$$\ddot{\phi} + \frac{p_3}{I_y}\dot{\phi} + \left(1 + \frac{h\omega_z\xi}{I_y}\right)\sin y - \frac{T_y}{I_y} = 0 \tag{15}$$

$$\ddot{\theta} + \frac{I_{xz}}{I_z}\omega_0^2\dot{\theta} - \frac{h}{I_z}\xi\sin z\omega_y - \frac{T_z}{I_z} = 0 \tag{16}$$

A simple evolution urged in Fig. (5-7) of the above model in MATLAB/RT-Lab software would be sagacious.

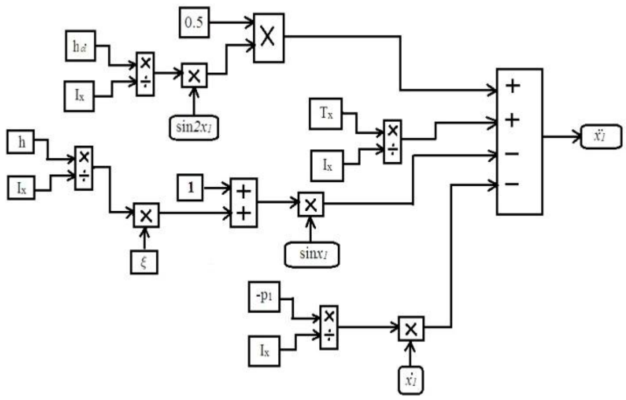

Fig. 5 Evolution of Yaw dynamics in simulink as mentioned in Eq. (14).

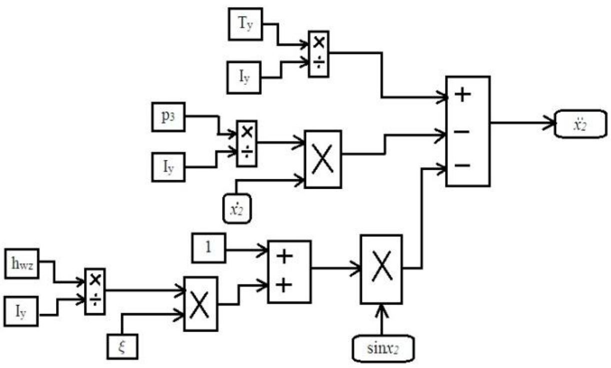

Fig. 6 Evolution of Roll dynamics in simulink as mentioned in Eq. (15).

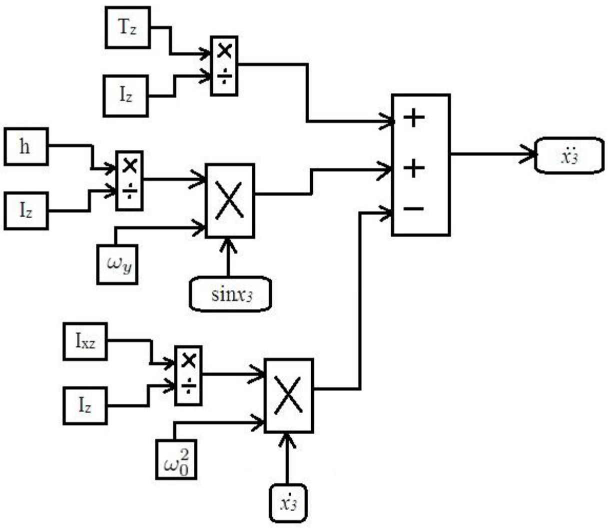

Fig. 7 Evolution of Pitch dynamics in simulink as mentioned in Eq. (16).

IV. EXTENDED KALMAN FILTER

The Kalman filters are all iterative processes which are named after Rudolf E Kalman, who was the only who advanced the Kalman filter based totally on already present statistical processes for filtering and mixed them to create the Kalman filter. This filter that's an ultimate filter with regards to minimizing rectangular error based on the sensor readings and the variance of the sensor readings. The authentic Kalman filter with all those homes has one predominant flaw which doesn't make it usable for this application and this is that it can't be used for anything besides linear systems. This disadvantage makes it no longer usable for most of the troubles as most effective fragments of the systems that might be filtered are linear. Position, pace or orientation are not a part of the fraction of systems which might be linear. Due to this cause that the Kalman filter most effectively works for linear systems, different types of variations of the authentic Kalman filter have been used. The extended Kalman clear out is as it's miles described with the aid of its call an extension to the original Kalman filter.

Retrieval Number: 100.1/ijeat.E25920610521
DOI:10.35940/ijeat.E2592.0610521
Journal Website: www.ijeat.org

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This extension method that it's miles linearising the structures in order that it extends the Kalman clear out from simply being used for linear structures. The blessings of the usage of the extended Kalman clear out is in its simplicity, as compared to other approaches for making use of the Kalman clear out to nonlinear systems. Another gain with a less complex set of rules for the filtering is the truth that it typically could have a shorter execution time in comparison to the more complicated versions of the Kalman filter out for the nonlinear systems.

The six state discrete Kalman filter has been utilized by Mehrjardi et al., (2014). To estimate angular rates of satellite based on control sensor noisy data. Noisy measurements were produced by sensor and these data sets are sent to the discrete Kalman filter part in order to estimate the attitude and it's rate. A real time tracking has been done to calculate azimuth and elevation angle of the satellite by Kocadag and Demirkol (2015) for uninterrupted broadcasting. Pham et al., (2015) proposed a gain-scheduled Extended kalman filter (EKF) to reduce the computational requirement in the nano-satellite attitude determination process. Rahimi et al., (2015) has derived a practice for boosting the fault detection scheme of reaction wheels alongside an enhanced adaptive unscented Kalman filter (AUKF) with a particle swarm optimization. In case of precise point positioning (PPP), Kalman filter proved to be a good choice for position and velocity estimation. A robust adaptive filter allowed Zhang et al., (2018) to achieve a more desirable positioning solution. A near optimal estimation of characteristic parameters for beidou satellite system (BDS) clock was carried successfully by Wang et al., (2018) who considered white, random walk and random run frequency modulation as the linear combination of several Gauss Markov process. Another real-time geolocation solution of a radio frequency (RF) emitter was presented by Ellis and Dowla (2018) using a constrained Unscented Kalman Filter which reduced the convergence time, high resiliency to noise, sub-kilometer geolocation accuracies and the maintenance of stability. The presence of sensor faults also leads to failure of Kalman filter and hence Adnane et al., (2018) developed the Fault Tolerant Extended Kalman Filter in view of improving the state estimation reliability.

In addition, a k^{th} - order local week observability of autonomous navigation in a disturbed satellite system with relative position measurement allowed the modified unscented kalman filter to refine the accuracy for the two-satellite system (Zhang and Li 2017). Spaceborne gravity gradients suggested by Sun et al., (2016) encouraged the autonomous orbit determination capabilities for near Earth satellites. An augmented state filter dealt with unknown significant measurement biases. Kang et al., (2015) worked on a time domain signal tracking and mitigation algorithm for estimating the frequency of interference in a global navigation satellite system (GNSS). Whereas, GPS receivers with provisions for inertial navigation system (INS) aiding were designed by Weiss (1996) with internal Kalman filters to produce an output of inertially smoothed position and velocity. The Kalman filter supplies a prime solution in the minimum-mean-square-error perception. A multirotor unmanned aerial vehicle (UAV) prepared with brushless DC (BLDC) motors become presented for an online pace estimation on system. The Kalman Filter changed into applied with averaged country-space version of brushless DC motor with the intention to estimate the speed of propeller (Krznar et al., 2020). To enhance country estimates via gaining knowledge of the distinction among the apriori model and the real gadget dynamics, a neural extended Kalman filter (NEKF) method turned into used in target tracking through Stubberud and Kramer (2010). Another method with the aid of Vukovich and Kim (2015) for the usage of a constant country Kalman Filter as a closed control loop controller and clear out changed into introduced. Kalman filters addressed the hassle of regulating the separation of two low earth orbiting satellites with good dynamic characteristics. However, mindset estimation the use of Kalman filter out technique became employed to predict the actual satellite's attitude in spite of the noise present in the system (Hamzah et al. 2014). To sum up, some of these researches lacked the tracking in real-time on a RT-Lab. However, the insertion of Gaussian noise does no longer produce a higher peak inside the celebrated attitude Euler angles as the output together with a constant state response. This shortcoming makes Extended Kalman Filter a more robust model to conform in real-time for non-linear complicated models. It is relevant when both state and measurement equations are linear and also when both system and measurement noise processes ω_k and v_k are Gaussian. It is presumed that both system and measurement noise processes $v_k$and ω_k have Gaussian distributions. The mean and covariance matrices are enumerated via Kalman filter's repetitive equations given below:

1. Prediction Stage :

$$\hat{x}_{k|k-1} = f(\hat{x}_{k-1|k-1}) \tag{17}$$

$$P_{k|k-1} = Q_k + \hat{F}_k P_{k|k-1} \hat{F}_k^T \tag{18}$$

2. Update Stage :

$$\hat{x}_{k|k} = \hat{x}_{k|k-1} + K_k(z_k - H_k \hat{x}_{k|k-1}) \tag{19}$$

$$P_{k|k} = (I - K_k H_k) P_{k|k-1} \tag{20}$$

3. Kalman Gain :

$$K_k = P_{k|k-1} H_k^T (H_k P_{k|k-1} H_k^T + R_k)^{-1}$$

where $\hat{x}_{k|k-1}$is the prior estimate of the state vector at step k and is also the optimal estimate prior to the incorporation of the measurement at this step. Whereas, $\hat{x}_{k|k}$ is the improved estimate, using the measurement at the step k. This is the best minimum square estimate that can be obtained about x at this step. $\hat{F}_k$is earned through Jacobians as follows:

Retrieval Number: 100.1/ijeat.E25920610521
DOI:10.35940/ijeat.E2592.0610521
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$$\hat{F}_k = \left[\nabla_{x_{k-1}} f^T(x_{k-1})\right]^T|_{x-1} = \hat{x}_{k|k-1} \quad (21)$$

V. ILLUSTRATIVE EXAMPLE

In this section, the accomplishment of the model for proposed extended kalman filter is graded by an example. In order to gain accurate target tracking, a clear and a better estimate of 3-dimensional target state $x = [p^T , v^T]$ with position and velocity is presented. The system model is then prescribed in discrete time space as

$$x_k = f(x_{k-1}, u_{k-1}) \quad (22)$$

Eq. (24) consists of process noise which has the covariance of W_{k-1}N(0, Q) and S_x , S_y , S_z as standard deviations of the process noise on velocity in *x*, *y* and *z* directions. Before considering the measurement update in the next step, the association between the measurement and the relative target state with respect to sensor contributes to the making of a complete measurement model

$$z_k = h(x_k) = \begin{bmatrix} atan(x_t - x_s/y_t - y_s) \\ atan(z_t - z_s/sqrt(x_t - x_s)^2 + (y_t - y_s)^2) \\ sqrt(x_t - x_s)^2 + (y_t - y_s)^2 + (z_t - z_s)^2 \end{bmatrix} + v_k \quad (23)$$

where, $p_k = [x_t, y_t, z_t]^T$ is the position vector of the target of $[x_s, y_s, z_s]^T$ sensor. Additionally, measurement has a non-linear relationship with target. If at-least one model is non-linear, then use of non-linear technique becomes a good choice. Consequently, to apply EKF, take the first derivative of process and measurement model

$$F_{k-1} = d_k/d_x|\hat{x}^+_{k-1}, u_{k-1}$$

$$H_k = d_h/d_x|\hat{x}^-_k$$

Above matrix Hk deviates with contrasting values of $[x, y, z]^T$ on which filtering result will depend. Therefore, for the measurements corrupted with gaussian noise with standard deviations as $[0.02, 0.02, 1]^T$ the filter's measurement covariance matrix R will have the following statistics

$$R = \begin{bmatrix} 0.02^2 & 0 & 0 \\ 0 & 0.02^2 & 0 \\ 0 & 0 & 1^2 \end{bmatrix}$$

Here, M = 100 are monte-carlo runs which were conducted with initial guess $\hat{X}^+_0 = x_0 + normrnd(0, [1, 1, 0, 0, 0, 0])$. It provides samples from a gaussian distribution with standard deviation. It can also be concluded that by making the process noise covariance a large number the filter measurements are more reliable, one can present at-least the position estimate from diverging.

VI. ADVANCE ADAPTIVE ROBUST CONTROL LAW

The control aim of Advance Adaptive Robust Control (AARC) is to make the satellite orbit in a circular path accurately and keep it pointing in a perfect and stable direction which is also one of the main objectives of this research. According to a new study, for situations like the existence of unobstructed noise an adaptive methodology proves to be the best choice. The disturbances present in space make the communication weak and difficult to track. Hence, an advanced adaptive robust controller helps to overcome all the above issues and tracks the yaw, pitch and roll angles as per desired criteria. An active fault-tolerant control (FTC) architecture for satellite attitude control system (ACS) introduced by Jia et al., (2012) for combining iterative learning ideology and unknown input observer (UIO). It also permitted attitude angular velocity estimation and robust reconstruction of adaptive law simultaneously. A robust model predictive control (RMPC) based on model reference adaptive system (MRAS) for the three degree of freedom satellite system was proposed by Pirouzmand et al., (2013). The effect of moment of inertia uncertainty and external disturbance was compensated for by the stability and performance of the closed loop system. Also, a higher order and adaptive control technique (Caudill et al.,2014) for maintaining the desired trajectory of the satellite formation in the presence of multiple perturbations proved an accurate tracking approach. The requirement of tracking the other spacecraft chaotic attitude plant was fulfilled by Liu et al., (2017). Zhong et al., (2018) introduced a fractional order operator and saturation function into the sliding surface so that a new adaptive fractional order sliding mode control allowed a faster deployment time without overshoot. Dizadji et al., (2018) designed an adaptive direct fuzzy control system of a typical satellite attaining desired orientation.

The satellite system considered here is exposed to parametric uncertainties owing to the moment of inertia vector α and uncertain non-linearities represented by $\hat{N}$. These nonlinearities arise from the uncompensated model because of hidden model errors, sensor errors and other distractions. The dynamics as in eq. (6) can be recasted as

$$I_{sat}\dot{\omega} + \omega \times (I_{sat}\omega + I_w\omega_w) + \tau_\omega = Y(\omega, \dot{\omega}, \dot{\omega}, \ddot{\omega}, I_w)\alpha + \tilde{N} \quad (24)$$

The succeeding empirical speculations are made

$$\alpha \in \gamma_\alpha \triangleq \{\alpha : \alpha_{min} < \alpha < \alpha_{max}\}, \tilde{N} \in \gamma_{\tilde{N}} \triangleq \left\{\tilde{N} : \left\|\tilde{N}\right\| \le \delta_{\tilde{N}}\right\}$$

also here

$$\alpha_{min} = [I_{1x\,min}, I_{1y\,min}, \dots, I_{3z\,min}]^T$$

$$\alpha_{max} = [I_{1x\,max}, I_{1y\,max}, \dots, I_{3z\,max}]^T$$

and $\partial\hat{N}$ are known for a set γ. Designate a switching function as

$$p = \dot{e} + K_1 e \quad (25)$$

$$p = \dot{\omega} - \dot{\omega}_{eq}, \quad (26)$$

$$\dot{\omega}_{eq} \triangleq \dot{\omega}_d - k_1 e \quad (27)$$

where $e = \omega - \omega_d$ is defined as the trajectory tracking error vector, ω_d is the desired trajectory to be tracked by ω and k_1 being the positive diagonal feedback matrix. Say if p coincides to a small value or zero, then e will converge to a small value or zero. In this perception, the governing output tracking error e is the same as synchronizing p.

$$I_{sat}\dot{\omega}_{eq} + \omega_{eq} \times (I_{sat}\omega + I_w\omega_w) + \tau_\omega = Y(\omega, \dot{\omega}, \dot{\omega}_{eq}, \ddot{\omega}_{eq}, I_w)\alpha \quad (28)$$

Blending eq. (6) and (24), the control input and the system uncertainties are correlated to p along with a first-order dynamic equation given by

$$I_{sat}\dot{p} + p \times (I_{sat}\omega + I_w\omega_w) + \tau_\omega = \tau - Y(\omega, \dot{\omega}, \dot{\omega}_{eq}, \ddot{\omega}_{eq}, I_w)\alpha - \tilde{N} \quad (29)$$

Suppose h(ω, ω, ˙ ω˙eq Iw) be a bounding function satisfying

$$\left\| Y(\omega, \dot{\omega}, \dot{\omega}_{eq}, \ddot{\omega}_{eq}, I_w)\tilde{\alpha} - \tilde{N} \right\| \le h(\omega, \dot{\omega}, \dot{\omega}_{eq}, \ddot{\omega}_{eq}, I_w) \quad (30)$$

For instance select
$$h(\omega, \dot{\omega}, \dot{\omega}_{eq}, \ddot{\omega}_{eq}, I_w) = \| Y(\omega, \dot{\omega}, \dot{\omega}_{eq}, \ddot{\omega}_{eq}, I_w)\alpha_M \| + \delta_{\tilde{N}}$$

here αM = ‖ αmax − αmin‖ with reference to the model in eq. (29), the adaptive robust control law is designed as:

$$\bar{u} = \bar{u}_a + \bar{u}_s, \bar{u}_a \triangleq Y(\omega, \dot{\omega}, \dot{\omega}_{eq}, \ddot{\omega}_{eq}, I_w)\hat{\alpha}$$

here $\bar{u}_a$ is the variable model reimbursed for attaining flawless tracking, and $\bar{u}_s$ being a vigorous control function having the appearance of

$$\bar{u}_s = \bar{u}_{s1} + \bar{u}_{s2}, \bar{u}_{s1} = -k_{s1}p \quad (31)$$

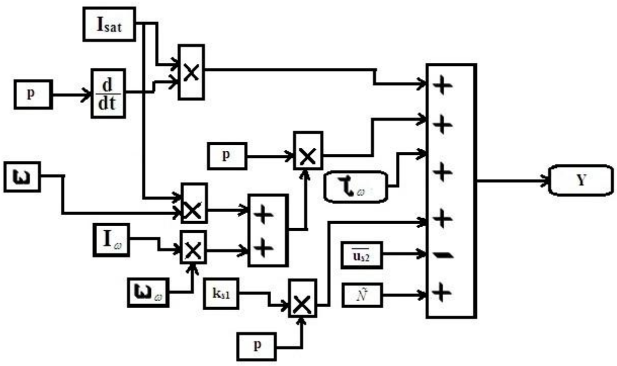

Fig. 8 Simulink block for implementing Satellite dynamics with an adaptive law as mentioned in eq. (32).

where $\bar{u}_{s1}$ is for stabilizing the nominal system, ks1 is any positive definite diagonal matrix, $\bar{u}_{s2} = -k_{s2}(p)p$ being arobust feedback term used to diminish the result of uncertainties and $k_{s2}(p)$ is a non-linear feedback gain. With reference to adaptive robust control law, the tracking error dynamics is formed as

$$I_{sat}\dot{p} + p \times (I_{sat}\omega + I_w\omega_w) + \tau_\omega = -k_{s1}p + \bar{u}_{s2} + Y(\omega, \dot{\omega}, \dot{\omega}_{eq}, \ddot{\omega}_{eq}, I_w)\tilde{\alpha} - \tilde{N} \quad (32)$$

Here, the application of the suggested controller as in above eq. (32) is plotted clearly in Fig. 8 with the help of Simulink control system toolbox.

VII. SIMULATION RESULTS

The analysis is done on the described dynamics of the plant model. The actuator model, satellite's newton-euler equation with external torque and disturbance as mentioned in section III is implemented in simulink model of MATLAB software. The experimental testbed utilized in this paper is Real-Time laboratory (OPAL-RT) setup. It is installed on desktop, interfacing with the master computer. This setup requires RT version 11.1 with two computers, one acting as a Master and the other as Slave. The output being observed on the CRO or DSO. In Fig. 9, a comparison of tracking and stability performance of the satellite being hit by the atmospheric disturbance before t = 4s is recorded. This perturbation disappears after t = 4s. Consequently there are some inertia forces from the satellite. The motive of this occasion is to check the performance of the two controllers. In the presence of disturbance, the AARC can spot the desired route swiftly.

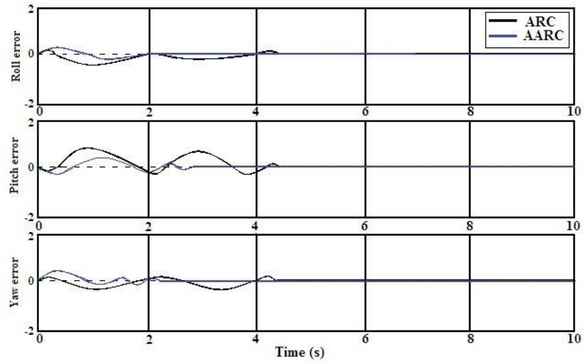

Fig. 9 Comparison of tracking and stability performance with non-persistent disturbance (Jiang *et al.*, 2012)

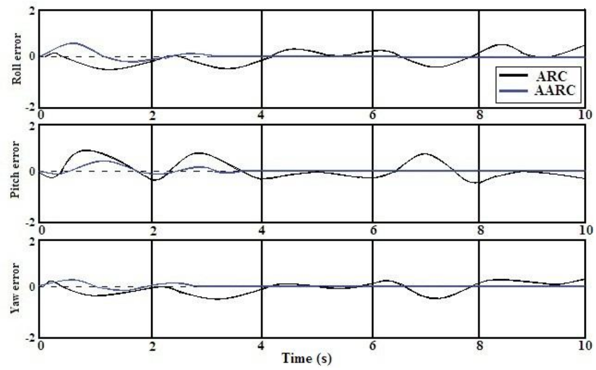

Fig. 10 Comparison of tracking and stability performance with persistent disturbance (Jiang *et al.*, 2012)

Retrieval Number: 100.1/ijeat.E25920610521
DOI:10.35940/ijeat.E2592.0610521
Journal Website: www.ijeat.org

Published By:
Blue Eyes Intelligence Engineering and Sciences Publication

International Journal of Engineering and Advanced Technology (IJEAT)
ISSN: 2249-8958 (Online), Volume-10 Issue-5, June 2021

A similar comparison in Fig. 10 has disturbance living all the time, during the beginning of the tracking. The AARC can track the desired trajectories accurately with good transient responses. The tracking errors *e* lasted in minor area. The tracking error and the tracking rate are much of higher quality in AARC. The respective euler angles (ϕ, θ, ψ) present their real-time validation in RT-LAB. Simulation response is recorded when both with minimum settling time for T = 100s. Fig. (11-13) presents data of EKF showing roll, pitch and yaw angle with accurate estimation results.

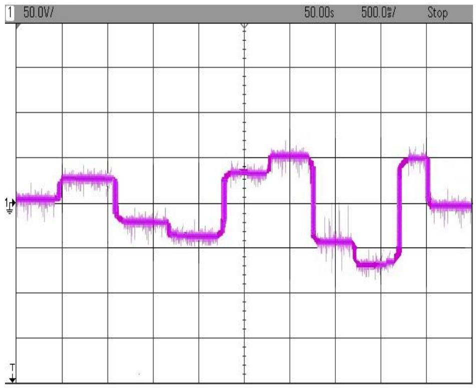

Fig. 11 Euler angle plot representing (Roll angle) in RT-LAB.

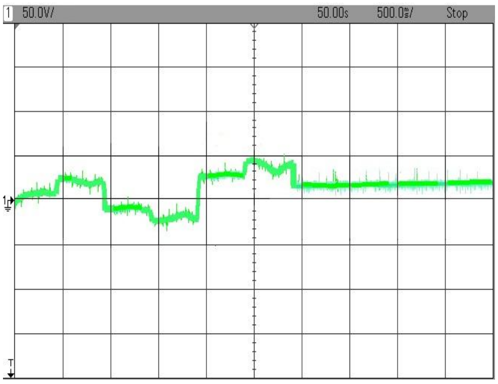

Fig. 12 Euler angle plot representing (Pitch angle) in RT-LAB.

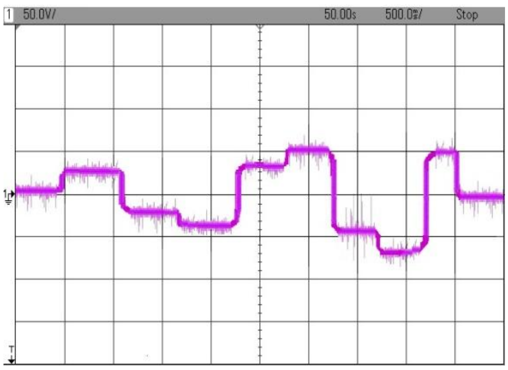

Fig. 13 Euler angle plot representing (Psi angle) in RT-LAB.

A step reaction coadjuvant is produced classically from the satellite non-linear model with the existence of disturbances (colored noise). The radical analysis involves the discrepancy of the control weighting angle as ks1 = 100 for t < 50, then ks1 = 1 for the interval 50 < t < 100, and then lastly ks1 = 0. Further, the proposed advanced adaptive robust controller operates on an active range of control lines at a sample time of T = 0.5. The confounding variable dampers are slackened. Another observation from Fig. (14-16) reveals that as the control weighting line is diminished, the output production is boosted at the expense of vigorous confounding variables. Therefore, an advanced adaptive robust controller (AARC) has delivered a high quality response by including an adaptive model of system with uncertainties and thereby performing the tracking online in RT-LAB for respective euler angles.

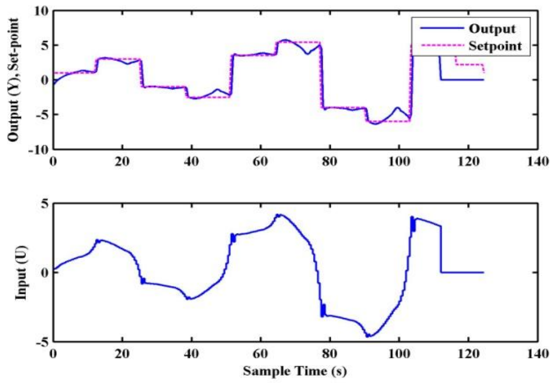

Fig. 14 Advance adaptive robust control (AARC) for K_1 = 1.3 and τ_ω =2.5.

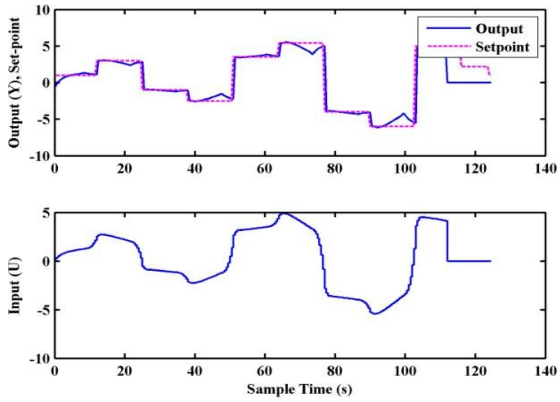

Fig. 15 Advance adaptive robust control (AARC) for K_1 = 1.1 and τ_ω =0.25.

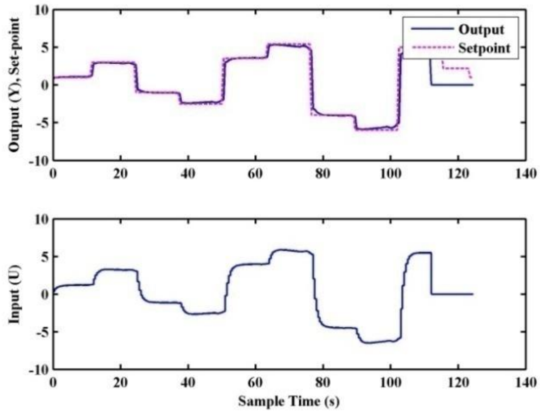

Fig. 16 Advance adaptive robust control (AARC) for K_1 = 0.9 and τ_ω =0.125.

Retrieval Number: 100.1/ijeat.E25920610521
DOI:10.35940/ijeat.E2592.0610521
Journal Website: www.ijeat.org

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VIII. CONCLUSION

A brief discussion regarding maneuver of satellite is presented with dynamics given by the first order nonlinear differential equation. The problem developed by atmospheric distractions have resulted in an inappropriate orientation of the satellite system. This theme is reiterated by modeling the problem into a 2 dimensional Ito stochastic equation. The MIMO (multi-input multi-output) non-linear model developed with the design of stochastic dynamics having distractions alongside the orbit represents the unique parameters to be taken care of. For more analysis, the EKF estimate observance technique is quoted well. The exact positioning for the required attitude parameters is experimentally validated with the response recorded in OPAL-RT hardware. The augmentation of AARC (advanced adaptive robust control) promotes an additional benefit of gaining stability with accuracy in the performance of satellite systems. Also to sum up, the comparison presented reveals the better response achieved with designed AARC in this paper. To sum up, this paper has briefly visited the issues related to the proposed system with an acceptable outcome. The main contribution involves the development of a stable and accurate system, an attitude model with EKF, an exact positioning of satellite along with expected tracking of concerned parameters in RT-Lab setup within a stipulated period.

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