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Effect of Control Model on Internal Variable Dynamic Characteristics of a Plant: A State Feedback Controlled Satellite Antenna

B. O. Ekengwu[1], A. E. Jonathan[2], P. C. Eze[3]

1Department of Electronic Engineering
University of Nigeria Nsukka, Nigeria (UNN)
Nsukka, Nigeria
bonaventure.ekengwu@unn.edu.ng
2Department of Electrical and Electronic Engineering
Federal University Otueke
Otueke, Nigeria
amajoe2002@yahoo.com
3Department of Electrical and Electronic Engineering
Imo State University
Owerri, Nigeria
paulinuseze1@gmail.com

Abstract: *This paper has examined the dynamic characteristics performance of the state variables of a full state feedback controlled satellite dish antenna in distributed mobile telemedicine. The object is to examine the behaviour of the internal variables of industrial process or plant when the structure or algorithm of the control technique used is modified or altered. The dynamic equations of a dish antenna position control system used in distributed mobile telemedicine nodes were obtained in the form of transfer function models in continuous time domain. The transfer function models were transformed into equivalent state space models. The state space equations were represented by different features of Simulink used to model the system in MATLAB/Simulink environment. The performance of the system was studied in terms of stability, controllability, and observability. Simulations were carried out in MATLAB/Simulink environment. The results obtained showed that the characteristics performances of the state variables are influenced by changes in the structure and complexity of the control algorithm.*

Keywords: *Full state feedback, Mobile telemedicine, Satellite antenna, State variables*

1. INTRODUCTION

In the analysis and design of feedback system in traditional control theory, many techniques are taken into consideration like root locus and frequency responses [1,2]. These techniques are generally based on a simple relationship representing the input-output of the mathematical model of the process in the form of a transfer function [3]. Even though the transfer function expression offers simple and great analysis and design methods [1,4] the method does not provide the designer with the knowledge of the interior structure of the plant [3]. This means that for a given input, only the response is depicted without any information concerning the internal states of the system provided. There are certain limitations to the transfer function technique: a) it can only be used to study Linear Time Invariant (LTI) systems due to the intricacy that comes with using it in multi-input multi-output (MIMO). b) Its design and analysis is mainly applicable to single input single output (SISO) systems.

In modern control theory, the shortcomings associated with the transfer function technique in terms of providing detailed description of the dynamic features of a plant are addressed. The description provided by modern control theory considers not only the relationship between the input and output but also depicts the internal dynamic variables of the system called state variables.

State variables are mathematical equations usually referred to as state space equations. These equations represent a set of combined first-order differential equations of internal (or state) variables and in concert with a set of algebraic equations which integrate the state variables into output variables [3]. State variable technique can be used to design and analyse linear, nonlinear, time invariant or time varying MIMO [1,2].

The use of state variable equations in the design and analysis of dynamics of a plant has been well studied. A study on the transient simulation of transmission line by modelling voltage and current distributions as state variables was carried out by [5]. Sang et al. [6] presented the analysis and modelling of non-volatile memory devices with identified internal state variables for dynamic characteristics. A study on using state variable technique for the drying section of a paper-making machine based mass and energy balance relationships established for steam, paper, cylindrical heater wall and moisture was presented by Berrada et al. [7]. A solar power system was studied by Chattopadhyay et al. [8] using state variable technique. Njoku et al. [1] used state variable method to study dynamics of a linearized mechanical system that represents idle speed model of engine.

The objective of this paper is to analyse the dynamic characteristics of the internal variable of a telemedicine mobile node antenna system using the principle of state space variable with full state feedback control.

2. LITERATURE REVIEW

The state represents a set of variables that summarizes the history of the system in an attempt to predict the future responses. The state variable is directly a time domain technique that offers a basis for modern control theory and system optimization. It also serves as a very powerful scheme for the analysis and design of linear, and nonlinear, time-invariant or time varying multi-input-multi-output (MIMO) system [1]. Figure 1 depicts a structure of plant model in terms of the state variable. Linear Time Invariant (LTI) system can be expressed in state space form given by:

$$\dot{x} = Ax + Bu$$
$$y = Cx + Du$$

(1)

where A, B, C and D are the constant matrices such that A is the state matrix, B is the input matrix, C is the output matrix, and D is the direct transition matrix.

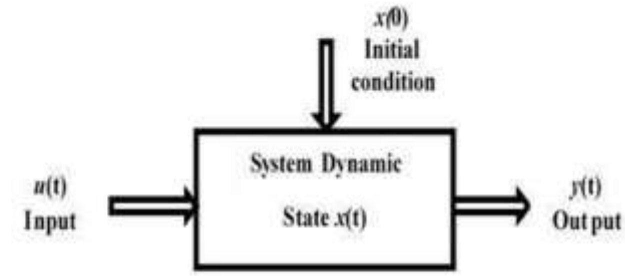

Fig.1. Block diagram representation of state variables [9]

3. SYSTEM MODELLING AND CONFIGURATION

3.1 State Space Modelling

In this paper, the plant under consideration is a dish antenna whose open loop block diagram is shown in Figure 2 and the transfer function given by Eq. (2) [10]:

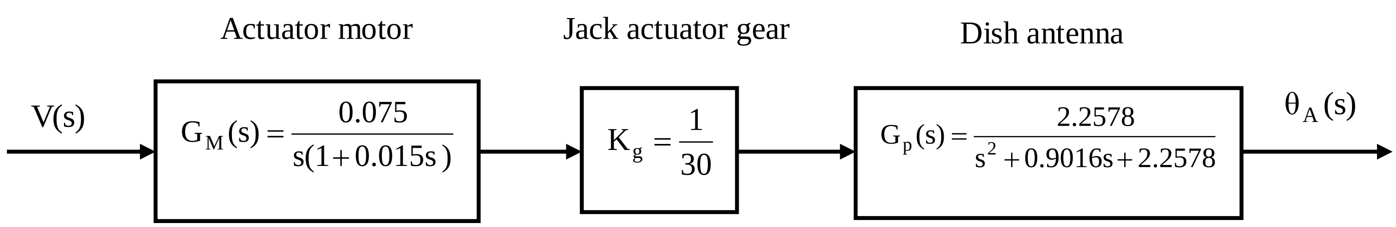

Fig. 2. Cascaded block diagram of the components of the outdoor dish antenna [11]

$$G_p(s) = \frac{\theta_A(s)}{V(s)} = \frac{3.76}{s^4 + 67.56s^3 + 62.36s^2 + 150.52s} \qquad (2)$$

where $V(s)$ is the input voltage and is the reference dish position in radian.

However, the system being considered is influenced by the time delay in the forward and feedback paths during communication. These delays are given by [12]:

$$\left.\begin{aligned} G_{d1}(s) &= e^{-T_1 s} \\ G_{d2}(s) &= e^{-T_2 s} \end{aligned}\right\} \qquad (3)$$

where:
T_1 = Feed forward delay from base station to the node in seconds and
T_2 = Feedback delay from the node to base station in seconds.
Now, assuming that the feed forward time delay is equal to feedback time delay, such that $T_1 = T_2 = T$.
Equation (4) can be expressed as:

$$G_{d1} = G_{d2} = G_d = e^{-Ts} \qquad (4)$$

The maximum and minimum time delay was determined to be 0.2502s and 0.2469s.

The transfer function expressions given by Eq. (2) and defines the direct relation between the input and the output. Equation (2) provided the knowledge for the input and output of the jack actuator and dish antenna position model (that is the plant). In this paper, the transfer function is further expressed to describe the internal variables of the system using state-space representation. This is obtained as follow by using the approach by [13].

Step 1: state space of plant model [1]:

$$\frac{Y(s)}{U(s)} = \frac{3.76}{s^4 + 67.56s^3 + 62.36s^2 + 150.52s}$$

(5)

where Y(s) and U(s) are the output and input of the plant. Assuming zero initial conditions, Equation (5) can be expressed in the form of Eq. (6):

$$s^4Y(s) + 67.56s^3Y(s) + 62.36s^2Y(s)$$
$$+150.52sX(s) = 3.76U(s)$$

(6)

Let $y = x_1$ then Eq. (6) can be resolved as in Eq. (7).

$$\left.\begin{aligned} x &= x_1 \\ \dot{x}_1 &= x_2 \\ \dot{x}_2 &= x_3 \\ \dot{x}_3 &= x_4 \\ \dot{x}_4 &= -150.52x_2 - 62.36x_3 - 67.56x_4 + 3..76(t) \end{aligned}\right\}$$
(7)

Transforming Equation (7) into state space form, gives:

$$H = \begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \\ \dot{x}_4 \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & -150.52 & -62.36 & -67.56 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 0 \\ 3.76 \end{bmatrix} u(t)$$
(8)

$$y = \begin{bmatrix} 1 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix}$$
(9)

The state matrix A is given by:

$$A = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & -150.52 & -62.36 & -67.56 \end{bmatrix}$$

The input matrix B is given by: $B = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 3.76 \end{bmatrix}$

The output matrix C is given by: $C = \begin{bmatrix} 1 & 0 & 0 & 0 \end{bmatrix}$

The matrix D is given by: $D = 0$.

3.2. Properties of System

This subsection presents four basic properties of a system, which are studied in detail from a state-space perspective. This is necessarily important because each property will have an impact on the control technique used in this work. The properties are: stability, steady-state error, controllability and observability.

Stability: is a key property in to understanding the dynamic performance of a system. The natural response of a system and its stability can be understood from the system pole locations. For instance, if the poles of a system are located at the left half plane (LHP) of the complex frequency such that s = -3 or s = -5±2j, the system either produced damped sinusoid or an exponential decay it time response. However, when the poles are on the imaginary $(j\omega)$ axis or in the right half plane (RHP) such that s = 3 or s = 3±2j, the outcome is unstable or exponentially increasing responses. It can be conclusively said that a system whose poles is located in the LHP is stable. In this paper the poles of the system are obtained using the MATLAB code given by:

$$[z, p, k] = ss2zp(A, B, C, D)$$
(10)

where z, p, k means zero, pole, and gain. The poles, p = 0, -66.6584, -0.4508±1.4335j. Since the poles are all in the LHP, the system is stable.

*Controllabilit*y: If it is possible to take every system state variable from any initial state to any desired final state in a given finite time by a control input, the system is said to be controllable. Otherwise the system is uncontrollable. Determining whether a system is controllable usually seems to be difficult, as a result of the size and complexity of the state-space model. In such conditions, a simple test can be employed to find out whether a system is controllable. The mathematical approach for determining controllability can be obtained in [1]. The first thing to do when determining the controllability of a system is to form the controllability matrix given by:

$$C_{matrix} = \begin{bmatrix} B & AB & A^2B & .... & A^{n-1}B \end{bmatrix}$$
(11)

If the controllability matrix is of full rank, a system is said to be controllable. For single input single output (SISO) systems, this is done so as to verify that the determinant of the controllability matrix is non-zero.

$$C_{matrix} = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 4 & 300. \\ 0 & 3.76 & -254 & 16900 \\ 3.76 & -254.0256 & 16927 & 1128300 \end{bmatrix} \qquad (12)$$

Rank = 4

Since the matrix of the 4th other model is of full rank, that is 4, the system is completely controllable.

*Observabilit*y: If by the measurement of the outputs over a finite time interval can result to the complete identification of the initial state, the system is said to be completely observable. Otherwise the system is not observable. For a system to be observable, its output must have an element with respect to each state. This means that a link must exist from each state to the output. A test on observability can be carried out to determine whether it is observable when there is no clear evidence. A simple test of observbility can be achieved by forming the observability matrix given by:

$$O_{matrix} = \begin{bmatrix} C & CA & CA^2 & .... & CA^{n-1} \end{bmatrix}^T$$
(13)

A system that is observable is one whose observability matrix is of full rank. For SISO systems, this is achieved by verifying the determinant of the matrix in order to ascertain if it is non-zero.

If the determinant matrix is non-zero, the system is observable. In this paper, the observability of the plant model of a dish antenna position system is determined by obtaining the values of the elements of the observability matrix defined by Eq. (13).

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$$O_{matrix} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \text{Rank} = 4 \quad (14)$$

Since the rank of the observability matrix is 4, the system is observable.

3.3 Full State Variable Feedback

A full state variable feedback is a pole placement design strategy in which all desired poles are selected at the beginning of the design process. Figure 3.8 shows the closed loop plant and control. In order to demonstrate that this strategy can place the pole in any desired location, it is initially assumed that the reference is zero, and is simply expressed by:

$$u = -Kx$$

(15)

where u is the control input, K is the feedback gain, and x is a state variable. Substituting Eq. (15) into Eq. (1) gives:

$$\dot{x} = (A - BK)x \quad (16)$$

which has a solution of $x(t) = x(0)e^{-(A-BK)t}$. Therefore, by properly selecting of gains, K can adjust the response of the system as desired. A full state variable feedback system is shown in Fig. 3.

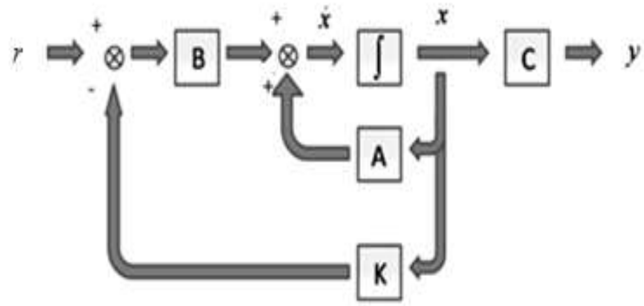

Fig. 3 Full state variable feedback system

Calculation of Feedback Gain: In order to determine the feedback gain K, the eigenvalues of (A-BK) is obtained. Given the state variable feedback matrix K, such that:

$$K = [K_1 \quad K_2 \quad K_3 \quad K_4]$$

(17)

$$(A - BK) = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ -3.76K_1 & -150.52 - 3..76K_2 & -62.36 - 3.76K_3 & -67.56 - 3.76K_4 \end{bmatrix}$$

(18)

In order to determine the eigenvalues, the expression defined by Eq. (19) is used and applied:

$$\det[\lambda I - (A - BK)] = 0$$

(19)

Hence,

$$\det[\lambda I - (A - BK)] = \begin{vmatrix} \lambda & -1 & 0 & 0 \\ 0 & \lambda & -1 & 0 \\ 0 & 0 & \lambda & -1 \\ 3.76K_1 & 150.52 + 3.76K_2 & 62.36 + 3.76K_3 & \lambda + 67.56 + 3.76K_4 \end{vmatrix} = 0 \quad (20)$$

Solving Equation (18) gives:

$$\lambda^4 + \lambda^3(67.56 + 3.76K_4) + \lambda^2(62.36 + 3.76K_3) + \lambda(150.52 + 3.76K_2) + 3.76K_1 = 0 \quad (21)$$

A desired characteristics equation is chosen using:

$$E_{ch} = (\lambda^2 + 2\zeta\zeta_n\lambda + \omega_n^2)(\lambda^2 + a\lambda + b)$$

(22)

Since $\zeta = 0.69$ for minimal overshoot, the settling time, $T_s = 1s$, and the natural frequency $\omega_n = 5.77$, and (a, b) are chosen as (16,100), substituting these values into Equation (22) gives:

$$E_{ch} = \lambda^4 + \lambda^3(7.963 + a) + \lambda^2(33.293 + 7.963a + b) + \lambda(33.293a + 7.963) + 33.293b \quad (23)$$

Solving Equations (21) and (23) gives:

$$67.56 + 3.76K_4 = 7.963 + a \Rightarrow K_4 = -11.60$$

$$62.36 + 3.76K_3 = 33.293 + 7.963a + b \Rightarrow K_3 = 52.75$$

$$150.52 + 3.76K_2 = 33.293a + 7.963b \Rightarrow K_2 = -313.4$$

$$3.76K_1 = 33.293b \Rightarrow K_1 = 885.5$$

Therefore, Equation (17) can be written as:

$$K = [885.5 \quad 313.4 \quad 52.75 \quad -11.60]$$

(24)

Forward path gain: the problem of using full state feedback alone is that possibility of tracking a step input is not certain. In order to address this problem, a forward path gain is implemented as shown in Figure 4.

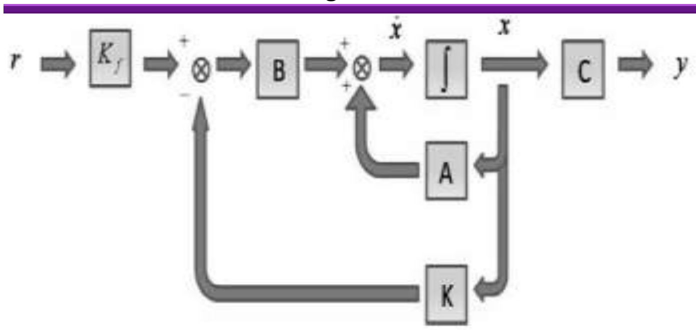

Fig. 4 Full state feedback integrating forward path gain

From Figure 4, it can be seen that the control put can be given by:

$$u = K_f r - Kx \tag{25}$$

where K_f is the forward path gain, r is the desired or reference input. Substituting Eq. (25) into Eq. (1), gives:

$$\dot{x} = (A - BK)x + BK_f r = A_{CL}x + B_{CL}r$$

(26)

where $A_{CL} = (A - BK)$ and $B_{CL} = BK_f$. The transfer function of the system can be shown to expressed by:

$$G_{CL}(s) = \frac{Y(s)}{U(s)} = C_{CL}\varphi_{CL}B_{CL} = C(sI - A_{CL})^{-1}BK_f$$

(27)

Using the final value theorem and given a step input as the reference signal, then

$$y(\infty) = \lim_{s \to 0} sY(s) =$$

$$sC_{CL}(sI - A_{CL})^{-1}B_{CL}K_f \frac{r}{s} = -C_{CL}(A_{CL})^{-1}B_{CL}K_f r \tag{28}$$

The value of K_f was calculated to be 885.5.

Calculation of observer gain: The reason for implementing the observer is to estimate the actual plant so that even if the actual states are in no way measured, the ones estimated by the observer can be used in the state feedback control. Below is the mathematical theory of calculating and selecting observer gains.

From Figure 5, the observer state equation is given by:

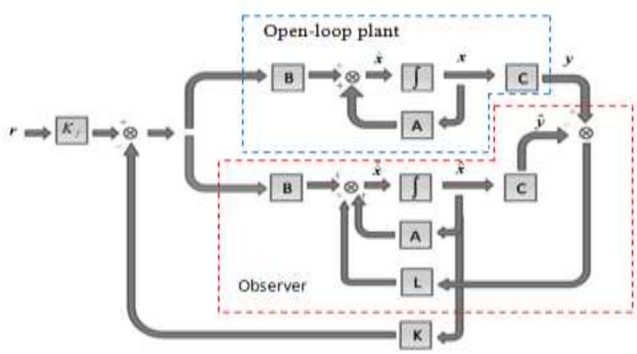

Fig. 5 Full state feedback with an observer

$$\left.\begin{aligned}\dot{\hat{x}} &= A\hat{x} + Bu + L(y - \hat{y}) \\ \hat{y} &= C\hat{x}\end{aligned}\right\}$$

(29)

where $u = K_f r - K\hat{x}$ and L is the observer gain given by:

$$L = [L_1 \quad L_2 \quad L_3 \quad L_4] \tag{30}$$

For an observer, the target is to reduce the error between the actual and the estimate states to zero.

$$\text{error}, e = x - \hat{x} \to 0$$

(31)

$$\dot{e} = \dot{x} - \dot{\hat{x}} = Ax + Bu - (A\hat{x} + Bu + L(y - \hat{y}))$$

$$= (A - LC)(x - \hat{x})$$

(32)

$$\dot{e} = (A - LC)e$$

(33)

The values of the feedback gains, $K = [K_1 \quad K_2 \quad K_3 \quad K_4]$, were substituted into the characteristics equation defined by Eq. (19) so as to obtain the eigenvalues which represent the desired closed loop poles, p. The characteristics equation for obtaining the eigenvalues is given by:

$$\lambda^4 + 23.944\lambda^3 + 260.7\lambda^2 + 1328.904\lambda + 3329.48 = 0$$

(34)

Solving Eq. (34) the values of the poles, p, of the closed loop system are obtained are stated as follows

$$\lambda_1 = p_1 = -7.9915 + 6.0318j$$

$$\lambda_2 = p_2 = -7.9915 - 6.0318j$$

$$\lambda_3 = p_3 = -3.9805 + 4.1676j$$

$$\lambda_4 = p_4 = -3.9805 - 4.1676j$$

The observer gain L is given by:

$$L = \text{place}(A', C', 10 * p) \tag{35}$$

$$L = \begin{bmatrix} 2000 \\ 14400 \\ 345500 \\ 9030600 \end{bmatrix}$$

This section has introduced a technique for studying the performance characteristics of internal variables of dish antenna for distributed mobile telemedicine nodes using state feedback that incorporates a forward path gain and an observer.

4 Simulation Results

The characteristics of the internal (state) variables in terms of step response performance are presented in this subsection. Simulation plots for three case scenarios namely, state variable performance responses for full state feedback without forward path gain shown in Figure 6, full state feedback with forward path gain (or simply full state feedback) shown in Fig. 7, and full state full back with an observer shown in Fig. 8. The summary of the performance parameter values is presented in Table 1.It should be noted that all analysis of the various performance response obtained from the simulations conducted in this paper were carried out using linear analysis

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tool (LAT) of the MATLAB/Simulink control design linear analysis tool (CDLAT) via linear analysis point (LAP).

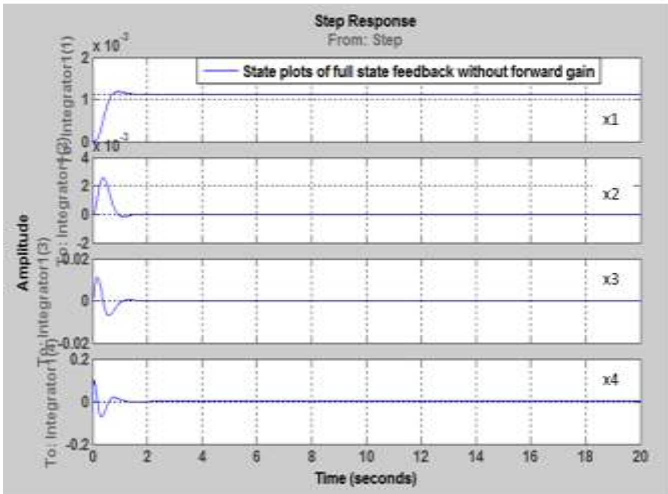

Fig. 6. State variable performance to a step input for full state feedback (no forward path gain)

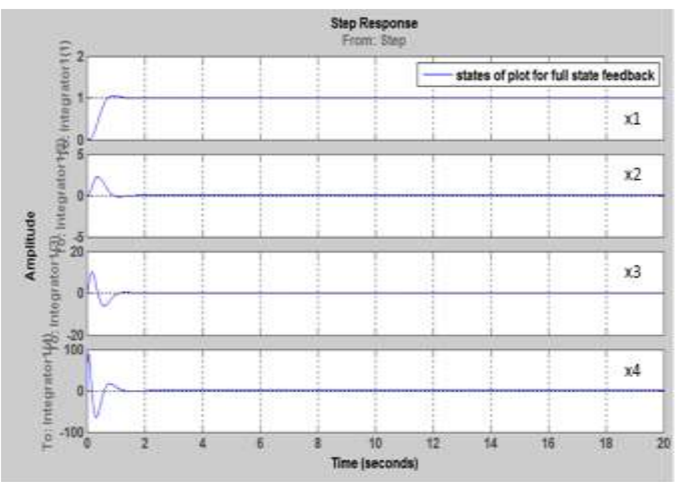

Fig. 7 State variable performance to a step input for full state feedback (with forward path gain)

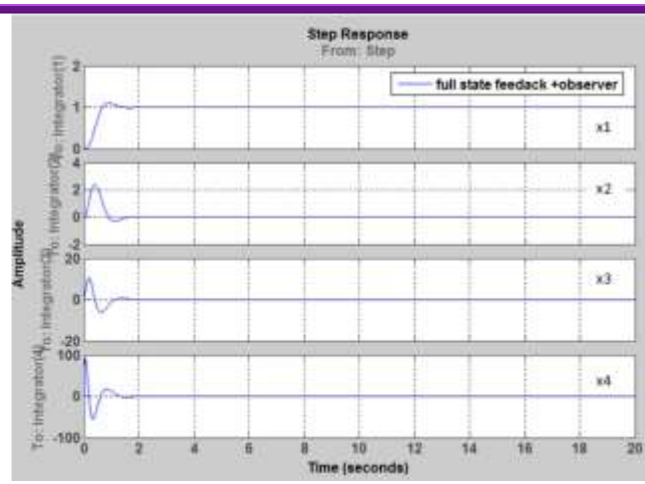

Fig. 8. State variable performance to a step input for full state feedback with an observer

Table 1 Analysis of state variable performance to a step input

Figure	Rise time (s)	Time to peak (s)	Settling time (s)	Overshoot (%)	Remark
Fig. 6	x_1= 0.42, x_2 = 0, x_3= 0, x_4 = 0	x_1= 0.945, x_2 = 0.392, x_3= 0.184, x_4 =0.0692	x_1= 1.22, x_2 = 1.44, x_3 = 1.54, x_4 = 1.22	x_1= 4.9, x_2 = Inf, x_3 = Inf, x_4 = inf	Unit step response not tracked
Fig. 7	x_1= 0.42, x_2 = 0, x_3= 0, x_4 = 0	x_1= 0.945, x_2 = 0.392, x_3= 0.184, x_4 =0.0692	x_1= 1.22, x_2 = 1.44, x_3 = 1.54, x_4 = 1.22	x_1= 4.9, x_2 = Inf, x_3 = Inf, x_4 = inf	Unit step response tracked
Fig. 8	x_1= 0.39, x_2 = 2.06e-12, x_3= 3.39e-15, x_4 = 5.11e-15	x_1= 0.913, x_2 = 0.396, x_3= 0.183, x_4 = 0.0609	x_1= 1.31, x_2 = 1.54, x_3= 1.72 , x_4 = 1.67	x_1= 10, x_2 = 1.65e+16, x_3 = 2.65e+15, x_4 = 1.08e+15	Unit step response tracked

The analysis on focused on the continuous time domain response performance of state variables to unit step input for a full state feedback controlled dish antenna positioning control system. The time domain parameters considered are rise time, time to peak, settling time and percentage overshoot. Looking at Table 1, it is obvious that the values of the state variables change with respect to changes in the full state feedback controller condition. With respect to the state variable x_1 which represents the required position to be tracked, Figure 6 showed that with only the full state feedback controller applied, the required step input was not attained. Whereas in Figures 7 and 8 wherein a forward path gain and an observer were included, a good step response tracking was attained with optimal performance in respect to the considered time domain parameters.

Generally, the results in Table1 revealed that the state variable (or internal dynamics) are actually influenced by the control loop configuration and complexity of the controller. It can be seen that the state variables x_1, x_2, x_3, and x_4 show varying characteristics performance for various control loop structure. This is the actually the essence of the study which is aimed at examining the behaviour of the internal variables of industrial process or plant when the structure or algorithm of the control technique used is modified or altered. The knowledge of which will aid proper design and implementation of practical control system.

5 CONCLUSION

This paper has examined the step response performance of state variables of full state feedback controlled satellite dish antenna positioning system in telemedicine node. The significant of this study is that the characteristic performances of the state variables which provide information on the interior dynamics of the structure of the plant are established. This will assist in choosing the appropriate control strategy that will meet the required system performance. It has also revealed the effectiveness of the full state feedback control method implemented in this paper. The study has also provided insight and educational knowledge on full state feedback design considering complex telecommunication system with fourth order dynamic characteristics.

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