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Optimization of Standard Prosthetic Arm Introducing Control System

Swati Barui[1] and Biswarup Neogi[2*]

[1] Electronics and Communication Engineering, Maulana Abul Kalam Azad University of Technology, Kolkata, West Bengal 700064, India

[2] Electronics and Communication Engineering, JIS College of Engineering, Kalyani, West Bengal, India

Abstract

Realization of artificial limb to restore the originality of concerned for overall function of the living system is the science popularly known as prosthetic. Whenever some body part or limb is replaced artificially, that replaced part needs to be well connected to the original connecting organ for faithful function of overall system. Hence, the essential requirement of prosthetic limb that the limb should be capable of processing various intelligences as obtainable from the total living system. The present work deals with the design of such one prosthetic arm which not only is connected mechanically to the living organ, but also is capable of holding material processing motor action. Here the controllability and observability are determined in this article for optimizing the functionality and system design of the prosthetic arm. Hence lies the efficacy of the system.

Keywords: *Prosthetic, IBM Electric Arm, Valduz hand, biofeedback Otto-Bock arm, controllability, observability*

1. Introduction

Biofeedback is based on the concepts, confirmed by scientific studies, that people have the innate potential to influence with their minds many of the automatic, involuntary functions of their bodies [22]. A biofeedback researcher uses signals from special monitoring equipment for teaching control of certain body functions and their responses, such as: Brain activity, Blood pressure, Muscle tension, Heart rate, Skin temperature [11]. The present study on prosthetic is developed using muscle tension [8]. The term prosthesis is generated from Greek word "prostithenai" [23], means artificial body parts. In the development of prosthetic control, some important prosthetic arms are demonstrated here. The first mechanical arm is pneumatic hand [3]. The IBM arm (fig.1) is one of the significant developments of prosthetic science [25].

The Vaduz Hand or French Hand (fig.2) is complicated in the mechanical adaptation [10]. The preferable cosmic and flexible development if prosthetic arm technology is myoelectric Otto-bock arm (fig.3) [2,26]. With development of device and IC technology the first transistor utilized prosthetic hand is Russian Hand [7].

The externally powered prosthesis needs an input for control the arm action with appropriate feedback response. From an engineering perspective, the components in a prosthetic device can be viewed as a feedback control system [5].

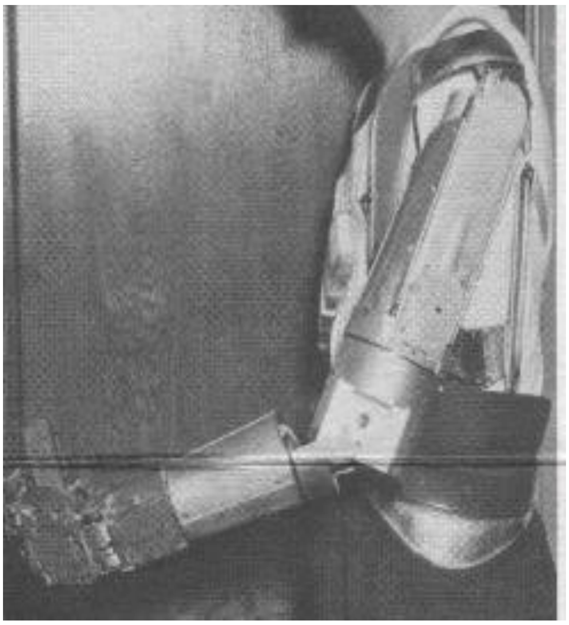

Fig. 1 An early model of the Alderson-IBM Electric Arm [25]

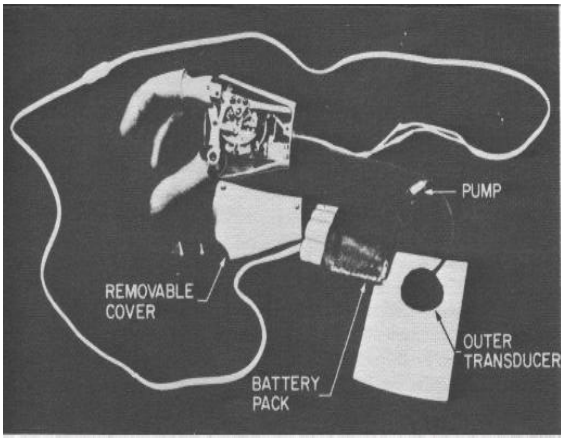

Fig. 2 The "Valduz" hand and control system [10]

Fig. 3 Diagram of EMG Controlled Otto-Bock arm.

The entire system is composed of subsystems based on the simple feedback control system. The subsystems in the prosthesis system are input system (input signal), effector system (plant), and feedback system (feedback signal). In addition to these sub-systems, the prosthesis system has one added system as support system [6].

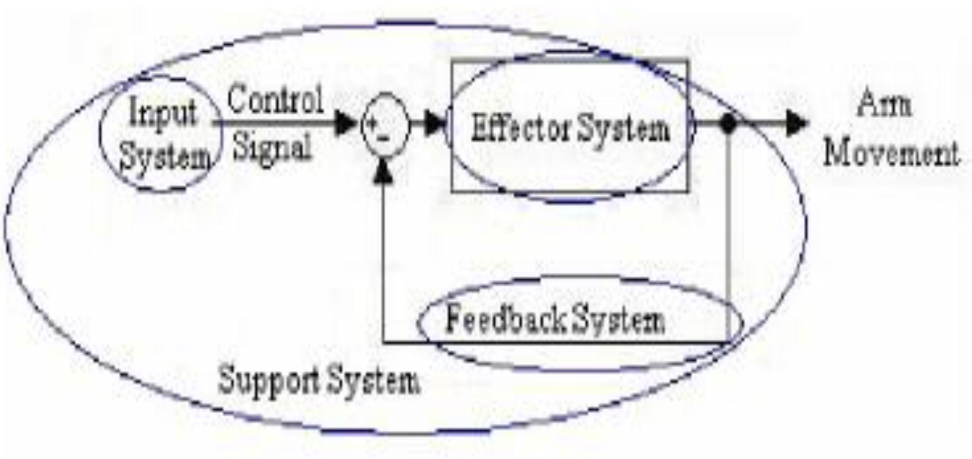

Fig 4: Simple Block Representation of Prosthetic Arm [4].

2. Block Representation of Total Bio Feedback Prosthetic Arm System

The sundered control block representation is presented in the Fig 5. to generate the transfer function in control domain. The technology is based on electro myographic (EMG) Signals and error control system.

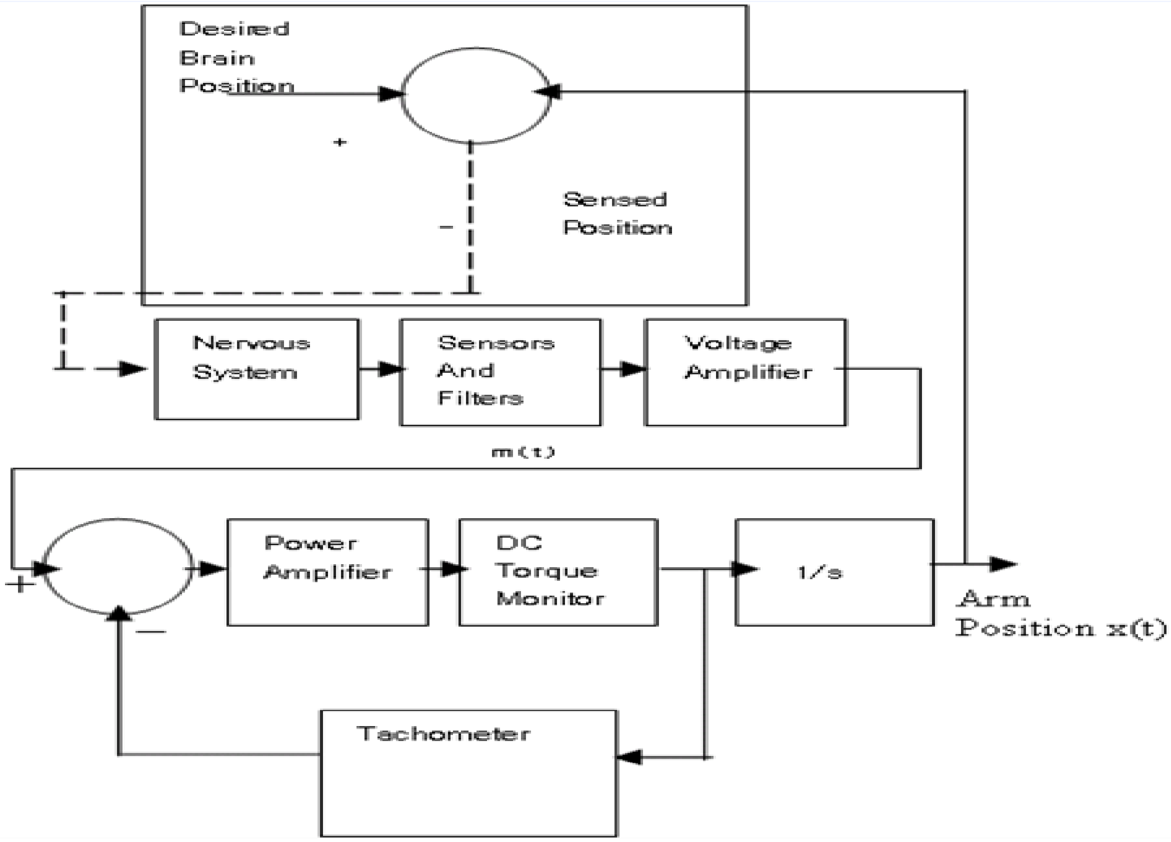

Fig 5 Prosthetic Control system Model.

This Fig 5 shows a block for a bionics arm in a close-loop system with the body [12, 15, 17, 18, 24]. For simplicity, motion is considered in one dimension only. The brain monitors the desired position and the sensed position, generating an error signal to the nervous system. Special sensor picks up the electro myographic (EMG) Signal impulses, and an amplifier produces a voltage to drive a micro control motor [14, 17, 19]. The motor circuit involves tachometer feedback, as shown in fig 5. The output of the motor circuit is the velocity of the limbs in one dimension, which, when integrated yields the limb position.

3. Appropriate Transfer Function Generation

A control system is to be designed for a complicated system such as this, some course of action must be planned. In this case, a simplified block diagram will be created and the control will evolve by stabilizing the loops, starting with the inner loops, then progressing outward until all parameters have been selected. The simplified model of the brain action is assumed with the transfer function $G_B(s)$

Where $G_B(s) = 1+0.1/s$

Which involves consideration of both the position error and its integral. The nervous system is modeled by the first-order system with transfer function.

$$G_N(s)= \frac{1/T}{s+1/T} = \frac{4}{s+4}$$

T= ¼, the time constant, approximated here to define the neuromuscular delay time [20]. The electro myographic (EMG) Signal is sensed and amplified

$$G_m(s) = \frac{5}{s^2 + 11s + 10} = \frac{5}{(s+1)(s+10)}$$

with the gain K_B to form the amplified voltage m(t). Power amplifier, control motor, and mechanical load have second-order transfer

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function, relating motor control voltage m(t) to arm velocity. The block Fig 5 exhibits time constant of 1 sec, associated with mechanical inertia, and 1/10 s,

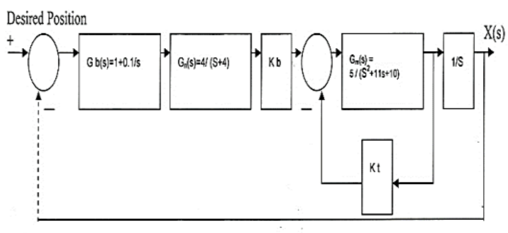

Fig 6 Parameter Designed Prosthetic Arm Control Model.

for the motor and arm, giving the following overall transfer function of those components.

$$G_t(S) = \frac{G_m(S)}{\{1+K_t\, G_m(S)\}}$$

$$= \frac{5/(s^2 + 11s + 10)}{1+5\,Kt/(s^2 + 11s + 10)}$$

$$= \frac{5}{\{s^2+11s+(10+Kt)\}}$$

Appling root locus technique fig. 7 plots for this motor-arm subsystem, $G_t(s)$, in terms of the

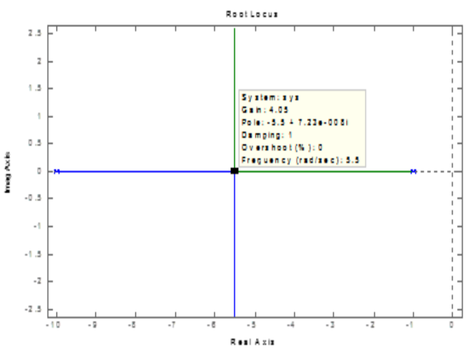

Fig 7 Root Locus of Motor Arms Block.

The adjustable gain Kt (critical damping) with the support of step response represented in fig 8 and fig 9 of the motor control block.

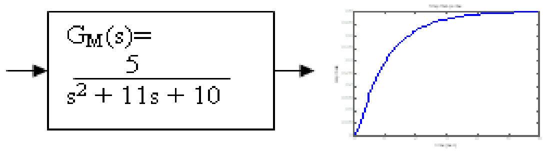

Fig 8 Motor Arm Control Block without Tachometer with its step response.

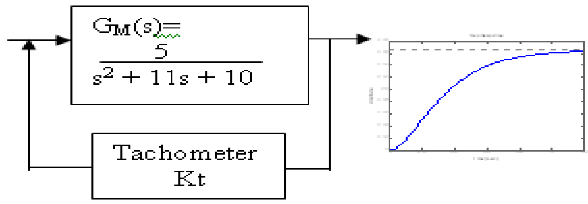

Fig 9 Motor Arm Control Block introducing Tachometer with its step response.

For this value of Kt, the subsystem has a maximum relative stability of 5.5 units larger values of Kt reducing the damping without enhancing stability. This local feedback makes the subsystem to act, as if, it was a better motor, with faster response. Huge improvements in response speed, when they are possible, generally require that the device being controlled be driven with very large input signals, as is the case if one wants a motor to transfer function.

Very large inputs can cause damage and usually drives the device into a nonlinear region of operation. Now the Transfer Function of the Prosthetic system as a whole becomes quickly speed up.

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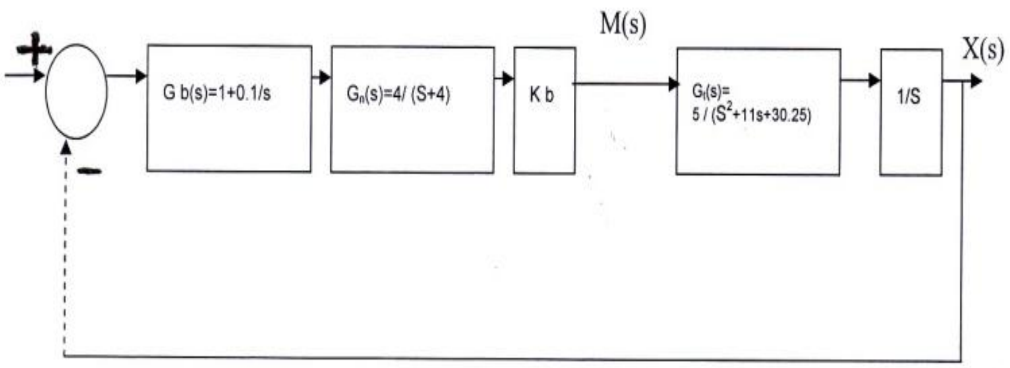

Fig 10 Simplified Form of Prosthetic Control Block

$$T(S) = \frac{\{G_b(s)G_n(s)K_bG_t(s)(1/s)\}}{[1-\{G_b(s)G_n(s)K_bG_t(s)(1/s)\}]}$$

$$= \frac{\dfrac{\{20(s+0.10)K_b\}}{s^2\ (s+4)(\ s^2+11s+30.25)}}{1 + \dfrac{\{20(s+0.10)K_b\}}{s^2\ (s+4)(\ s^2+11s+30.25)}}$$

$$= \frac{\{20(s+0.10)K_b\}}{\{s^5+15s^4+74.25s^3+121s^2+20K_b s+2K_b\}}$$

4. Approximated K_b (Gain Factor) Estimation Technique

The calculation of motor arms control block determines the optimal values of Kt. The block diagram shown in fig 10 represents the desired block diagram [21] of prosthetic arms control model. The value of K_b is vital to determine for stability. The simulation technique is introduced in the system to determine the approximated K_b value. The Routh-Harwith test and root locus technique is applied by simulation.

Routh-Harwith Test :

S5	1	74	$20K_b$
S4	15	121	$2K_b$
S3	65.9	$19.86K_b$	
S2	121-4.52K	$2K_b$	
S1	$\frac{2271^{Kb}-89.76^{Kb2}}{121-4.54K_b}$		
S0	$2K_b$		

Then $121-4.52K_b > 0$

$K_b\ (2271-89.76K_b)>0$

$2K_b>0$

$K_b< 26.8$

$K_b< 25.3$ for positive K_b

$K_b>0$

Stable condition range $0< K_b<25.3$

The root locus test simulation in terms of Kb is shown in fig 11.

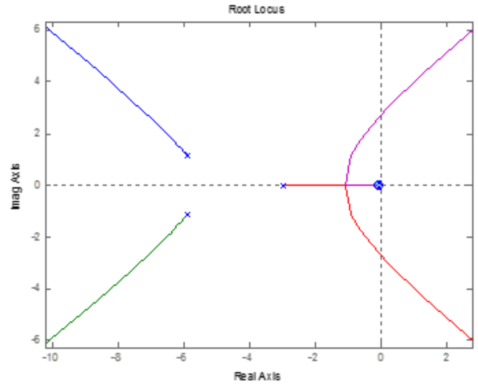

Fig11 Root locus of [Gb(s)Gn(s)Gt(s)(1/s)]

These are two poles at the origin and a zero at s = - 0.1 in the open loop transmittance of $[G_b(s)G_n(s)G_t(s)(1/s)]$. It is expected that very

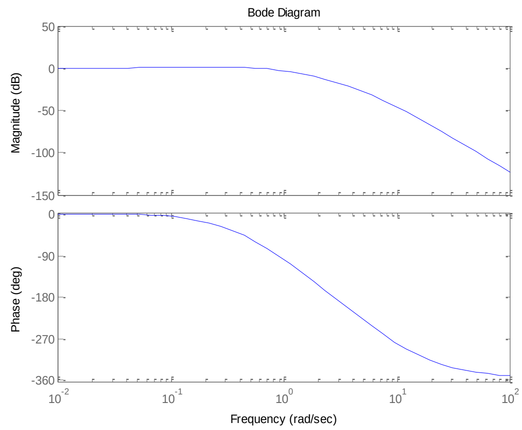

Fig 12 Bode Plot of Prosthetic Control.

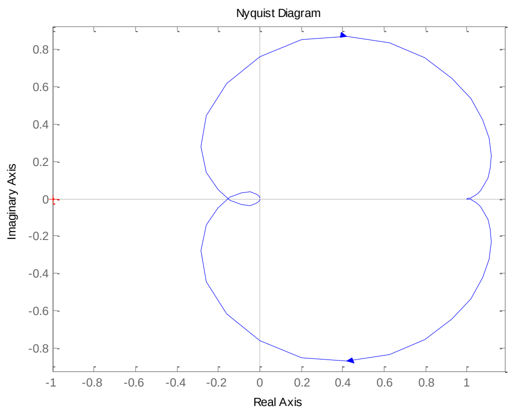

Fig 13 Nyquist plot of prosthetic Control system.

Near to those roots, the locus is virtually the same as if a single pole were in the region. The root locus crosses the imaginary axis at K_b= 25.3. The bode plot Fig 12 and Nyquist plot Fig 13 also determine the gain margin and phase margin aspect. The step response is the better criteria to determine the optimal value of K_b, so for different value of K_b the step responses are to be determine. The gain K_b value should be optimal to determine perfect transfer function. The EMG Signal sensed by the sensitive electrode and develop its amplitude with free noise. In the view of hard ware it is difficult and complicated to sense the micro volt range signal. The electro EMG signal have micro range power value so it should be amplified with the amplification factor K_b. As per the simulation aspect with the help of control analogy approximated K_b value attempted to develop here.

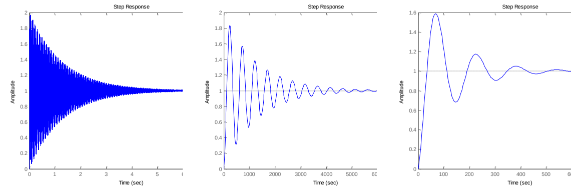

Fig14a (Kb=0.00001) Fig14b (Kb =0.01) Fig14c(Kb =0.1)

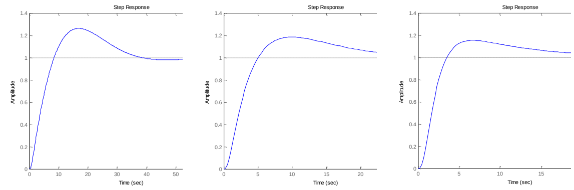

Fig14d(Kb =1) Fig14e (Kb =2) Fig14f (Kb =3)

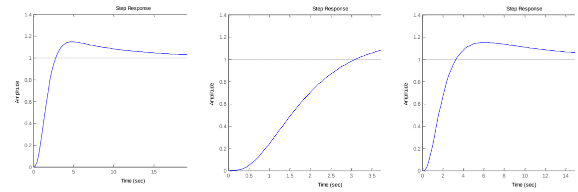

Fig14g (Kb =3.2) , Fig14h (Kb =3.3) Fig14i(Kb=3.6)

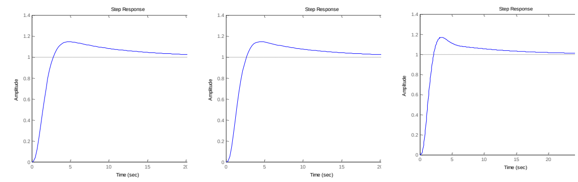

Fig14j(Kb=3.8) Fig14k (Kb =4) Fig14l(Kb=5)

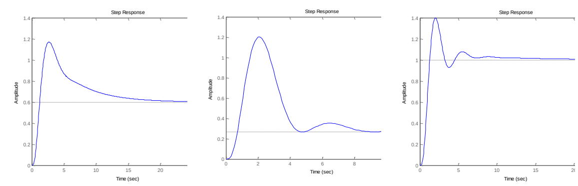

Fig14m (Kb =6) Fig14n (Kb =8) Fig 10o (Kb =10)

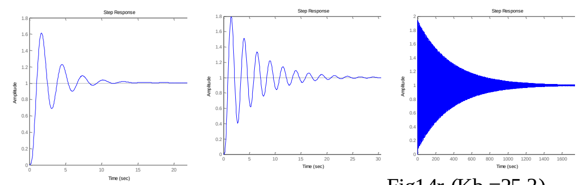

Fig14p(Kb =15) Fig14q(Kb =20) Fig14r (Kb =25.3)

The Fig 14a to Fig 14r simulate the step response with the rltool to determine the optimal value of K_b. In this simulation method the range of K_b taken from Routh-Horwath test ($0< K_b<25.3$). Changing the value of K_b in between this range step response is to be plotted. For minor value of K_b

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(K_b=0.00001) it is imposable to define the system that mean without K_b the system is unstable shown in Fig 14a to Fig14c.Applying unity gain voltage follower (K_b=1) the system is determined in Fig 14d implies the stability in curtain time. Again incrising the value of K_b it is optimize that the K_b = 3 range make its critically damped. Now increasing the value of K_b with short duration it tenses to some stable condition. The K_b=3.2, K_b=3.4 are K_b=3.6 very probable condition for designed the amplification factor. Among this three values K_b=3.4 is to be affected for set the transfer function. Now again gradually changing the value of K_b= 4, K_b=5, K_b=6, K_b=8, K_b=10, K_b=15, K_b=20 and K_b=25.3 the step response is determining here. So, the optimal transfer function of prosthetic control arm determines by K_b=3.3. Then the transfer function:

$$T(s)= \frac{\{20(s+0.10)K_b\}}{\{s^5+15s^4+74.25s^3+121s^2+20K_b s+2K_b\}}$$

$$= \frac{(66s + 6.6)}{\{s^5+15s^4+74.25s^3+121s^2+66s+6.6\}}$$

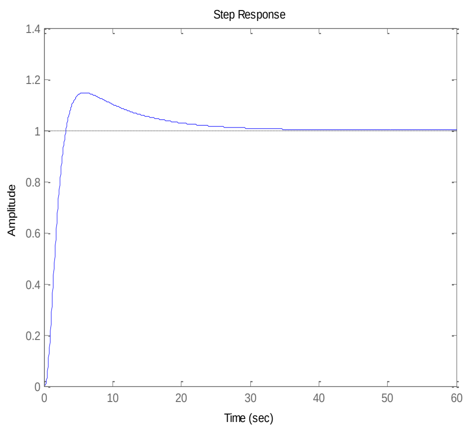

Fig 15 Optimal transfer function

5. Performance Analysis with Controllability And Obserbility Testing

The optimization of a system functionality and design depend on Two most important aspect the Controllability and observability. The controllability tends to direct a system to a particular stage through applying control input. So, determining the controllability is essential for controlling the system state. In other hand the observability checks initial states from the output segment. The observability of system determines the system condition from the output stage. The stabilization can be optimized by determining the observability. Suppose in a system initial state is x (t0) and desired state is x (t), the system will be completely controllable if in a finite time (t0 ≤ t ≤ T) x (t0) can be transferred to x (t) by an unconstrained control u(t). To make a system flexible i.e. all the closed loop system poles are placed arbitrarily, the need of completely controllable and observable system emerges. In order to determine whether the system is controllable or not, we need to deduce the state differential equation from the transfer function and hence calculating a sort of matrices we get the final controllability matrix. The canonical form of controllability with the dynamic equation of the system is

$x'(t) = Ax(t) + Bu(t)$…(i)

$y(t) = Cx(t) + Du(t)$…….(ii) [1]

For either type of model , the output equation may be written as

$y(t) = Cx(t)$;

here A = system matrix , B = input matrix and C = output matrix . So to study the performance of this prosthetic arm that the system is controllable or not, the controllability matrix is produces. The system is defined controllable if the determinant of the controllability matrix is non zero. The rank of the matrix n is equal to the system transfer function order, comments the system is controllable [24].

We know the transfer function is

$$T(s) = \frac{Y(s)}{U(s)}$$

$$= \frac{(66s + 6.6)}{\{s^5+15s^4+74.25s^3+121s^2+66s+6.6\}}$$

$$= \frac{(66s^{-4} + 6.6s^{-5})}{\{1+15s^{-1}+74.25s^{-2}+121s^{-3}+66s^{-4}+6.6s^{-5}\}}$$

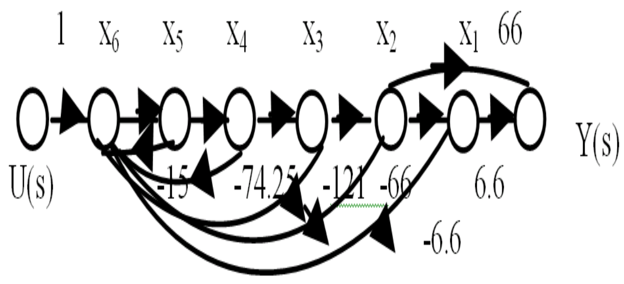

Fig 16 The signal flow graph of the system.

So, the state differential equation is

$x' = Ax + Bu$

A = system matrix , B = input matrix

$$x' = \begin{pmatrix} 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \\ -6.6 & -66 & -121 & -74.25 & -15 \end{pmatrix} x + \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 1 \end{pmatrix} u(t)$$

Let $6.6 = a_0$, $66 = a_1$, $121 = a_2$, $74.25 = a_3$, $15 = a_4$

$$\text{Now } A = \begin{pmatrix} 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \\ -a_0 & -a_1 & -a_2 & -a_3 & -a_4 \end{pmatrix}$$

$$A^2 = \begin{pmatrix} 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \\ -a_0 & -a_1 & -a_2 & -a_3 & -a_4 \\ a_0a_4 & (a_1a_4 - a_0) & (a_2a_4 - a_1) & (a_3a_4 - a_2) & (a^2_4 - a_3) \end{pmatrix}$$

$$A^3 = \begin{pmatrix} 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \\ -a_0 & -a_1 & -a_2 & -a_3 & -a_4 \\ a_0a_4 & (a_1a_4 - a_0) & (a_2a_4 - a_1) & (a_3a_4 - a_2) & (a^2_4 - a_3) \\ -a_0(a^2_4 - a_3) & \{-a_1(a^2_4 - a_3) + a_0a_4\} & \{-a_2(a^2_4 - a_3) + a_1a_4 - a_0\} & \{-a_3(a^2_4 - a_3) + a_2a_4 - a_1\} & \{-a_4(a^2_4 - a_3) + a_3a_4 - a_2\} \end{pmatrix}$$

$$A^4 = \begin{pmatrix} 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \\ -a_0 & -a_1 & -a_2 & -a_3 & -a_4 \\ a_0a_4 & (a_1a_4 - a_0) & (a_2a_4 - a_1) & (a_3a_4 - a_2) & (a^2_4 - a_3) \\ -a_0(a^2_4 - a_3) & \{-a_1(a^2_4 - a_3) + a_0a_4\} & \{-a_2(a^2_4 - a_3) + a_1a_4 - a_0\} & \{-a_3(a^2_4 - a_3) + a_2a_4 - a_1\} & \{-a_4(a^2_4 - a_3) + a_3a_4 - a_2\} \\ \{a_0(a_3a_4 - a_2) + a_0a_4 (a^2_4 - a_3)\} & \{-a_1(a_3a_4 - a_2) + (a_1a_4 - a_0)(a^2_4 - a_3)\} & \{a_0a_4 - a_2(a_3a_4 - a_2) + (a_2a_4 - a_1)(a^2_4 - a_3)\} & \{(a_1a_4 - a_0) - a_3(a_3a_4 - a_2)(a^2_4 - a_3)\} & \{(a_2a_4 - a_1) - a_4(a_3a_4 - a_2)(a^2_4 - a_3)^2\} \end{pmatrix}$$

For this case,

$$A = \begin{pmatrix} 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \\ -6.6 & -66 & -121 & -74.25 & -15 \end{pmatrix}$$

$$A^2 = \begin{pmatrix} 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \\ -6.6 & -66 & -121 & -74.25 & -15 \\ 99 & 983.4 & 1749 & 992.75 & 50.75 \end{pmatrix}$$

$$A^3 = \begin{pmatrix} 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \\ -6.6 & -66 & -121 & -74.25 & -15 \\ 99 & 983.4 & 1749 & 992.75 & 150.75 \\ -994.95 & -9850.5 & -17257.35 & -9444.2 & -1268.5 \end{pmatrix}$$

$$A^4 = \begin{pmatrix} 0 & 0 & 0 & 0 & 1 \\ -6.6 & -66 & -121 & -74.25 & -15 \\ 99 & 983.4 & 1749 & 992.75 & 150.75 \\ -994.95 & -9850.5 & -17257.35 & -9444.2 & -1268.5 \\ 8372.1 & 82726.05 & 143638 & 76928.763 & 9583.313 \end{pmatrix}$$

$$\text{and} \quad B = \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 1 \end{pmatrix}$$

Therefore,

$$AB = \begin{pmatrix} 0 \\ 0 \\ 0 \\ 1 \\ -15 \end{pmatrix} \qquad A^2B = \begin{pmatrix} 0 \\ 0 \\ 1 \\ -15 \\ 150.75 \end{pmatrix}$$

$$A^3B = \begin{pmatrix} 0 \\ 1 \\ -15 \\ 150.75 \\ -1268.5 \end{pmatrix} \qquad A^4B = \begin{pmatrix} 1 \\ -15 \\ 150.75 \\ -1268.5 \\ 9583.313 \end{pmatrix}$$

Now the controllability matrix is

$$P_C = \begin{pmatrix} 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 1 & -15 \\ 0 & 0 & 1 & -15 & 150.75 \\ 0 & 1 & -15 & 150.75 & -1268.5 \\ 1 & -15 & 150.75 & -1268.5 & 9583.313 \end{pmatrix}$$

Determinant of P_C

$$= 1 \begin{pmatrix} 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & -15 \\ 0 & 1 & -15 & 150.75 \\ 1 & -15 & 150.75 & -1268.5 \end{pmatrix}$$

$$= (-1) \begin{pmatrix} 0 & 0 & 1 \\ 0 & 1 & -15 \\ 1 & -15 & 150.75 \end{pmatrix}$$

$$= (-1)\begin{bmatrix} 0 & 1 \\ 1 & -15 \end{bmatrix} = (-1)(-1) = 1$$

As $P_C = 1 \neq 0$

Hence the system is controllable.

Applying MATLAB simulator rank of the P_C matrix is determine

Pc =

1.0e+003 *

0	0	0	0	0.0010
0	0	0	0.0010	-0.0150
0	0	0.0010	-0.0150	0.1508
0	0.0010	-0.0150	0.1508	-1.2685
0.0010	-0.0150	0.1508	-1.2685	9.5833

rank = 5

The determinant of the P_C is non zero as well as the rank of the system is equal to the system order so the designed system is controllable. The observability properties of a plant have important practical consequence in analysis and, more importantly, designed of modern feedback control system [13]. If x(0) be the initial state and u(t) be the given control, then the system will be completely observable if x(0) can be determined from observation history y(t) for a finite time T. Observability is the ability of state variable estimation. The determinant of observability matrix is non zero for maintaining the observability of the system. If the rank of the observability matrix P_O is equal to the order of the system transfer function then the system is observable [16]. From the previously discussed transfer function we get the

output y(t) = Cx , where C = output matrix

$$= \begin{bmatrix} 6.6 & 66 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \\ x_5 \end{bmatrix}$$

Now $C = \begin{bmatrix} 6.6 & 66 & 0 & 0 & 0 \end{bmatrix}$

So, $CA = \begin{bmatrix} 0 & 6.6 & 66 & 0 & 0 \end{bmatrix}$

$CA^2 = \begin{bmatrix} 0 & 0 & 6.6 & 66 & 0 \end{bmatrix}$

$CA^3 = \begin{bmatrix} 0 & 0 & 0 & 6.6 & 66 \end{bmatrix}$

$CA^4 = \begin{bmatrix} -435.6 & -4356 & -7986 & -4900.5 & -983.4 \end{bmatrix}$

$$P_O = \begin{bmatrix} C \\ CA \\ CA^2 \\ CA^3 \\ CA^4 \end{bmatrix}$$

$$= \begin{bmatrix} 6.6 & 66 & 0 & 0 & 0 \\ 0 & 6.6 & 66 & 0 & 0 \\ 0 & 0 & 6.6 & 66 & 0 \\ 0 & 0 & 0 & 6.6 & 66 \\ -435.6 & -4356 & -7986 & -4900.5 & -983.4 \end{bmatrix}$$

Determinant of P_O

$$= 6.6 \begin{bmatrix} 6.6 & 66 & 0 & 0 \\ 0 & 6.6 & 66 & 0 \\ 0 & 0 & 6.6 & 66 \\ -4356 & -7986 & -4900.5 & -983.4 \end{bmatrix}$$

$$- 66 \begin{bmatrix} 0 & 66 & 0 & 0 \\ 0 & 6.6 & 66 & 0 \\ 0 & 0 & 6.6 & 66 \\ -435.6 & -7986 & -4900.5 & -983.4 \end{bmatrix}$$

$$= (6.6)^2 \begin{bmatrix} 6.6 & 66 & 0 \\ 0 & 6.6 & 66 \\ -7986 & -4900.5 & -983.4 \end{bmatrix}$$

$$- 6.6 \times 66 \begin{bmatrix} 0 & 66 & 0 \\ 0 & 6.6 & 66 \\ -4356 & -4900.5 & -983.4 \end{bmatrix}$$

$$+ (66)^2 \begin{bmatrix} 0 & 66 & 0 \\ 0 & 6.6 & 66 \\ -435.6 & -4900.5 & -983.4 \end{bmatrix}$$

$$= (6.6)^3 \begin{bmatrix} 6.6 & 66 \\ -4900.5 & -983.4 \end{bmatrix} - (6.6)^2 \times 66 \begin{bmatrix} 0 & 66 \\ -7986 & -983.4 \end{bmatrix}$$

$$+ 6.6 \times (66)^2 \begin{bmatrix} 0 & 66 \\ -4356 & -983.4 \end{bmatrix} - (66)^3 \begin{bmatrix} 0 & 66 \\ -435.6 & -983.4 \end{bmatrix}$$

$$= (6.6)^3 \; (-6.6 \times 983.4 + 4900.5 \times 66)$$
$$- (6.6)^2 \times 66\, (66 \times 7986) + 6.6 \times (66)^2\, (4356 \times 66)$$
$$- (66)^3 \; (66 \times 435.6)$$

= 91119718.23 – 1515322417 + 8265395002 - 8265395002

= - 1424202698.77

Therefore, $P_O \neq 0$

Applying the MATLAB simulator, the rank of the observable matrix is developed.

P_o =

1.0e+003 *

0.0066	0.0660	0	0	0
0	0.0066	0.0660	0	0
0	0	0.0066	0.0660	0
0	0	0	0.0066	0.0660
-0.4356	-4.3560	-7.9860	-4.9005	-0.9834

rank = 5

The determinant of the observable matrix is non zero. The generated rank using the MATLAB simulator equal to the order of the system. Hence the system is observable.

6. Conclusions

Naturally the biological system is nonlinear system. The described system is proceeded with assuming the system linear consideration. The performance study is determined the system is controllable and observable for defining the system properly in terms of stability. This controllability and observability are key factors for optimizing system performance and design. In future the nonlinearity effect is imposed for this particular system.

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