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Review Article

Monitoring Stability in Myoelectric Prostheses Using a Regulator with Automatic Control

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Abstract

The article presented below is an alternative analysis for energy optimization in servomotors providing power to electromyography prostheses using the Poles Location method and its consequent associated stability. This document aims to find new working elements of the servomotor system through the use of an efficient regulator. This development is carried out from Biomedical Engineering point of view considering different factors and parameters to achieve the objective. Usually the power supply factors of the servomotors are not considered; if these are not regulated, the battery expenditure is high and this solution (prosthesis), becomes in a major problem in brief time. The acquired results denote that the use of this tool improves performance as long as the variables were considered for each particular case.

Keywords: State Space; Regulator; Stability

Introduction

Engineering has evolved, its participation in the life sciences has generated relatively new disciplines.

Examples include: Bioinstrumentation, Biomechanics, Biocybernetics, Bionics, Bioinformatics, Medical Robotics, Digital Biosignal Processing, etc. These disciplines are applied in different fields of Medicine (diagnosis, therapeutics, healthcare systems, hospitals, emergency services), Public Health (prevention, hygiene, sports, food) and Rehabilitation of the disabled, among others. Engineering in the area of rehabilitation is the biomedical area that produces the greatest impact. The contribution of biomedical engineering to this problem is the design of devices that are very useful to automate these therapies and give patients the autonomy necessary for better performance [1]. Assistive devices and technologies such as wheelchairs, prosthetics, mobility aids, hearing aids, visual aids, specialized software and hardware increased mobility, hearing, vision, and communication skills. With the help of these technologies, people with a loss of functioning are better able to live independently and participate in their societies. However, in many low- and middle-income countries, only 5% to 15% of people who require assistive devices and technologies have access to them [2]. Access to rehabilitation and habilitation can lessen the consequences of illness or injury, improve health and quality of life, and decrease the use of health services. While global data on the need for rehabilitation and habilitation, the type and quality of planned measures, and estimates of unmet needs do not exist, data at the national level reveal large gaps in the provision of and access to these services.

Electromyography (EMG) studies aspects such as the detection, analysis and use of electrical signals from skeletal muscles. In the field of rehabilitation of amputee patients, EMG is of interest when it comes to robotic prostheses. It is a valuable tool as long as it allows detecting and classifying different movements of the body. The more degrees of freedom we have, the greater the similarity to the natural movements of the limbs, but the greater the complexity of the system. In particular, the state of knowledge of surface electromyography is an enigma. Many very useful and important applications can be carried out, however, it also has limitations that must be understood, considered and eventually overcome in order to become a discipline with a more scientific basis and less dependent on the technique of use.

As engineers, we apply mathematical laws and physics to solve problems, such as those mentioned. Through modern control theory it is possible to deal with any problematic situation by means of equations of state. Some mathematical rules, such as the principle of superposition, present in recursive algorithms are excluded in this new approach. The consequent simplification of developments is reflected in new findings, giving value to new concepts such as controllability and stability [3].

Within the biomedical area, it can be considered that the area of rehabilitation engineering is the one that produces the most impact. According to the WHO (World Health Organization), 6% of the population worldwide has disability problems and 25% of people affected by their care.

This paper aims to find new elements of servo motor system working signal analysis by using a regulator, allowing for more controllable and stable performance. The servo motor presented here is designed to generate movements of the joint of a robotic arm designed for the rehabilitation of a patient's movement.

Development

It is considered the direct current motor in Figure 1 that drives a load through a rigid shaft. If the field current is kept constant at an If value or the field flow comes from a permanent magnet, this machine can be controlled only by the voltage va(t) applied to the armature.

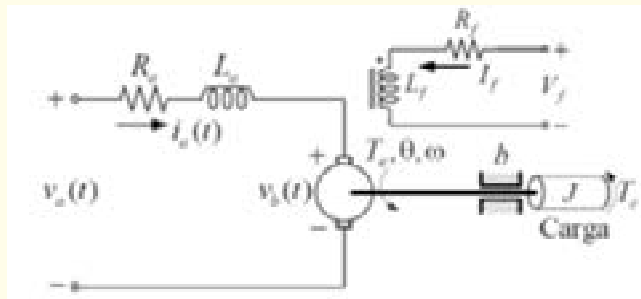

Figure 1: Model of the Servomotor.

The electric torque equation can be written as:

$$T_e(t) = K_r i_a(t) \quad (1)$$

Where $K_r = KI_f$ it is a constant.

When the motor drives the load, a counter-electromotive force develops in the armature circuit opposite to the applied voltage va(t). This tension is linearly proportional to the angular velocity developed in the axis, that is:

$$v_b(t) = K_b \frac{d\,\theta(t)}{dt} \quad (2)$$

Applying Kirchhoff's law of stresses to the mesh of the reinforcement circuit, we have:

$$v_a(t) - u(t) = R_a i_a(t) + L_a \frac{di_a(t)}{dt} + v_b(t) \quad (3)$$

Let be J the moment of total inertia of the load, the shaft and the rotor of the motor; θ the angular displacement of the load; b the viscous friction coefficient and T_c the torque produced by the load.

The torque that the engine must develop, necessary to overcome inertia, friction, and the reaction torque of the load is given by:

$$T_e(t) = J\frac{d^2\theta(t)}{dt^2} + b\frac{d\theta}{dt} + T_c \quad (4)$$

$$K_r i_a(t) = J\frac{d^2\theta(t)}{dt^2} + b\frac{d\theta}{dt} + T_c \quad (5)$$

For this first model T_c, it is not considered, which would represent the disturbance caused by the load on the motor shaft.

Pole assignment method

The location of the roots of the desired characteristic polynomial will depend on the performance criteria of the closed-loop system, including peak time, establishment time, overshoot, bandwidth, etc.

This region is limited as follows:

- On the right by a vertical line separated by a value equal to σ the imaginary axis. As the distance of this line to the jω axis increases, the response of the system is faster, since the damping coefficient increases proportionally;
- By two straight lines starting from the origin at an angle θ. As this angle grows, the overshoot of the transient response increases proportionally;
- If we place all the eigenvalues in the same point or small region, as shown in point "a", the response will be slow and the control action may be high. This leads the system to saturation or to the actuation of the control action limiters, so that the system behaves in a non-linear manner.
- It is therefore appropriate to place the eigenvalues within region **C**. The larger the radius "r" the faster the response, on the other hand the u(t) actuation signal may be high. In addition, the bandwidth of the closed-loop system can be large and with this the system ends up amplifying the disturbances and external noises, which are usually found in the high frequencies.

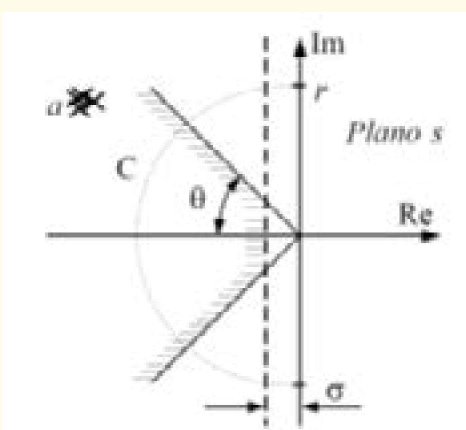

Figure 2: Desired region where the eigenvalues can be located in a closed loop.

In short, the determination of the position of the desired eigenvalues is a trade-off between the speed of the transient response (or the speed with which the error goes to zero) and the sensitivity to disturbances and measurement noises. This tells us that before the practical implementation of the system is carried out, the dynamic range of each internal variable in a closed loop must be verified by simulation, to avoid problems of saturation of the plant and/or actuators.

The design technique begins with the determination of the desired closed-loop poles from the transient response and/or frequency response specifications, as well as the steady-state requirements. By selecting an appropriate gain matrix for state feedback, it is possible to have the system have the poles in a closed loop at the desired positions, as long as the original system is fully controllable.

The pole placement method involves placing the poles in desired locations in a closed loop.

All state variables are assumed to be measurable and available for feedback.

Be a control system

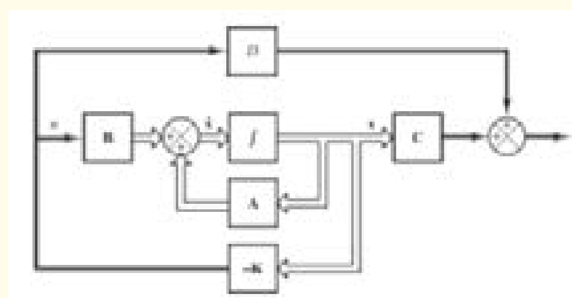

Figure 3: Control system with feedback and K-gain.

Matrix based,

$$\dot{\mathbf{x}} = \mathbf{A}\mathbf{x} + \mathbf{B}u \quad (6)$$
$$\mathbf{y} = \mathbf{C}\mathbf{x} + Du$$

Where,

$\dot{\mathbf{x}}$ ® Vector de Estado
$\mathbf{y}$ ® Vector de Salida
$\mathbf{A}$ ® Matriz de Estado
$\mathbf{B}$ ® Matriz de Entrada
$\mathbf{C}$ ® Matriz de Salida
D ® Matriz de Transmición Directa
$-\mathbf{K}$ ® Ganancia

Continuing with the design technique, an appropriate matrix for state feedback gains is selected, which makes it possible for the system to have the poles in a closed loop at the desired positions, only if the original system is fully controllable [4].

The control signal is selected as

$$u = -\mathbf{K}\mathbf{x} = \begin{bmatrix} K_1 & K_2 & \dots & K_n \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{bmatrix} \qquad (7)$$

Their goal is to keep the exit to zero. Because disturbances can occur, the output will deviate from zero. This output will return to the zero reference input due to the feedback scheme. A system of this nature is known as a regulatory system.

When we replace, we are left with

$$\dot{\mathbf{x}} = (\mathbf{A} - \mathbf{B}\mathbf{K})\mathbf{x} \qquad (8)$$

The eigenvalues of the matrix are called the poles of the regulator. Classical design procedures are based on the system transfer function, while pole location design is based on the system state model. It is also assumed that all the state variables of the system can be measured and are available to be fed back. This technique is based on the principle that if the system is completely controllable, it is possible to locate a set of poles of the system in a closed loop, in desired locations, by feeding back the system states in order to meet certain specifications of transient dynamic response and permanent regime. These specifications may be related to the characteristic parameters of the transient temporal response to step or impulsive entries.

The project by pole location can be summarized in two steps:

- Specify the location of the desired roots of the characteristic equation of the closed-loop system;
- The calculation of the profits to be able to locate these roots in the places determined in the previous point.

There are two (2) ways to determine the components of the K matrix.

Direct substitution method:

The characteristic equation of the closed-loop system is given by:

$$\det[\, s\mathbf{I} - \mathbf{A} + \mathbf{B}\mathbf{K} \,] = 0$$

When this determinant is developed, it results in a polynomial of order *n* in *s* that contains the gains of the matrix **K**. Now suppose that the desired locations of the poles are given by the roots $-\lambda_1,\ -\lambda_2,\ \dots,\ -\lambda_n$, then the desired characteristic equation is given by:

$$\alpha_c = (s+\lambda_1)(s+\lambda_2)\dots(s+\lambda_n)$$

The project is completed by equalizing the coefficients of equal power in s of the equations of the determinant and the desired characteristic polynomial.

Ackermann's formula:

Ackermann's formula is based on the similarity transformation that transforms a given state model into its controllable canonical form $(\mathbf{AB}) \rightarrow (\mathbf{A}_c\mathbf{B}_c)$, through a new state vector $\mathbf{x} = \mathbf{T}\mathbf{z}$, secondly obtaining the gains, resulting in the law of control $u = -\mathbf{K}_c\mathbf{z}$. To obtain the gains for the original equation of state, the gain matrix is transformed again through the matrix $\mathbf{T}$, i.e. $\mathbf{K} = \mathbf{K}_c\mathbf{T}^{-1}$.

These three steps are grouped in Ackermann's formula, given by:

$$\mathbf{K} = [0\ 0\ 0\ \dots\ 1][\mathbf{B}\ \ \mathbf{AB}\ \ \mathbf{A}^2\mathbf{B}\ \ \dots\ \ \mathbf{A}^{n-1}\mathbf{B}]^{n-1}\alpha_c(\mathbf{A})$$

where $\alpha_c(\mathbf{A})$ is a polynomial of matrices formed with the coefficients of the desired characteristic equation,

$$\alpha_c(\mathbf{A}) = \mathbf{A}^n + \alpha_1\mathbf{A}^{n-1} + \alpha_2\mathbf{A}^{n-2} + \dots + \alpha_n\mathbf{I}$$

In the present work, Ackermann's formula was used. The "acker" (MatLab) statement [5] to find the components of the K profit matrix.

The system diagram to consider is.

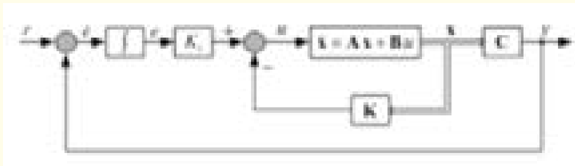

Figure 4: Servo motor system.

Considering that the closed-loop poles are located in positions such that the system is asymptotically stable, the output $y(\infty)$ will tend to the constant value r and the control signal $u(\infty)$ will tend to zero.

We choose as state variables of this system a,

$$x_1 = \theta(t)$$
$$x_2 = \dot{\theta}(t) = \omega(t) \quad (9)$$
$$x_3 = i_a(t)$$

x_1 is the angular position, x_2 angular velocity, and x_3 armature current.

$$\mathbf{A} = \begin{bmatrix} 0 & 1 & 0 \\ 0 & \frac{-b}{J} & \frac{K_t}{J} \\ 0 & \frac{-K_b}{L_a} & \frac{-R_a}{L_a} \end{bmatrix};\ \mathbf{B} = \begin{bmatrix} 0 \\ 0 \\ \frac{1}{L_a} \end{bmatrix} \quad (10)$$

$$\mathbf{C} = [1 \quad 0 \quad 0];\ D = 0$$

In the State Space, the matrix representation of the engine's operation is determined with the matrices A, B, C, and D.

$$\begin{bmatrix} \dot{\theta} \\ \dot{\omega} \\ \dot{i}_a \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 \\ 0 & \frac{-b}{J} & \frac{K_t}{J} \\ 0 & \frac{-K_b}{L_a} & \frac{-R_a}{L_a} \end{bmatrix} \begin{bmatrix} \theta \\ \omega \\ i_a \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ \frac{1}{L_a} \end{bmatrix} u(t) \quad (11)$$

$$y = [1 \quad 0 \quad 0] \begin{bmatrix} \theta \\ \omega \\ i_a \end{bmatrix}$$

From the block diagram in Figure 4 the following equations can be written:

$$\dot{\mathbf{x}}(t) = \mathbf{A}\mathbf{x}(t) + \mathbf{B}u(t)$$
$$y(t) = \mathbf{C}\mathbf{x}(t) \quad (12)$$
$$u(t) = -\mathbf{K}\mathbf{x}(t) + \mathbf{K}_I e(t)$$
$$\dot{e}(t) = r(t) - y(t) = r(t) - \mathbf{C}\mathbf{x}(t)$$

It is presumed that the plant is $\dot{\mathbf{x}}(t)$ controllable and does not have a zero at the origin to prevent it from canceling the integrator's pole.

Assuming that the reference is a step function, the dynamics of the system can be described as a linear combination of $\mathbf{x}(t)$ and $e(t)$.

The equations of state corresponding to the complete system are:

$$\begin{bmatrix} \dot{\mathbf{x}}(t) \\ \dot{e}(t) \end{bmatrix} = \begin{bmatrix} (\mathbf{A} - \mathbf{BK}) & \mathbf{BK}_I \\ -\mathbf{C} & 0 \end{bmatrix} \begin{bmatrix} \mathbf{x}(t) \\ e(t) \end{bmatrix} + \begin{bmatrix} 0 \\ 1 \end{bmatrix} r(t) \quad (13)$$

Stability criteria

In general we will always want systems not to stray too far from their point of operation, it is important then, before putting a system into operation, to make an analysis to predict whether the system will have variables that diverge or not (that it does not diverge is an indication that the system is "stable").

If the total energy of a system is continuously dissipated, then the system (linear or not) must eventually reach a point of equilibrium.

The equation,

$$\mathbf{A}^{\mathrm{T}}\mathbf{P} + \mathbf{P}\mathbf{A} = -\mathbf{Q} \quad (14)$$

It is known as the Lyapunov Equation. The stability criterion is based on finding P of this equation, previously choosing Q. Q = I is generally used.

Let xe = 0 be the equilibrium state of the invariant linear system described by the equation

$$\dot{\mathbf{x}}(t) = \mathbf{A}\mathbf{x}(t) \quad (15)$$

The quadratic form $\mathbf{V}(\mathbf{x}) = \mathbf{x}^{\mathrm{T}}\mathbf{P}\mathbf{x}$, called the Lyapunov function, is the one that is sought and must meet Sylvester's criterion [9] and be definite positive.

The most important characteristic of the dynamic behavior of a control system is absolute stability, i.e., whether the system is stable or unstable. A control system is in equilibrium if, in the absence of any disturbance or input, the output remains in the same state. A linear and time-invariant control system is stable if the output eventually returns to its equilibrium state when the system is subject to an initial condition. It is unstable if the output diverges without limit from its equilibrium state when the system is subject to an initial condition. The incorporation of the regulator is essential to be able to control the system and ensure its stability.

Discussion of Results

The data for the servomotor simulation were obtained from a real motor (Maxon®'s RE 40-40 mm model [6], frequently used to drive anthropomorphic myoelectric prostheses [7].

The following values were taken from the manufacturer's catalogue:

Ra = Armor resistance = 1.16Ω.

A = Armature inductance = 0.329 mH.

Kt = Constant del per motor = 60.3 mNm/A.

Kb = Speed constant = 158 rpm/V.

b = Coef. bearing friction = 3.04 rpm/mNm.

J = Motor moment of inertia and load = 138 gcm2.

For a system to be controllable, it is required that the nxnr dimension matrix,

$$C = \left[B \;\; AB \ldots A^{n-1}B \right]_{n \times nr} \qquad (16)$$

Has a range = n, or in other words, that it contains n linearly independent vectors, or that the determinant of the matrix $C \neq 0$ [8].

System Poles: [-1.77+j14.4 ; -1.77-j14.4 ; 0 ; 0]

Desired poles: [-8 ; -8 ; -4 + j4 ; -4 - j4]

Gains made using pole placement:

K(poles)= [771.7286 10.3801 6.7320 -1.5439e+003]

From this new dynamic system, whose order increases in the order of the integrator, it is possible to project the matrices of K and Ki gains in such a way that the system is asymptotically stable and that they tend to constant values respectively.

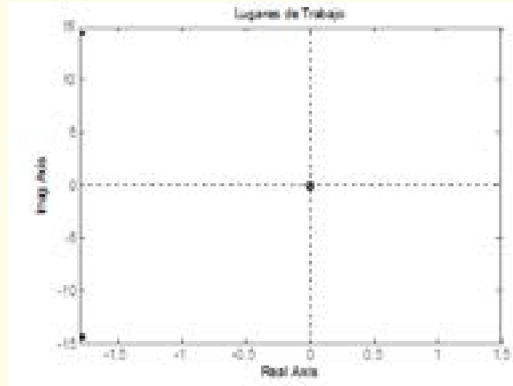

Figure 5: System Poles.

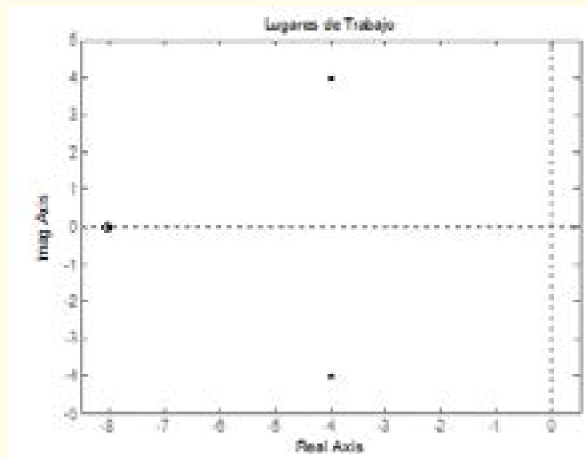

Figure 6: Desired poles.

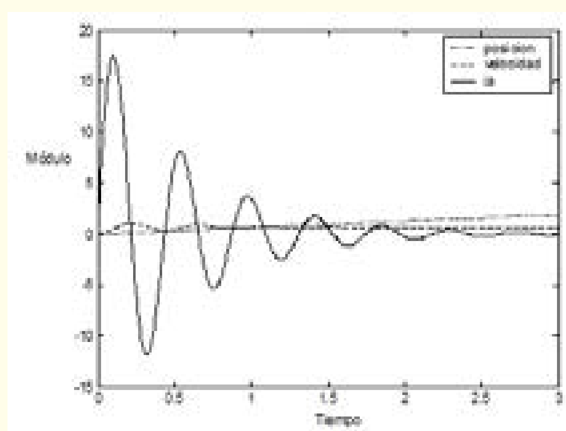

Figure 7: Evolution of the original system.

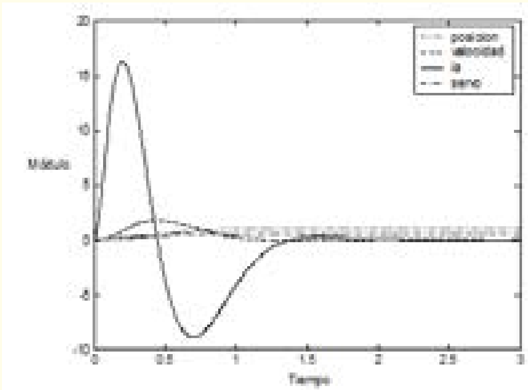

Figure 8: Evolution System Location of Poles.

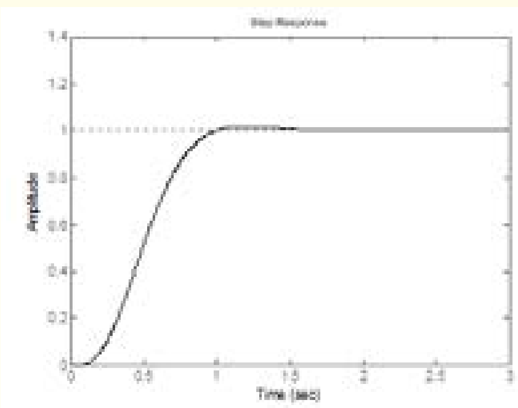

Figure 9: Servo Motor System response.

Figure 9 shows that the output meets pre-established design requirements, and a peak time of approximately 1.02 sec.

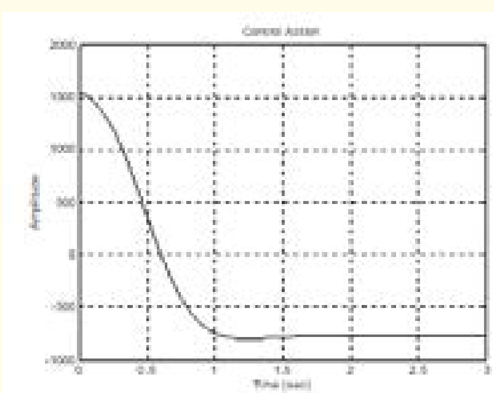

Figure 10: Control Action.

The control action (Figure 10) acquires a significant value to bring the states to the desired final values, canceling once the motor has acquired the desired position.

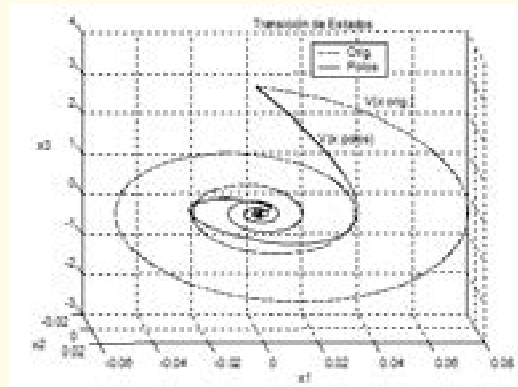

Figure 11: Lyapunov functions.

Figure 11 shows the stability and corresponding convergence of the entire servomotor system by applying Pole Location (solid line) to the point xe, compared to the original system (dotted line). This is achieved by working with the set of desired poles.

Conclusions

It is important to note that the matrix K is not unique to a given system, but depends on the desired positions of the closed-loop poles (which determine the speed and damping of the response). It should be noted that the selection of the desired closed-loop poles, or the desired characteristic equation, is a compromise between the speed of the response and the sensitivity to disturbances and noise in the measurement. That is, if the speed of response is increased, the adverse effects of disturbances and noise are usually increased to the extent. Therefore, when determining the state feedback gain matrix for a given system, it is advisable to examine the response characteristics of the system for several different K-matrices (based on some different desired characteristic equations) by means of computer simulations and choose the one that offers the best overall performance of the system.

The unresolved limitations of anthropomorphic prostheses controlled by electromyographic signals refer to the drive of servomotors that use external sources of energy, which require frequent charging and maintenance [10].

By making use of stability criteria, the system significantly shortens the trajectory from any generic state, i.e., it ensures its convergence to its equilibrium state.

Summary

The work presented is an alternative analysis for the optimization of energy in servomotors that feed electromyographic prostheses by means of the Pole Location method and its consequent associated stability. The objective is to find new working elements of the servomotor system by using a regulator; the development that is carried out from the point of view of Biomedical Engineering is addressed, taking into account different factors and parameters to be considered to achieve it. Normally the energy agents of servo motors are not considered; If these are not regulated, the battery consumption is high and in a short period of time this solution (prosthesis) becomes a major problem. The results obtained working in the state space indicate that the use of this tool improves performance as long as the parameters are adjusted for each particular case.

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