Revista Ibero- Americana de Humanidades, Ciências e Educação- REASE

doi.org/10.29327/217514.7.1-1

ADAPTIVE CONTROLLER FOR AUTOMATIC MANEUVER OF A SATELLITE DISH RECEIVER

Controlador adaptativo para manobra automática de um receptor de pratos de satélite

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ABSTRACT: The objective is to develop a control system capable of performing the automatic maneuver of a satellite dish and more accurately with less time maneuvering when compared to manual maneuver. The dish consists of a study on metal parabola 1.60 m in diameter, two sets of gears and two electric motors to perform the movements. The physical parameters of the mechanical system could be easily obtained from a three-dimensional modeling in a CAD software platform. For modeling the system dynamics we used the similarity of the physical system under study with an serial manipulator of two degrees of freedom that allowed it to apply concepts related to kinematics and modeling of robotic manipulators. Through the *Denavit-Hartenberg* notation of the direct kinematics of the antenna with two degrees of freedom was successfully obtained. The dynamic equations describing the motion of the system were raised through an automatic model implemented in symbolic manipulation software. To that end, an algorithm that describes the steps necessary to obtain the equations of motion of a robotic manipulator in open chain, from the *Lagrangian* method, was developed. A model reference adaptive control system was designed and implemented considering the uncertainties of the model arising from imperfections within the three-dimensional modeling. The results obtained by simulation of the system of closed loop control were satisfactory as well as the high rates of the perfect maneuver have been achieved.

Keywords: Serial manipulators. Dynamic equations of motion. Model reference adaptive control.

RESUMO: O objetivo deste trabalho é o de demonstrar o projeto de um sistema de controle adaptativo capaz de realizar o apontamento automático de uma antena parabólica de forma mais precisa e com menor tempo de apontamento quando comparado ao apontamento manual. A antena parabólica em estudo consta de uma parábola metálica de 1,60 m de diâmetro, dois conjuntos de engrenagens e dois motores elétricos para realização dos movimentos. Os parâmetros físicos do sistema mecânico foram facilmente obtidos a partir de uma modelagem tridimensional em um ambiente CAD. Para a modelagem dinâmica do sistema utilizou-se a similaridade do sistema físico em estudo com um manipulador de cadeia aberta de dois graus de liberdade, permitindo aplicar conceitos referentes à cinemática e modelagem de manipuladores

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robóticos. Através da notação de *Denavit-Hartenberg* a cinemática direta da antena com dois graus de liberdade foi obtida com sucesso. As equações dinâmicas que descrevem o movimento do sistema foram levantadas através da modelagem automática desenvolvida utilizando-se um *software* de manipulação simbólica. Para tanto foi desenvolvido um algoritmo que descreve os passos necessários para obtenção das equações de movimento de um manipulador robótico em cadeia aberta, a partir da formulação *Lagrangeana*. Um sistema de controle adaptativo por modelo de referência foi projetado e analisado, admitindo-se incertezas do modelo oriundas de imperfeições contidas na modelagem tridimensional. Os resultados obtidos por simulação do sistema de controle adaptativo se mostraram satisfatórios e os índices de desempenho esperados para um perfeito apontamento foram alcançados.

Palavras-chave: Manipuladores robóticos em cadeia aberta. Equações dinâmicas de movimento. Controle adaptativo por modelo de referência.

INTRODUCTION

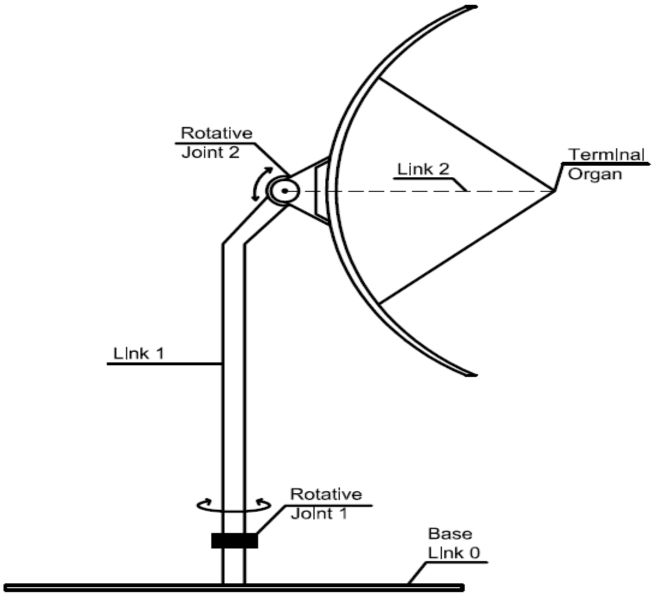
The media play a key role in the development of modern civilization. Many segments of society use this feature to a rapid and efficient dissemination of information. The satellite has been used as an effective solution for communication between distant points with each other, since the existing geostationary satellite coverage reaches kilometer (Ha, T.T., 1986.)

One of the disadvantages of satellite communications is the manual maneuvering of the satellite dishes of receipt. Besides being a process of high precision this maneuver demand a long time, especially when referring to the mobile receiving antennas need to adapt to geographic coordinates and climatic conditions and relief that will be exhibited in each use (Marins, C.N.M., 2004)

In this sense many efforts have been applied by telecommunications companies to improve the maneuver of antennas. The solutions range from systems based on microcontrollers (Cúnico, M., 2006) until the controllers proportional integrative (PI) and proportional integrative and derivative (PID) (Queiroz, K.I.P.M., 2006) (Souto, M.C.B., 2009). Classic modern control systems are presented as the solution to perform the pointing implements (Armellini, F., 2006) (Armellini, F., 2010) (Malaquias, I.M., 2009.)

This paper presents a control system able to perform the automatic appointment a satellite dish reception in order to minimize the disadvantages found in the manual maneuvering. Thus, it is accepted for study a parabola antenna made of metal with 1.6 m in diameter, an iron-based support for attachment to flat surface, and two sets of gears arranged in a way that enables the movement of the antenna in both directions of displacement: slope and azimuth. Figure 1 show the schematic of the physical system under study.

Fig. 1. Scheme of Antenna Receiver.



Source: Author.

The physical system has three rigid links, with a fixed link (link in the base), and two rotary joints with viscous friction coefficient. Comparing a serial manipulator of the two degrees of freedom (Schilling, R.J., 1990) (Fu, K., Gonzalez, R.C., Lee C.S.G., 1987) with the physical system under consideration, it is recognized that such a similarity allowed the assignment of the concepts of kinematics and dynamic modeling of robotic manipulators.

To develop the control system was used a control action consists of three terms associated with adaptive control action, a reference model (MRAC) and Computed Torque technique. A controller MRAC main characteristic is to impose on the system performance indicators in the reference model. In this work we chose to use an adaptive control action whose unknown parameters of the plant could be estimated online.

The analysis of the dynamic behavior of the model obtained, and the control system, took from its implementation in MATLAB/SIMULINK®.

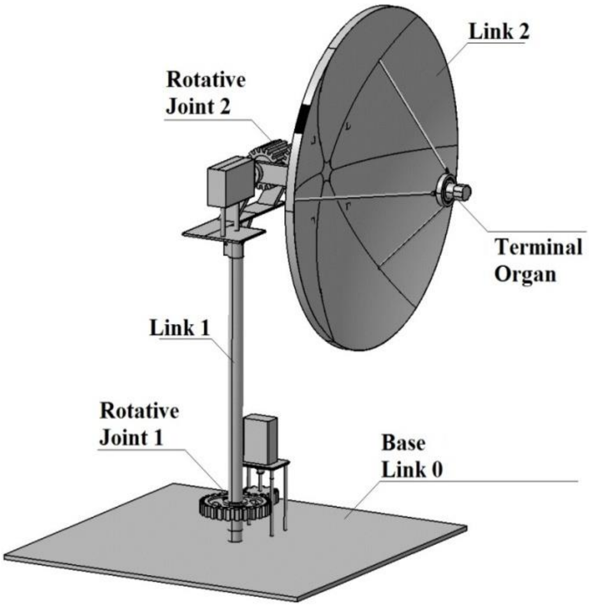
PHYSICAL SYSTEM SATELLITE RECEIVER

The prototype of the receiving antenna was designed using the software CATIA® V5 R19 in order to conduct a three-dimensional modeling of the physical system, demonstrating all the rigid links and rotary joints of the system. The physical parameters of the prototype were calculated automatically by the software, from the characteristics of materials used, geometric shapes, dimensions and coordinate systems defined for each hard link.

The satellite dish receiver consists of rigid links represented by: one support base, one support for the parables, the parable's metal, LNB (Low Noise Buffer), and rotary joints along the rented gear sets.

The physical system of the receiving antenna was modeled as an articulated system of rigid links together through the three-dimensional space, which corroborates with the definition of a robotic serial manipulator [11]. Figure 2 show the result of three-dimensional modeling of the physical system of the receiving antenna.

Fig. 2. Three-dimensional model of the Antenna Receiver.



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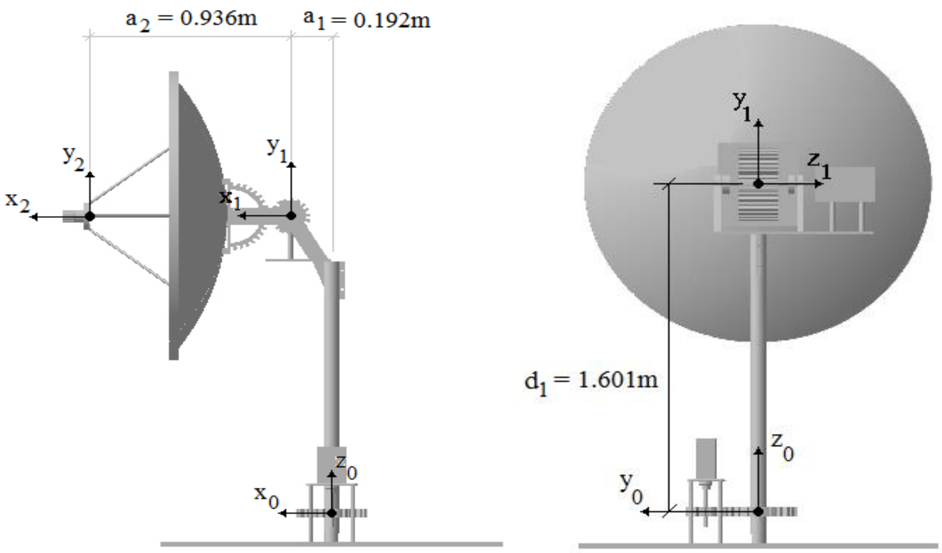
Direct Kinematics

The software CATIA® V5 R19 allows the inclusion of systems of coordinates in three-dimensional model [12]. Were assigned the coordinate systems for each link of the physical model of the receiving antenna following the methodology of Denavit-Hartenberg (DH) (Adade Filho, A., 1999) (Lopes, A.M., 2002.) Figure 3 shows the result obtained after applying the procedure DH.

Fig. 3. Receiving antenna with DH.



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The DH parameters of the antenna receiver are shown in Table 1.

Table 1. DH parameters of the antenna receiver.

Elo(i)	a_i (m)	α_i (rad)	d_i (m)	θ_i (rad)	Variável
1	0,19	$-\pi/2$	1,60	θ_1	θ_1 (rotação)
2	0,97	0	0	θ_2	θ_2 (rotação)

Source: Author

With the coordinate systems properly inserted the physical model of the receiving antenna, CATIA® V5 R19 calculates the moments of inertia and centers of gravity of each rigid link already referred to the coordinate system attached to the links. Table 2 presents the physical parameters of three-dimensional model. The moment of inertia for the nth rigid link was calculated over the n-th Cartesian system, located in the corresponding center of mass. The crossed moments of inertia are null.

Table 2. Physical parameters of the antenna receiver.

Elo (i)	Massa (kg)	Momento de Inércia (kg.m²)			Centro de Gravidade (m)		
	m_i	I_x	I_y	I_z	x_c	y_c	z_c
1	29,16	58,38	2,09	58,17	-0,14	-1,26	0,07
2	97,39	7,89	62,40	62,33	-0,76	0,00	0,00

Source: Author

DYNAMIC MODELING

The purpose of dynamic modeling is to obtain the equations of motion for each degree of freedom manipulator, allowing relating the movements (displacements) with the generalized forces (torques) applied at each joint (Latre, L.G., 1988.) According to (Lee, C.S.G.,1983) full knowledge of the dynamic model of a robot is essential for the computational implementation of its movement and the control system design.

There are several techniques for dynamic modeling of robotic manipulators (Santos, R.R., 2005.) Typically the two techniques are widely used in literature to obtain the dynamic model are the Euler-Lagrange method and the Newton-Euler method. The Newton-Euler method is to describe the dynamics of a mechanism based on the forces and moments applied to rigid bodies (links). It is based on two equations: Newton's equation that describes the translation of the center of mass of rigid body, and the Euler equation that describes the rigid body rotation around the center of mass. The Euler-Lagrange method is described in a scalar function of the Lagrangian which is formed by the difference between kinetic energy and potential energy for each joint system.

The dynamic model of a robotic serial manipulator is expressed by (Santos, R.R., 2005)

$$F_i = \sum_{k=1}^{n} D_{ik}\ddot{q}_k + \sum_{k=1}^{n}\sum_{m=1}^{n} H_{ikm}\dot{q}_k\dot{q}_m + C_i$$

(1)

In matrix shape:

$$F(t) = D(q(t))\ddot{q}(t) + H(q(t),\dot{q}(t)) + C(q(t)). \quad (2)$$

where:

$F(t)$	*n* x 1 generalized forces vector applied at joints;
$D(q(t))$	*n* x *n* symmetric matrix representing the inertia;
$H(q(t),\dot{q}(t))$	*n* x 1 nonlinear Coriolis and centrifugal force vector;
$C(q(t))$	*n* x 1 gravity loading force vector;
$q(t)$	*n* x 1 vector of position of the joint variables;
$\dot{q}(t)$	*n* x 1 vector of velocity of the joint variables;
$\ddot{q}(t)$	*n* x 1 vector of acceleration of the joint variables.

Euler-Lagrange method

To determine the dynamic model was used Euler-Lagrange formalism that describes the dynamic behavior of the system in terms of energy stored in the system (Adade Filho, A., 1999). The Euler-Lagrange equation is expressed as:

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{q}_j}\right) - \frac{\partial L}{\partial q_j} = F_j \qquad (3)$$

Where j is the index related to the rigid element (link), L is the Lagrangian of the system, given by the difference between kinetic energy and potential energy of the system, and F_j are the external loads from the potential non-conservative.

Using the Euler-Lagrange equation, the dynamic model of robotic serial manipulator with rigid links is given by (Fu, K., Gonzalez, R.C., Lee C.S.G., 1987)

$$\tau_i = \sum_{j=1}^{n}\sum_{k=1}^{j} Tr\left(U_{jk} J_j U_{ji}^T\right)\ddot{q}_k + \sum_{j=1}^{n}\sum_{k=1}^{j}\sum_{m=1}^{j} Tr\left(U_{jkm} J_j U_{ji}^T\right)\dot{q}_k \dot{q}_m - \sum_{j=1}^{n} m_j g U_{ji}\,{}^{j}r_j \qquad (4)$$

Comparing Eq. (1) with Eq. (4), are obtained separately the terms of the dynamic equation of motion:

$$D_{ik} = \sum_{j=\max(i,k)}^{n} Tr\left(U_{jk} J_j U_{ji}^T\right) \qquad (5)$$

$$H_{ikm} = \sum_{j=\max(i,k,m)}^{n} Tr\left(U_{jkm} J_j U_{ji}^T\right) \qquad (6)$$

$$C_i = \sum_{j=1}^{n} - m_j g U_{ji}\,{}^{j}r_j \qquad (7)$$

where:

U_{ji}	matrix that represents the effects of the motion of joint *i* on all the points on link *j*;
U_{jkm}	matrix that represents the interaction effects of the motion of joint *k* e *m* on all the points on link *j*;
J_j	matrix that contains moments of inertia of link *j*;
m_j	mass of link *j*;
g	acceleration of gravity vector referenced to the base coordinate system.

Dynamic Modelo f the Antenna Receiver

To obtain the dynamic model of the satellite dish receiver with two degrees of freedom will be considered the DH parameters and physical parameters contained, respectively, in Table 1 and Table 2.

An automatic model was developed using the software Maple ® 13 (Mariani, V.C., 2005) to implement the Euler-Lagrange formulation developed for a robotic serial manipulator, described in Eq. (4).

Applying the automatic model was obtained Eqs (8) and (9) that describe the dynamic model for the physical system of the receiving antenna.

$$\tau_1 = D_{11}\ddot{\theta}_1 + 2H_{112}\dot{\theta}_1\dot{\theta}_2 \tag{8}$$

$$\tau_2 = D_{22}\ddot{\theta}_2 + H_{211}\dot{\theta}_1^2 + C_2 \tag{9}$$

Assuming g = 9.81 m/s^2, then the equations will be presented for each term of the matrices and vectors that describe the dynamic equations of motion. The literal terms contained therein a_1, a_2, m_1 and m_2 respectively, DH parameter of the link 1, parameter DH of the link 2, and mass of link 1 and mass of link 2. The joints variables are θ_1 and θ_2 (rotary joints).

Terms of Inertia Matrix D_{ik}:

$$\begin{aligned} D_{11} = {} & 2a_1a_2m_2\cos(\theta_2) + a_1{}^2m_1 + a_1{}^2m_2 + \frac{1}{2}a_2{}^2m_2(1+\cos(2\theta_2)) - 0.29a_1m_1 \\ & -1.514a_1m_2\cos(\theta_2) - 0.757a_2m_2(1+\cos(2\theta_2)) + 27.2565\cos(2\theta_2) + 37.2375 \end{aligned} \tag{10}$$

$$D_{12} = 0 \tag{11}$$

$$D_{21} = 0 \tag{12}$$

$$D_{22} = a_2{}^2m_2 - 1.514a_2m_2 + 62.328 \tag{13}$$

Terms of the vector representing the Coriolis effects and centrifugal force, H_{ikm} :

$$H_{111} = 0 \tag{14}$$

$$\begin{aligned} H_{112} = {} & -a_1a_2m_2\sin(\theta_2) - \frac{1}{2}a_2{}^2m_2\sin(2\theta_2) + 0.757m_2(a_1\sin(\theta_2) + a_2\sin(2\theta_2)) \\ & -27.2565\sin(2\theta_2) \end{aligned} \tag{15}$$

$$\begin{aligned} H_{121} = {} & -a_1a_2m_2\sin(\theta_2) - \frac{1}{2}a_2{}^2m_2\sin(2\theta_2) + 0.757m_2(a_1\sin(\theta_2) + a_2\sin(2\theta_2)) \\ & -27.2565\sin(2\theta_2) \end{aligned} \tag{16}$$

$$H_{122} = 0 \tag{17}$$

$$H_{211} = a_1 a_2 m_2 \sin(\theta_2) + \frac{1}{2} a_2{}^2 m_2 \sin(2\theta_2) - 0.757 m_2 (a_1 \sin(\theta_2) + a_2 \sin(2\theta_2)) + 27.2565\sin(2\theta_2) \tag{18}$$

$$H_{212} = 0 \tag{19}$$

$$H_{221} = 0 \tag{20}$$

$$H_{222} = 0 \tag{20}$$

Terms of the vector representing the effects of gravity acceleration C_i:

$$C_1 = 0 \tag{21}$$

$$C_2 = 0.757 m_2 g \cos(\theta_2) - m_2 a_2 g \cos(\theta_2) \tag{22}$$

The Eqs. (8) e (9) can be placed in matrix shape:

$$\begin{bmatrix} \tau_1 \\ \tau_2 \end{bmatrix} = \begin{bmatrix} D_{11} & 0 \\ 0 & D_{22} \end{bmatrix} + \begin{bmatrix} 2H_{112} & 0 \\ 0 & H_{211} \end{bmatrix} \cdot \begin{bmatrix} \dot{\theta}_1 \dot{\theta}_2 \\ \dot{\theta}_1^2 \end{bmatrix} + \begin{bmatrix} 0 \\ C_2 \end{bmatrix} \tag{23}$$

ADAPTIVE CONTROL SYSTEM

The main objective of a system of closed loop control is to maintain a satisfactory level of performance even when subjected to disturbances and variations in the control system (Dias, S.M., 2010.)

However, some plants have such wide variations and significant effects on the dynamic behavior that a classic controller with feedback gain linear and constant coefficients are unable to provide the necessary flexibility to the system (Tambara, R.V., Gründling, H.A., Della Flora, L., 2010.)

The basic idea of operation of the adaptive control is to calculate the control signal using estimates of uncertain parameters of the plant or directly to the controller parameters obtained through real-time information from the measurable signals of the system (Slotine, J J., Li, W., 1991.)

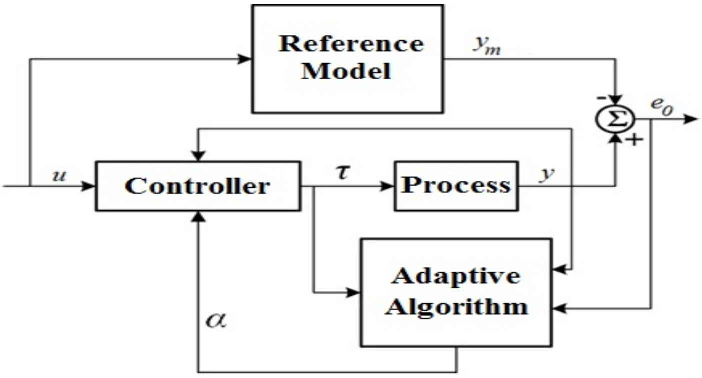
Model Reference Adaptive Control (MRAC)

The strategy *Model Reference Adaptive Control* (MRAC) is considered one of the main approaches in the literature on adaptive control (Mareels, I.M.Y., Polderman, J.W., 1996.) In some applications, the plant parameters are not completely known. An alternative to control solution in these cases is the use of MRAC, where, besides the features of the MRC, the system inserts a parametric adaptation algorithm which estimates the uncertain parameters of the model (Tambara, R.V., Gründling, H.A., Della Flora, L., 2010.)

In the MRAC system performance is expressed in terms of a reference model, which generates a desired response to a given reference signal. The error between model output and the output of the plant (e_o) is measured, and through methods of parameter estimation (MIT Rule) controller parameters are modified so that the system behaves like the reference model (Guerra Vale, M.R.B., Fonseca, D.G.V., Maitelli, A.L., 2008.)

Figure 4 shows the schematic of a MRAC controller.

Fig. 4. Block diagram of a generic MRAC.



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Thus, the error between the plant output and the output of the reference model is used to adapt the algorithm to adjust the controller parameters, so that this error tends to zero, thus allowing the tracking of the asymptotic model (Gonçalves, J.B., 2006.)

MIT Rule

The essential problem of MRAC is to determine the adjustment mechanism so as to obtain a stable system in which the error signal between the plant output and the output of the reference model is minimized. The adjustment mechanism called *MIT Rule* is the original approach used in MRAC (Bueno, L.P.P., 2006.)

This rule states that for a given error signal e_o, a cost function $J(\alpha)$ is calculated, being α the parameter of the controller to be adjusted. The cost function is defined by:

$$J(\alpha) = \frac{1}{2} e_0^2 \qquad 24$$

In order to minimize the cost related to the error, the parameter α can be changed according to the negative gradient of J, so (Ioannou, P., Sun, J., 1995)

$$\frac{d\alpha}{dt} = -\gamma \frac{\partial J}{\partial \alpha} = -\gamma e_0 \frac{\partial e_0}{\partial \alpha}. \qquad 25$$

The Eq. (26) expresses the MIT Rule. The partial derivative $\partial e_0 / \partial \alpha$ is called the derived sensitivity of the system and shows how the error (e_o) is influenced by the adjustable parameter (α). The parameter γ determines the rate of adaptation of the system (adaptive gain).

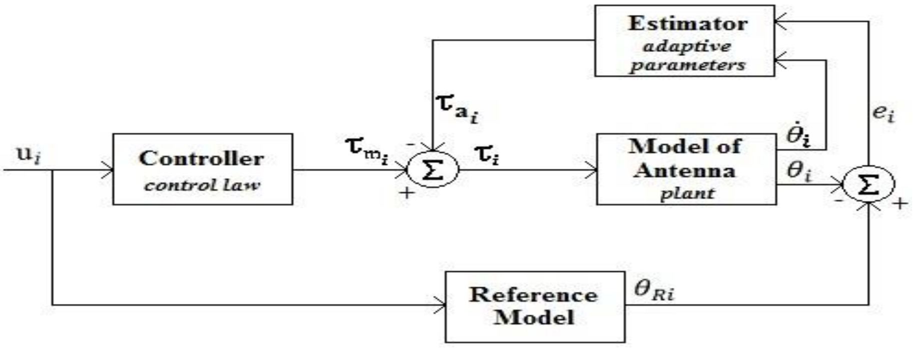
The mechanism for setting parameters through the MIT Rule is non-linear due to multiplication of the error with the partial derivative. Application of this mechanism can result in unstable systems, particularly if the adaptive gain γ is relatively high (Resende, J. M. O. S. A., 1995.)

MRAC Controller Antenna Receiver

The dynamic model obtained for the physical system of the receiving antenna has a non-linear as can be seen in Eqs (8) and (9). A linearization technique called Computed Torque was applied. The purpose of this linearization is to transform all or part of a nonlinear dynamic system, resulting in a system to which to apply linear control techniques (Slotine, J J., Li, W., 1991.)

The technique MRAC was used in the control design of receiving antenna, in order to identify the unknown parameters of the plant, so online. Figure 5 shows the block diagram of the control technique used in automatic maneuvering of the receiving antenna.

Fig. 5. MRAC block diagram of antenna receiver.



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Model Uncertainty

For the design of the control system of the antenna receiver is efficient it is necessary that the dynamic model is as close as possible to the real physical system. It is assumed that the term refers to energy dissipation is not known and therefore not included in the equations that define the dynamic model of the receiving antenna (Eqs. 8 and 9). Therefore the dynamic model of the receiving antenna must be rewritten with the inclusion of the unknown term energy dissipative.

Admitting $\hat{B}$ as the vector that represents the dissipative forces unknown to the model given by:

$$\hat{B} = \begin{bmatrix} \hat{b}_1 \\ \hat{b}_2 \end{bmatrix} \qquad 26$$

The dynamic equations of motion of the antenna receiver can be rewritten as:

$$\tau_1 = D_{11}\ddot{\theta}_1 + 2H_{112}\dot{\theta}_1\dot{\theta}_2 + \hat{b}_1\dot{\theta}_1 \qquad 27$$

$$\tau_2 = D_{22}\ddot{\theta}_2 + H_{211}\dot{\theta}_1^2 + C_2 + \hat{b}_2\dot{\theta}_2 \qquad 28$$

In matrix shape:

$$\begin{bmatrix} \tau_1 \\ \tau_2 \end{bmatrix} = \begin{bmatrix} D_{11} & 0 \\ 0 & D_{22} \end{bmatrix} + \begin{bmatrix} 2H_{112} & 0 \\ 0 & H_{211} \end{bmatrix} \cdot \begin{bmatrix} \dot{\theta}_1\dot{\theta}_2 \\ \dot{\theta}_1^2 \end{bmatrix} + \begin{bmatrix} C_1 \\ C_2 \end{bmatrix} + \begin{bmatrix} \hat{b}_1 & 0 \\ 0 & \hat{b}_2 \end{bmatrix} \cdot \begin{bmatrix} \dot{\theta}_1 \\ \dot{\theta}_2 \end{bmatrix} \qquad 29$$

Reference Model

For the design of the control system of the receiving antenna was used as a reference model of a 2nd order system widely discussed in (Nise, N.S., 2009.) Such systems have the well-defined performance index which allows to easily establish desirable conditions for the plant output, is in transition and in steady state. Eq. (31) presents the reference model adopted expressed in the time domain and in the function of natural frequency ω_n and damping ratio ζ:

$$\ddot{\theta}_{Ri} = \omega_{ni}^2 u_i - 2\zeta\omega_{ni}\dot{\theta}_{Ri} - \omega_{ni}^2\theta_{Ri} \qquad 30$$

In matrix shape:

$$\ddot{\theta}_R = \Omega u - Z\dot{\theta}_R - \Omega\theta_R \qquad 31$$

where:

$$\Omega := \begin{bmatrix} \omega_{n1}^2 & 0 \\ 0 & \omega_{n2}^2 \end{bmatrix}$$

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$$Z := \begin{bmatrix} 2\zeta_1\omega_{n1} & 0 \\ 0 & 2\zeta_2\omega_{n2} \end{bmatrix} \qquad 33$$

$$u := \begin{bmatrix} u_1 \\ u_2 \end{bmatrix} \qquad 34$$

$$\theta_R := \begin{bmatrix} \theta_{R1} \\ \theta_{R2} \end{bmatrix} \qquad 35$$

The natural frequency ω_n and damping ratio ζ can be determined from an index of performance imposed on the closed loop system. In order to perform an automatic pointing of the antenna receiving satisfactory, it is an overshoot $\%UP$ = 15%, and a transient peak time T_p = 1.8 s.

The relationship between the overshoot $\%UP$ and the transient peak time T_p, with the natural frequency ω_n, and damping ratio ζ, are given by:

$$\%UP = e^{-(\zeta\pi/\sqrt{1-\zeta^2})} \qquad 36$$

$$T_p = \frac{\pi}{\omega_n\sqrt{1-\zeta^2}} \qquad 37$$

Solving Eqs. (37) and (38), result: ω_n = 2 rad/s e ξ = 0.5.

Control law

From the control scheme shown in Figure 5, the adaptive control law used in the antenna receiver is given by:

$$\tau_i = \tau_{m_i} + \tau_{a_i} \qquad 38$$

In order τ_{m_i} is the term of the model expressed in terms of nominal values obtained in the dynamic model. Already τ_{a_i} is the term adaptive expressed as a function of adaptive parameter to be estimated.

Applying the technique of Computed Torque wishing to eliminate the nonlinearity of the plant and, considering the uncertain terms of the model $\hat{b}_1\dot{\theta}_1$ and $\hat{b}_2\dot{\theta}_2$, the terms of the model control law, τ_{m_1} and τ_{m_2}, can be written as:

$$\tau_{m_1} = D_{11}\left(\Omega u_1 - Z\dot{\theta}_{R1} - \Omega\theta_{R1}\right) + 2H_{112}\dot{\theta}_1\dot{\theta}_2 \tag{39}$$

$$\tau_{m_2} = D_{22}\left(\Omega u_2 - Z\dot{\theta}_{R2} - \Omega\theta_{R2}\right) + H_{211}\dot{\theta}_1^2 + C_2 \tag{40}$$

The adaptive terms of the control law, τ_{a_1} e τ_{a_2}, are:

$$\tau_{a_1} = \alpha_1\dot{\theta}_1 \tag{41}$$

$$\tau_{a_2} = \alpha_2\dot{\theta}_2 \tag{42}$$

Where, α_1 e α_2 are the parameters of adaptive control to be set by the estimator.

Therefore, the control law given in Eq. (39) can be rewritten for each degree of freedom system:

$$\tau_1 = D_{11}\left(\Omega u_1 - Z\dot{\theta}_{R1} - \Omega\theta_{R1}\right) + 2H_{112}\dot{\theta}_1\dot{\theta}_2 + \alpha_1\dot{\theta}_1 \tag{43}$$

$$\tau_2 = D_{22}\left(\Omega u_2 - Z\dot{\theta}_{R2} - \Omega\theta_{R2}\right) + H_{211}\dot{\theta}_1^2 + C_2 + \alpha_2\dot{\theta}_2 \tag{44}$$

Estimator – MIT Rule

To estimate the parameters of the adaptive controller was used to MIT rule. In this rule it is desired that the estimated parameter α converges to α^* (optimal value), this implies that $\lim_{t\to\infty} e_0(t) = 0$, where e_o is the error signal (Guerra Vale, M.R.B., 2008.)

The adaptive parameter of controller is a function of the partial derivative of the plant output θ_i with respect to parameter α_i multiplied by the error signal. The estimates of the parameters of the controller can be represented by (Ioannou, P., Sun, J., 1995)

$$\dot{\alpha}_1 = -\gamma\left(\frac{s}{s^2 + Zs + \Omega}\theta_1\right)e_1 \tag{45}$$

$$\dot{\alpha}_2 = -\gamma\left(\frac{s}{s^2 + Zs + \Omega}\theta_2\right)e_2 \tag{46}$$

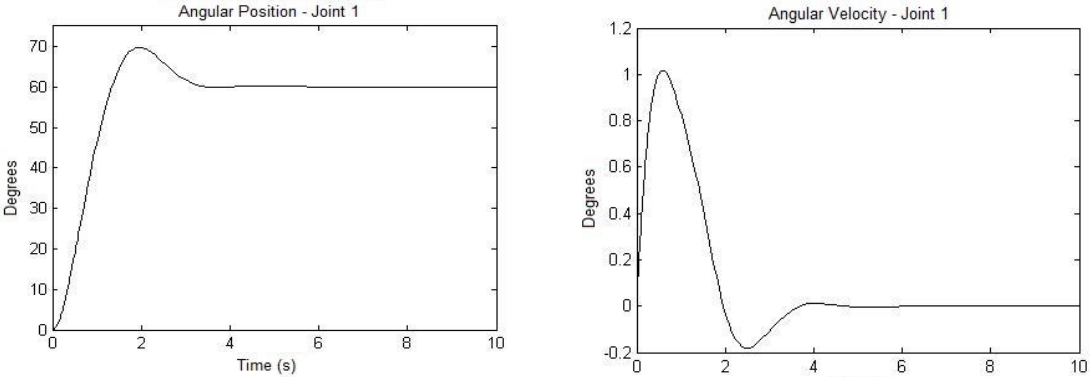
Simulation and results

The implementation of the control system was performed in MATLAB® software through the toolbox SIMULINK®, which features an intuitive graphical language programming offering an alternative to the classical approach to numerical simulation of engineering problems (Matsumoto, É.Y., 2004.)

In the simulations step functions were used as inputs of the system. Each entry represents the desired angular displacement for each joint of the system, such that: $u_1 = 60°$, $u_2 = 30°$.

Figure 6 and 7 show the outputs of the plant being controlled by MRAC for the joint 1 and joint 2, respectively, with a fixed gain adaptive (γ_i) given by: $\gamma_1 = 750$, $\gamma_2 = 900$.

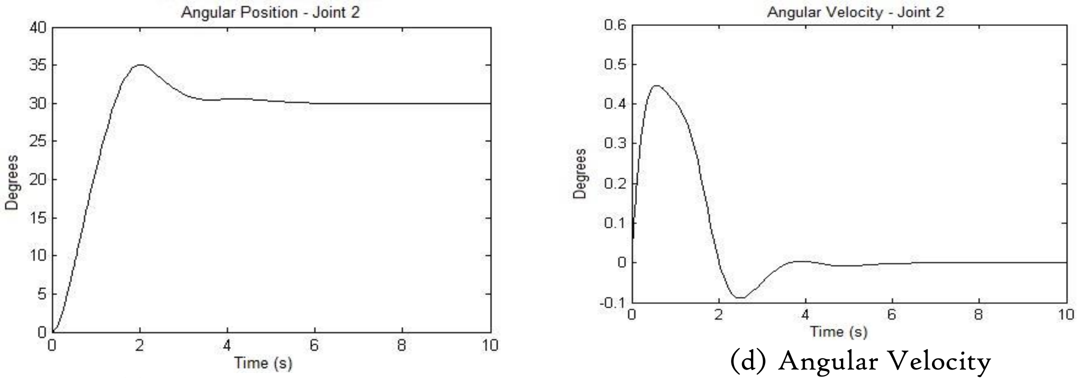
Fig. 6. Outputs of the control system – joint 1.



(a) Angular Displacement

(b) Angular Velocity

Fig. 7. Outputs of the control system – joint 2.



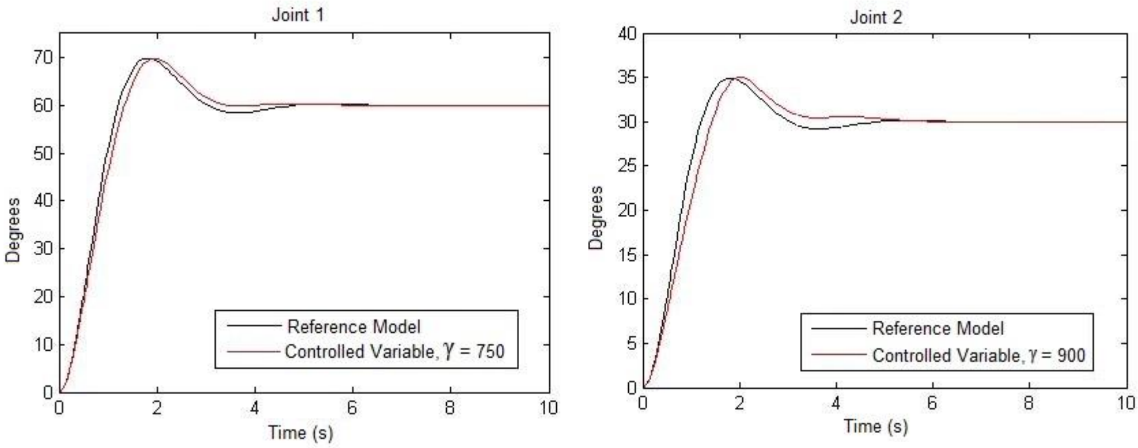
(c) Angular Displacement

(d) Angular Velocity

Source: Author

The main characteristic to be observed in an MRAC is the behavior of the controlled variable relative to the reference model. The latter is chosen so as to impose on the system the desired levels of performance. Figure 8 shows the output signal (controlled variable) compared to the reference model adopted.

Fig. 8. Analysis of output signal (controlled variable).

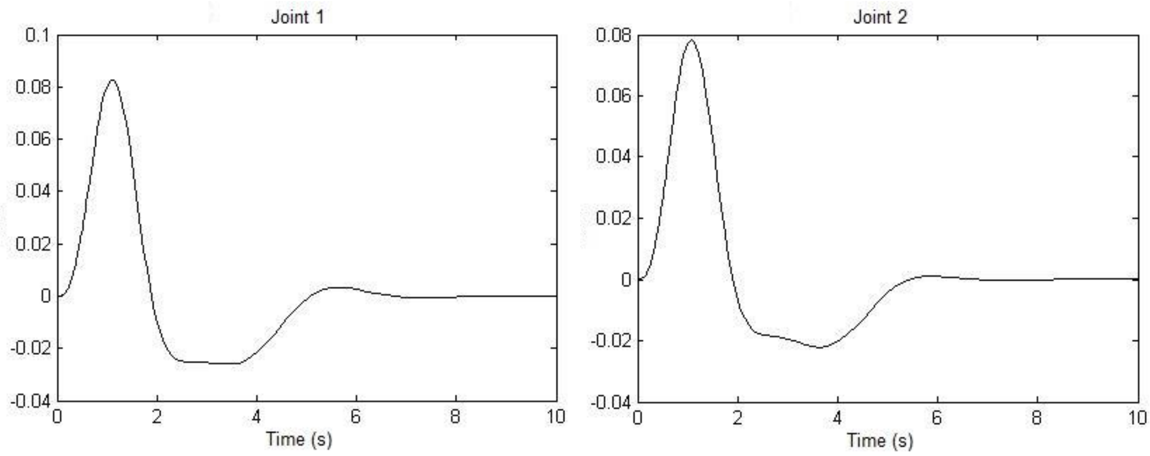


(a) Controlled Variable – joint 1 (b) Controlled Variable – joint 2

Source: Author

The error signal is obtained by the difference between the reference model and the output signal of the system. Figure 9 shows the error signal for the joint 1 and 2 of the antenna receiver.

Fig. 9. Error signal.



(a) Error Signal of the joint 1 (e_1) (b) Error Signal of the joint 2 (e_2)

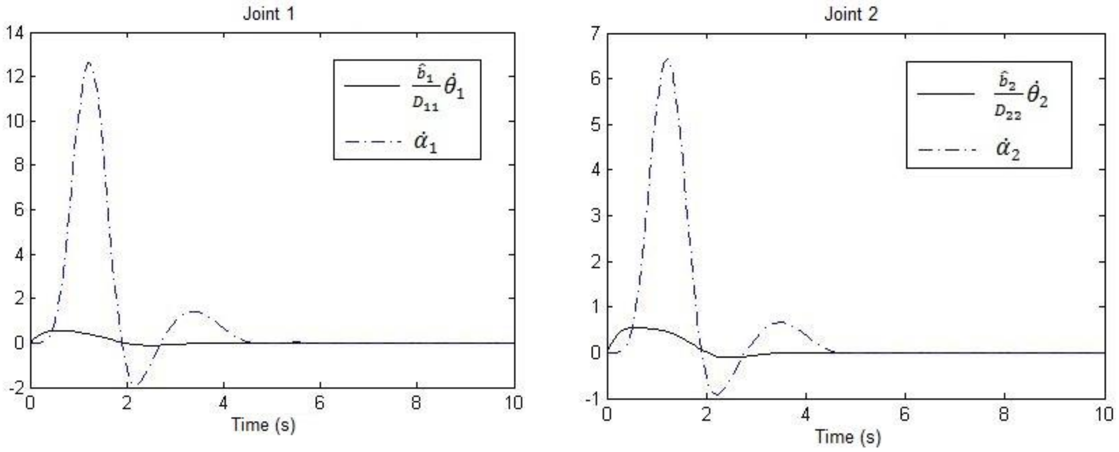
Source: Author

It is observed that the error signals of Figure 9 have small values which show the effective control action for both joints of the system of antenna receiver.

The model uncertainties are compensated by the parameter adaptive control. For the purpose of simulation was added to the model with a dissipative term to evaluate the behavior of parameter adaptive control.

Figure 10 (a) provides for the joint 1, the behavior between the dissipative term inserted $\left(\frac{\hat{b}_1}{D_{11}}\dot{\theta}_1\right)$, and the parameter adaptive control $\dot{\alpha}_1$, Figure 10 (b) provides for the joint 2, the behavior between the dissipative term inserted $\left(\frac{\hat{b}_2}{D_{22}}\dot{\theta}_2\right)$, and the parameter adaptive control $\dot{\alpha}_2$. The values of the adaptive gains are set: $\gamma_1 = 750$, $\gamma_2 = 900$.

Fig. 10. Analysis of the adaptive controller parameter.



(a) Controller parameter – joint 1 (b) Controller parameter – joint 2

Source: Author

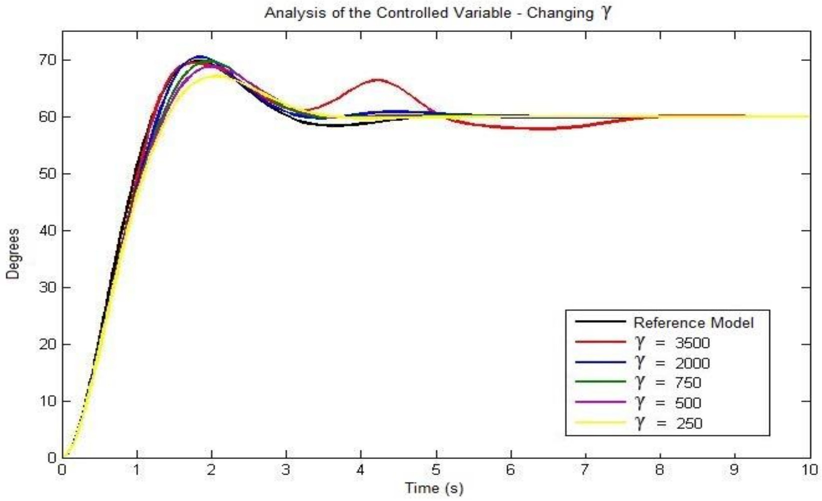
Analyzing Figure 10 shows that the contribution of the dissipative term included in the model rapidly tends to zero (about 5s). This is due to the fact that the velocity also tends to zero in this short period of time. Satisfactorily the contribution of the adaptive control parameter influences the system output at the same time interval in which the dissipative term acts. Note also that the adaptive control parameter tends to zero at the same instant in which the dissipative term is significant in the system.

The variation of the adaptive gain γ has a direct influence on the behavior of the MRAC. As the system of the antenna receiver has a fixed gain at its plant the adjusting of the γ occurred empirically, that is, as varying the γ analyzing the behavior of the output.

Figure 11 and 12 show the influence of γ at the output of a system to seal and joint 2 respectively.

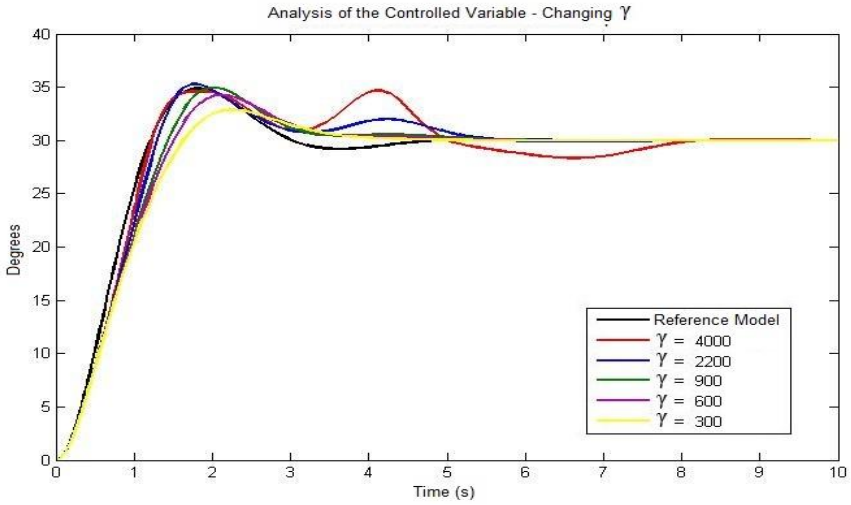
With very high values of γ the systems begin to show features of instability. To perform the pointing of the antenna receiver with satisfactory levels of play can be considered an adaptive gain to the joint 1 such that: $\gamma_1 \in [710, 830]$ and for joint 2: $\gamma_2 \in [880, 990]$.

Fig. 11. Influence of γ on output system – joint 1.



Source: Author

Fig. 12. Influence of γ on output system – joint 2.



Source: Author

CONCLUSION

This work was presented an adaptive control system for the automatic maneuvering of a receiver dish. For the basis of studies have been adopted the physical and construction characteristic of a antenna receiver widely used in satellite communications professionals systems.

The three-dimensional modeling of the physical system made it possible for the antenna receiver to obtain the physical parameters of the system. This modeling was done in CATIA® V5 R19. The features offered by this software enabled the physical model obtained contemplate all the constituent parts of the schematic constructive prepared for the mechanism of the antenna receiver, making it possible to identify the links in the system. The systematic location of Cartesian coordinate systems in the joints of the system, according to the Denavit-Hartenberg rules, was also easily performed by this software.

The similarity of the physical system obtained with a robotic serial manipulator allowed to use the concepts of kinematics and dynamic modeling of manipulators. The Euller-Lagrange formalism was used in modeling the dynamics of the antenna receiver. To that end, we developed an algorithm that describes the steps necessary to obtain the dynamic equations of motion for a robotic serial manipulator. The implementation of this algorithm occurred in the software MAPLE® 13. As a result of this implementation was developed automatic modeler that is capable of resulting equations of motion for these manipulators.

The implementation of the MRAC control system adopted to control the movements of the antenna receiver, took from its implementation in MATLAB® using the toolbox SIMULINK®.

As the dynamic model obtained was a non-linear model by a feedback linearization technique (Computed torque) was applied in order to eliminate the nonlinear terms of the model. The reference model adaptive control action was adopted to control the plant. The reference model chosen was a standard system of 2nd order, which in addition to the simplicity of implementation allows the desired levels of performance for the system to be easily established. The parameters of adaptive controller were estimated by MIT rule that evaluates the sensitivity of the error derivative with respect to the parameter of the controller. The adaptive gain γ, which determines the rate of adaptation of the system, was adjusted empirically, drawing upon the expertise of the designer.

Simulations of the control system designed were satisfactory and levels of performance of the system have been achieved. Were also performed simulations varying the adaptive gain. It was noticed that for high values of γ the system becomes unstable.

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