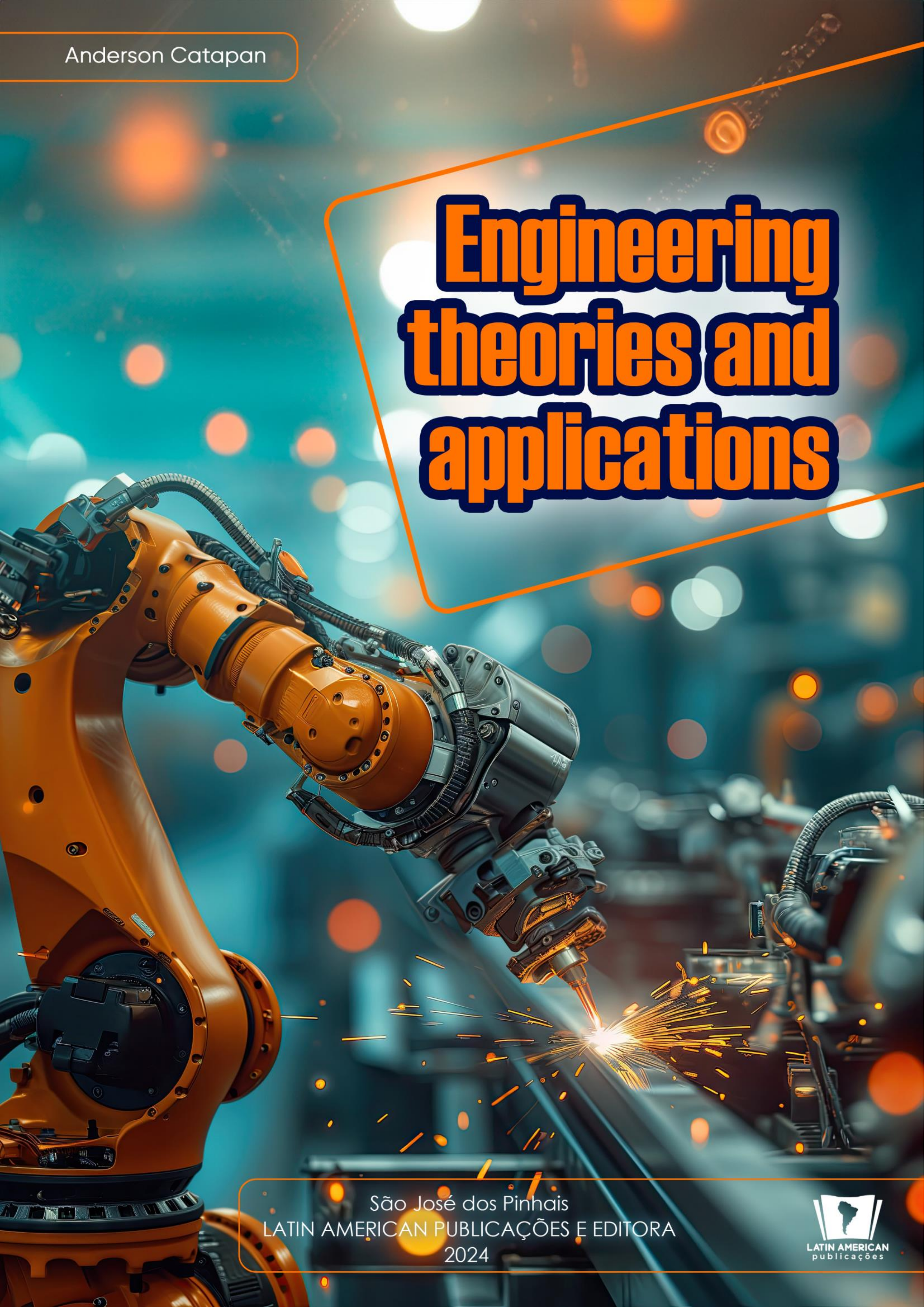

Anderson Catapan

Engineering theories and applications

São José dos Pinhais
LATIN AMERICAN PUBLICAÇÕES E EDITORA
2024

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Latin American Publicações
2024

Editora Executiva: Barbara Luzia Sartor Bonfim Catapan
Diagramação: Sabrina Binotti Alves
Arte: Sabrina Binotti Alves
Revisão: Os autores

Conselho Editorial:

Dados Internacionais de Catalogação na Publicação (CIP)

Engineering theories and applications / organizanizer Anderson Catapan**.** São José dos Pinhais: Latin American Publicações, 2024.

Vários autores
PDF
ISBN: 978-65-85645-05-8

1. Technological engineering 2. Robots 3. Constructions 4. Catapan, Anderson 5. Título

Latin American Publicações
São José dos Pinhais – Paraná – Brasil
www.latinamericanpublicacoes.com.br/
editora@latianamericanpublicacoes.com.br

Ano 2024

SUMÁRIO

PRESENTATION

A engenharia, uma disciplina essencial que molda o mundo moderno, continua a evoluir em resposta aos desafios e oportunidades emergentes. "Engineering: Theories and Applications - 1st Edition" é uma obra que se propõe a explorar essa evolução, oferecendo uma visão abrangente das teorias fundamentais e suas aplicações práticas em diversas áreas da engenharia.Este livro reúne contribuições de especialistas, abordando uma vasta gama de tópicos que vão desde os princípios básicos da engenharia até as inovações mais recentes. Com uma abordagem que integra teoria e prática, a obra oferece uma perspectiva única sobre como os conceitos fundamentais são aplicados para resolver problemas complexos no mundo real.Para profissionais da engenharia, estudantes e interessados no tema, "Engineering: Theories and Applications - 1st Edition" é uma leitura essencial. O livro proporciona uma compreensão profunda das bases teóricas da engenharia.Os leitores são incentivados a explorar as interconexões entre diferentes disciplinas de engenharia e a considerar como a integração dessas áreas pode levar a soluções inovadoras e eficientes. "Engineering: Theories and Applications - 1st Edition" não é apenas um compêndio de conhecimento técnico, mas também um convite à reflexão sobre o papel da engenharia na construção de um futuro sustentável e tecnologicamente avançado.Para aqueles que buscam aprofundar seus conhecimentos e estar na vanguarda das inovações na engenharia, este livro é uma fonte de informações e um guia prático que inspira e orienta o desenvolvimento de soluções engenhosas para os desafios do século XXI.

CHAPTER 01

DECENTRALIZED ADAPTIVE CONTROL APPLIED TO TWO LINKS OF A FIVE DEGREES OF FREEDOM ROBOT, USING THE POLYNOMIAL TECHNIQUE

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ABSTRACT: The objective of this work is to design and implement decentralized adaptive controllers in order to perform the position control of two links of an electromechanical manipulator robot with five degrees of freedom (DOF 5). The manipulator robot is consisted of five rotational joints, four links and a claw. Five DC motors are used to drive the robot and the motion transmission from the motors to the joints is achieved by gear trains. Models of the manipulators robots are obtained using Newton-Euler or Lagrange equations; and are coupled and nonlinear. In this work, the model of the links of the manipulator robot is obtained in real time for each sampling period. The parameters of the links to be controlled are identified by recursive least squares (RLS) method, according to data from the links, and are used in the designs of adaptive controllers for the positions control of the joints of the links under analysis. In the end, the experimental results are presented, like the evaluation of the performance achieved by the manipulator robot links.

KEYWORDS: Robotics; Systems identification; Adaptive control.

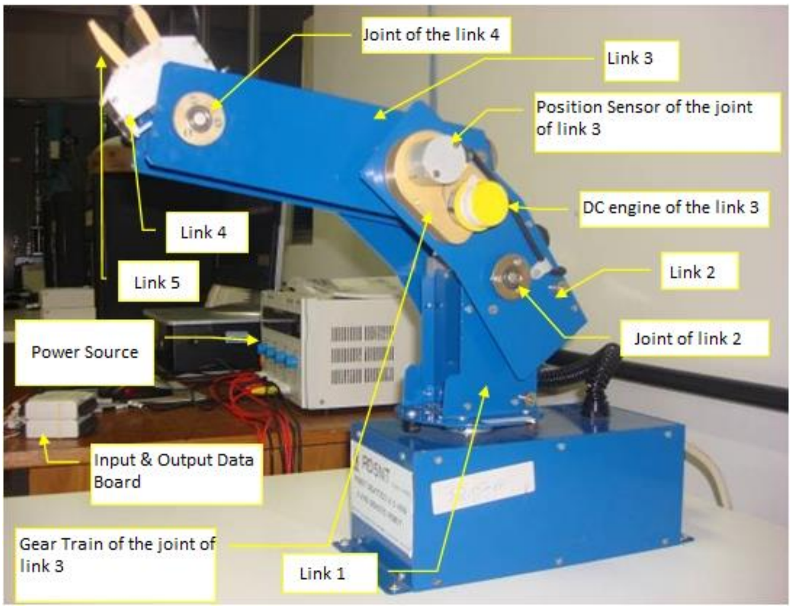
RESUMO: O objetivo deste trabalho é projetar e implementar controladores adaptativos descentralizados para realizar o controle de posição de dois elos de um robô manipulador eletromecânico com cinco graus de liberdade (GDL 5). O robô manipulador é composto por cinco juntas rotacionais, quatro elos e uma garra. Cinco motores CC são usados para acionar o robô e a transmissão do movimento dos motores para as articulações é realizada por trens de engrenagens. Modelos dos robôs manipuladores são obtidos utilizando equações de Newton-Euler ou Lagrange; e são acoplados e não lineares. Neste trabalho o modelo dos elos do robô manipulador é obtido em tempo real para cada período de amostragem. Os parâmetros dos links a serem controlados são identificados pelo método dos mínimos quadrados recursivos (RLS), de acordo com os dados dos links, e são utilizados nos projetos de controladores adaptativos para o controle de posições das juntas dos links em análise. Ao final, são apresentados os resultados experimentais, bem como a avaliação do desempenho alcançado pelos links do robô manipulador.

PALAVRAS-CHAVE: Robótica; Identificação de sistemas; Controlo adaptativo.

1. INTRODUCTION

This paper aims to control the position, through adaptive techniques, of two links of an electromechanical manipulator robot with five degrees of freedom (5 DOF). The links 1 and 2 to be controlled are shown in Fig. 1. The mathematical model of a system can be obtained by physical laws, known as white box model or parametric identification technique, known as black box model, which relies on real system data. White box models of robot manipulators are nonlinear (Spong and Vidyasagar, 1989; Craig, 1989), while the black box identification generates linear models (Aguirre, 2000; Astrom & Wittenmark, 1995; Isermann, 1980) that can be used to design and implement adaptive controllers.

Figure 1. Manipulator Robot of 5 DOF.



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The models are obtained in real time, and represent adequately the nonlinear dynamics of the system, since it is evaluated for each instant of time, depending on the sampling time used. The white box models, when used in the design of controllers, demand a high amount of calculations, therefore, they imply the use of large machines, due to computational effort required (Koivo and Guo, 1983; Shih and Tseng, 1995; Carvalho et al., 2008). When using black box models, their structures are defined *a priori*, and thus, the choice of models of the first or second order, which represent well the real systems, and that require the use of low computational effort. As the dynamics of the robot links is coupled and nonlinear, the adaptive controllers are applied, seeking a good performance for the system, since they are obtained at each sampling period and in real time. In this paper, the algorithm of recursive least squares (RLS) is used in real time to obtain the parameters of links 1 and 2 of the robot under consideration, and these are used in projects and implementation of decentralized adaptive controllers, which use polynomial technique, proposed by Kubalcik and Bobál (2006), aiming to control the position of links 1 and 2 of the robot. The identification of the links is done considering the coupling between them, but the designed adaptive controllers do not take it into consideration. Finally, experimental results are presented showing the performance obtained for the two links of the robot, given the imposed performance specifications.

2. SYSTEM DESCRIPTION

The manipulator robot, shown in Fig. 1 is a didactic robot, weighing about 7 kg, reference RD5NT, manufactured by Didacta Italy company, consisting of five rotary joints, four links and a claw. The first rotary joint refers to the angular movement of the base, with maximum displacement of 293°; the second rotary joint makes reference to the shoulder, with angular displacement up to 107º; the third rotary joint is related to the elbow, with maximum angular displacement of 284º; the fourth rotary joint pertains to the pulse with maximum angular displacement of 360º and the fifth rotary joint refers to a system crown / worm screw, responsible for the course of the claw, a maximum of 22 mm, clamping capacity load 350 grams and stopped automatically by a micro switch operating with adjustable closing speed. The links of the manipulator robot represent the trunk, arm, forearm and wrist. The transmission of each movement is done by engine block gear, with two reduction stages, and overall gear ratio of 1 / 500. The engine blocks are DC, reference 2139.906-22.112-050, manufactured by Maxon Motor, with power of 2.5 watts and long life capacitor. The nominal voltage of DC motors is 12 volts and maximum speed without load is 6480 rpm. Reproduction of the angular displacement of joints and claw movement is ensured by means of linear rotary potentiometers, reference 78CSB502, manufactured by Sfernice with resistance of 5 kΩ. A HP Compaq computer with AMD Athlon dual core 985 MHz and 786 MB of RAM is used to send commands to drive DC motors and receive signals from potentiometric sensors. The communication between the robot and the computer is accomplished through two input and output data boards, NI USB-6009, and a computer program in LabView and Matlab platforms. Considering the characteristics of voltage and maximum current capacity of the input and output data boards, it was necessary to introduce a power amplifier to serve as a source of supply for DC motors of the manipulator robot. This amplifier besides providing the power required to drive each motor, supplies the proper polarity for its operation in the desired direction. The decision of the rotation direction depends on the excitation voltage applied at its input terminals.

3. IDENTIFICATION OF THE TWO LINKS OF MANIPULATOR ROBOT

The systems identification is an area of knowledge that studies alternative techniques of mathematical modeling. One of the characteristics of these techniques is that little or no prior knowledge of the system is necessary and, therefore, such methods are referred to as modeling (or identification) black box modeling or empirical (Aguirre, 2007). The identification of black box type of modeling is used in links 1 and 2 of the manipulator robot under analysis, through the algorithm of recursive least squares (RLS), in real-time, according to Eq. (1).

$$\hat{\theta}(t+1) = \hat{\theta}(t) + K(t+1)\varepsilon(t+1) \tag{1}$$

where:

$$K(t+1) = \frac{P(t)j(t+1)}{\lambda + j^T(t+1)P(t)j(t+1)} \tag{2}$$

$$P(t+1) = \frac{1}{\lambda}\left\{P(t) - \frac{P(t)j(t+1)j^T(t+1)P(t)}{\lambda + j^T(t+1)P(t)j(t+1)}\right\} \tag{3}$$

K (t +1) - estimator gain with forgetting factor λ;

P (t) - covariance matrix with forgetting factor;

$\hat{\theta}(t+1)$ - vector of estimated parameters by RLS;

$\varepsilon(t+1) = v(t+1) - \hat{v}(t)$ - prevision error;

v (t +1) - output of the system;

$\hat{v}(t)$ - estimated output of the system;

t = kTs - discrete time;

k = 1, 2, 3 ..., N - number of samples;

Ts - sampling time.

The manipulator robot of 5 DOF is articulated, as shown in Fig. 1, then the dynamics of the links is connected, and the identification is performed by considering the dynamic coupling between the links and pre-structure of each link as follows:

- Pre-structure of second order (two poles, one zero and a transportation delay).

$$\hat{\theta}_1 = [a_1\ a_2\ a_3\ a_4\ b_1\ b_2\ b_3\ b_4] \quad (4)$$

$$\hat{\theta}_2 = [a_5\ a_6\ a_7\ a_8\ b_5\ b_6\ b_7\ b_8] \quad (5)$$

The vector of measures is given by Eq. (6).

$$j^T(t-1) = [-\beta_1(t-1) - \beta_1(t-2) - \beta_2(t-1)\ -\beta_2(t-2)\ u_1(t-1)\ u_1(t-2)\ u_2(t-1)\ u_2(t-2)] \quad (6)$$

The estimated responses $\hat{\beta}_1(t)\, e\, \hat{\beta}_2(t)$ are obtained according to Eq. (7) and Eq. (8), respectively.

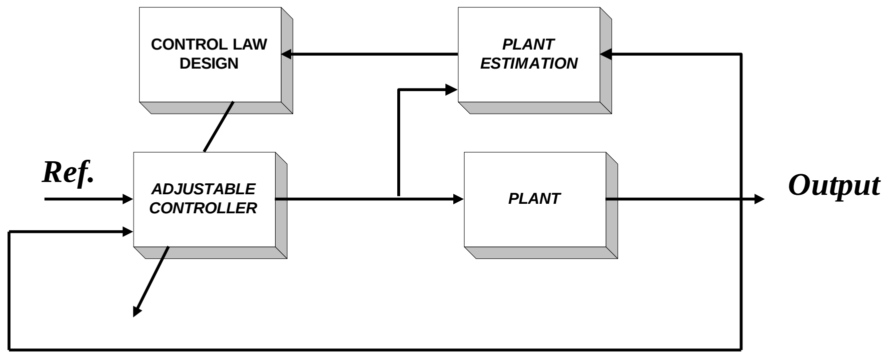
$$\hat{\beta}_1(t) = j_1^T(t-1)\hat{\theta}_1(t) \quad (7)$$

$$\hat{\beta}_2(t) = j^T(t-1)\hat{\theta}_2(t) \quad (8)$$

4. ADAPTIVE CONTROLLER

Aström and Wittenmark (1995) define an adaptive controller as a controller with adjustable parameters and an adjustment mechanism. The self-tuning controller (STR) automates the tasks of mathematical modeling, design and implementation of control law. In STR estimates of system, parameters are updated and the controller parameters are obtained by solving a design that uses the estimated parameters of the system (plant). A block diagram of a STR controller and plant is shown in Fig. 2. In the block diagram two closed-loops are highlighted. The lower loop is represented by the system and the feedback output. The higher loop stands out the presence of three components: the estimation of parameters, the controller design and the adjustable controller. The first component has the function to estimate the parameters of the plant. As a consequence, it uses a recursive estimator; the second one consists in the adaptation mechanism whose task is to perform real-time controller design and the third one is a controller with adjustable parameters. The STR is very flexible in the choice of the controller design method and the algorithm for estimating the system parameters. The estimated parameters are considered as being the actual parameters of the system, hence, the estimation of the parameters is the essence of the adaptive controller (Rubio et al, 1996).

Figure 2. Block diagram of the STR Controller and plant



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At this stage, decentralized adaptive controllers will be designed and implemented, based on the polynomial technique, proposed by Kubalcik and Bobál (2006), to perform, in real time, the position control of the links 1 and 2 of the manipulator in Fig. 1. This technique is suitable for adaptive control because it allows the expression of the controller parameters to be written as a function of the parameters of the controlled process. The controller design is reduced to the solution of linear diophantine equations that converted to a set of algebraic equations, it can be solved through an appropriate computational algorithm.

The links 1 and 2 of the robot are represented by the transfer matrix given by Eq. (9).

$$G(z^{-1}) = \frac{Y(z^{-1})}{U(z^{-1})} = \begin{bmatrix} G_{11}(z^{-1}) & G_{12}(z^{-1}) \\ G_{21}(z^{-1}) & G_{22}(z^{-1}) \end{bmatrix} \tag{9}$$

where U (z^{-1}) is the input vector, given by Eq. (10) and Y (z^{-1}) is the output vector, given by Eq. (11).

$$U(z^{-1}) = \left[u_1(z^{-1}), \;\; u_2(z^{-1}) \right]^T \qquad (10)$$

$$Y(z^{-1}) = \left[\beta_1(z^{-1}), \quad \beta_2(z^{-1}) \right]^T \qquad (11)$$

The variables $u_1(z^{-1})$ and $u_2(z^{-1})$ are the inputs of electric voltage of DC motors that drive the joints of the links 1 and 2 of the robot, respectively. β_1 and the variables (z^{-1}) and β_2 (z^{-1}) are the angular positions of joints 1 and 2 of the robot.

It is assumed that the dynamic behavior of the system can be described near the steady state for linear discrete model in the form of matrix fraction (Kubalcik and Bobál, 2006), according to Eq. (12).

$$G(z) = \frac{Y(z)}{U(z)} = A^{-1}(z^{-1})B(z^{-1}) \qquad (12)$$

The polynomial matrices A and B belonging to the R22 (z^{-1}) represent the factorization of the matrix G (z), coprime to the left, and are defined as Eq. (13) and Eq. (14), using the parameters defined in Eq. (4) and Eq. (5).

$$A(z^{-1}) = \begin{bmatrix} 1 + a_1 z^{-1} + a_2 z^{-2} & a_3 z^{-1} + a_4 z^{-2} \\ a_5 z^{-1} + a_6 z^{-2} & 1 + a_7 z^{-1} + a_8 z^{-2} \end{bmatrix} \qquad (13)$$

$$B(z^{-1}) = \begin{bmatrix} b_1 z^{-1} + b_2 z^{-2} & b_3 z^{-1} + b_4 z^{-2} \\ b_5 z^{-1} + b_6 z^{-2} & b_7 z^{-1} + b_8 z^{-2} \end{bmatrix} \qquad (14)$$

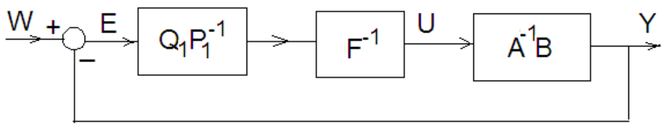
Substituting Eq. (10), Eq. (11), Eq. (13) and Eq. (14) into Eq. (12), we obtain Eq. (15) and Eq. (16).

$$\begin{aligned} \beta_1(t) = \quad & - a_1 \beta_1(t-1) - a_2 \beta_1(t-2) \\ & - a_3 \beta_2(t-1) - a_4 \beta_2(t-2) \\ & + b_1 u_1(t-1) + b_2 u_1(t-2) + \\ & b_3 u_2(t-1) + b_4 u_2(t-2) \end{aligned} \qquad (15)$$

$$\begin{aligned}\beta_2(t) = & -a_5\beta_1(t-1) - a_6\beta_1(t-2) \\ & - a_7\beta_2(t-1) - a_8\beta_2(t-1) \\ & + b_5u_1(t-1) + b_6u_1(t-2) \\ & + b_7u_2(t-1) + b_8u_2(t-2)\end{aligned} \qquad (16)$$

The control structure of 1 DOF (one degree of freedom) to be used is shown in Fig. 3 and contains only one feedback.

Figure 3. Block Diagram of the Controller of 1 DOF and System



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In Figure 3, the polynomial matrices Q_1 and P_1 of the controller are defined in the following sections, during the design of controllers. In the same Fig. 3, F^{-1} (z^{-1}) is an integrator, where the matrix F (z^{-1}) is Eq. (17).

$$F(z^{-1}) = \begin{bmatrix} 1-z^{-1} & 0 \\ 0 & 1-z^{-1} \end{bmatrix} \qquad (17)$$

In this work, the controllers are designed without an integrator, thus F (z^{-1}) is described by Eq. (18).

$$F(z^{-1}) = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \qquad (18)$$

In the structure of the Fig. 3, the control variable U is given by Eq. (19).

$$U = F^{-1}Q_1P_1^{-1}E \qquad (19)$$

In Equation (19), the error vector E is modified according to Eq. (20) and Eq. (21).

$$E = W - Y \Rightarrow W = Y + E \qquad (20)$$

$$Y = A^{-1} B U \qquad (21)$$

The vector E is found, conveniently providing the Eq. (19), Eq. (20) and Eq. (21), and getting the Eq. (22).

$$E = P_1^{-1} (FAP_1 + B\,Q_1\,)^{-1} AFW \qquad (22)$$

Substituting Eq. (19) into Eq. (21) and using Eq. (20), we obtain Eq. (23).

$$Y = A^{-1} B\,F^{-1} Q_1 P_1^{-1} (W - Y) \qquad (23)$$

Developing, as appropriate, Eq. (19), we have Eq. (24).

$$Y = P_1 (AFP_1 + BQ_1\,)^{-1} B\,Q_1 P_1^{-1} W \qquad (24)$$

According to Kubalcik and Bobál (2006), the controller must be designed for the system to achieve stability in closed-loop and closed-loop system is stable when the diophantine equation given by Eq. (25) is satisfied.

$$(AFP_1 + BQ_1\,) = M \qquad (25)$$

The determinant of the denominator of Eq. (24) is the characteristic polynomial of the multivariable system (MIMO), whose roots are dominant factors for the behavior of the closed-loop system. For the system to be stable, these roots should be inside a unit circle in the complex plane of Gauss (Kubalcik and Bobál, 2006).

4.1 Project of the decentralized adaptive controller of 1 DOF without integrator for links 1 and 2 of the robot

For the decentralized adaptive controller design without integrating, the polynomial matrices A (z^{-1}) and B (z^{-1}) given by Eq. (13) and Eq. (14) are diagonal, since the coupling between the links 1 and 2 is being despised and they are represented by Eq. (26) and Eq. (27).

$$A(z^{-1}) = \begin{bmatrix} 1 + a_1 z^{-1} + a_2 z^{-2} & 0 \\ 0 & 1 + a_7 z^{-1} + a_8 z^{-2} \end{bmatrix} \qquad (26)$$

$$B(z^{-1}) = \begin{bmatrix} b_1 z^{-1} + b_2 z^{-2} & 0 \\ 0 & b_7 z^{-1} + b_8 z^{-2} \end{bmatrix} \qquad (27)$$

Using a matrix P_1 with polynomials of grade 1, the polynomial AFP_1 of Eq. (25) will have grade 3. Knowing that the matrix B has grade 2, polynomials BQ_1 of Eq. (25) will have the same grade 3 if the matrix Q_1 has grade 1 polynomials as follows in the Eq. (28) and Eq. (29).

$$P_1(z^{-1}) = \begin{bmatrix} 1 + p_1 z^{-1} & 0 \\ 0 & 1 + p_2 z^{-1} \end{bmatrix} \qquad (28)$$

$$Q_1(z^{-1}) = \begin{bmatrix} q_1 + q_2 z^{-1} & 0 \\ 0 & q_3 + q_4 z^{-1} \end{bmatrix} \qquad (29)$$

The matrix $M(z^{-1})$, shown in Eq. (25), has polynomials of grade 3, and it is a stable diagonal matrix given by Eq. (30).

$$M(z^{-1}) = \begin{bmatrix} 1 + m_1 z^{-1} + m_2 z^{-2} + m_3 z^{-3} & 0 \\ 0 & 1 + m_1 z^{-1} + m_2 z^{-2} + m_3 z^{-3} \end{bmatrix} \qquad (30)$$

Using the matrices A (z^{-1}), B (z^{-1}), F (z^{-1}), P1 (z^{-1}) and $Q_1(z^{-1})$ given by Eq. (26), Eq. (27), Eq. (18), Eq. (28) and Eq. (29) respectively, in Eq. (25) and assigning the coefficients of the resulting matrix R of α_{11}, α_{12}, α_{21} and α_{22}, we obtain Eq. (31).

$$R = AFP_1 + BQ_1 = \begin{bmatrix} \alpha_{11} & \alpha_{12} \\ \alpha_{21} & \alpha_{22} \end{bmatrix} = M \qquad (31)$$

Substituting in Eq. (31) the matrix M (z^{-1}) given by Eq. (30), we have the Eq. (32).

$$\begin{bmatrix} \alpha_{11} & \alpha_{12} \\ \alpha_{21} & \alpha_{22} \end{bmatrix} = \begin{bmatrix} 1 + m_1 z^{-1} + m_2 z^{-2} + m_3 z^{-3} & 0 \\ 0 & 1 + m_1 z^{-1} + m_2 z^{-2} + m_3 z^{-3} \end{bmatrix} \qquad (32)$$

In Equation (32), the coefficients α_{ij} with i, j = 1, 2, are given by Eq. (33) to Eq. (36) and the coefficients m_i, i = 1, 2, 3 are defined from the pole allocation made, for the closed-loop system is stable.

$$\begin{aligned} \alpha_{11} &= [a_2 p_1 + b_2 q_2] z^{-3} + [a_1 p_1 + b_1 q_2 + b_2 q_1 + a_2] z^{-2} \\ &\quad + [p_1 + b_1 q_1 + a_1] z^{-1} = 1 + m_1 z^{-1} + m_2 z^{-2} + m_3 z^{-3} \end{aligned} \qquad (33)$$

$$\alpha_{12} = 0 \qquad (34)$$

$$\alpha_{21} = 0 \qquad (35)$$

$$\begin{aligned} \alpha_{22} &= [a_8 p_2 + b_8 q_3] z^{-3} + [a_7 p_2 + b_8 q_3 + b_7 q_4 + a_8] z^{-2} \\ &\quad + [p_2 + b_7 q_3 + a_7] z^{-1} + 1 = 1 + m_1 z^{-1} + m_2 z^{-2} \\ &\quad + m_3 z^{-3} \end{aligned} \qquad (36)$$

Making equality between the coefficients of the matrices given by Eq. (32), using Eq. (33) to Eq. (36), and equating coefficients of same grade, we have the result in Eq. (37) and Eq. (38).

$$\begin{aligned} a_2 p_1 + b_2 q_2 &= m_3 \\ a_1 p_1 + b_2 q_1 + b_1 q_2 &= m_2 \\ p_1 + b_1 q_1 + a_1 &= m_1 \end{aligned} \qquad (37)$$

$$\begin{aligned} a_8 p_2 + b_8 q_4 &= m_3 \\ a_7 p_2 + b_8 q_3 + b_7 q_4 + a_8 &= m_2 \\ p_2 + b_7 q_3 + a_7 &= m_1 \end{aligned} \qquad (38)$$

Writing the Eq. (37) and Eq. (38) in matrix form, we have Eq. (39) and Eq. (40).

$$\begin{bmatrix} a_2 & 0 & b_2 \\ a_1 & b_2 & b_1 \\ 1 & b_1 & 0 \end{bmatrix}\begin{bmatrix} p_1 \\ q_1 \\ q_2 \end{bmatrix} = \begin{bmatrix} m_3 \\ m_2 - a_2 \\ m_1 - a_1 \end{bmatrix} \qquad (39)$$

$$\begin{bmatrix} a_8 & 0 & b_8 \\ a_7 & b_8 & b_7 \\ 1 & b_7 & 0 \end{bmatrix}\begin{bmatrix} p_2 \\ q_3 \\ q_4 \end{bmatrix} = \begin{bmatrix} m_3 \\ m_2 - a_8 \\ m_1 - a_7 \end{bmatrix} \qquad (40)$$

The controller parameters p_1, p_2, q_1, q_2, q_3 and q_4 are then obtained by solving systems of linear algebraic Eq. (39) and Eq. (40). The parameters a_i and b_j of the matrices that represent the links 1 and 2, of the manipulator robot, are obtained at each sampling period during the identification of the links. Using the controller parameters, obtained from Eq. (39) and Eq. (40), and the matrix F (z^{-1}) given by Eq. (18), in Eq. (19), the control law is determined, as given by Eq. (41).

$$\begin{bmatrix} u_1 \\ u_2 \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}\begin{bmatrix} q_1 + q_2 z^{-1} & 0 \\ 0 & q_3 + q_4 z^{-1} \end{bmatrix}\begin{bmatrix} 1 + p_1 z^{-1} & 0 \\ 0 & 1 + p_2 z^{-1} \end{bmatrix}^{-1}\begin{bmatrix} e_1 \\ e_2 \end{bmatrix} \qquad (41)$$

Making the products of Eq. (41), we have the control law given by Eq. (42).

$$\begin{bmatrix} u_1 \\ u_2 \end{bmatrix} = \begin{bmatrix} \dfrac{e_1 q_1 + (e_1 q_2)z^{-1}}{(p_1)z^{-1} + 1} \\ \dfrac{e_2 q_{10} + (e_2 q_4)z^{-1}}{(p_2)z^{-1} + 1} \end{bmatrix} \qquad (42)$$

Representing Eq. (42) in the form of difference equations, we obtain the control laws for the links 1 and 2 of the manipulator robot, given by Eq. (43) and Eq. (44).

$$u_1(k) = (-p_1)u_1(k-1) + q_1 e_1(k) + (q_2)e_1(k-1) \qquad (43)$$

$$u_2(k) = (-p_2)u_2(k-1) + q_3e_2(k) + (q_4)e_2(k-1) \quad (44)$$

In the following section, the characteristic polynomial of the adaptive controller / system, in closed-loop, is determined by considering as the performance specifications for the links of the robot 1 and 2: maximum percentage overshoot (Mp) of 10% and steady-state error percentage (ess) of ± 5%

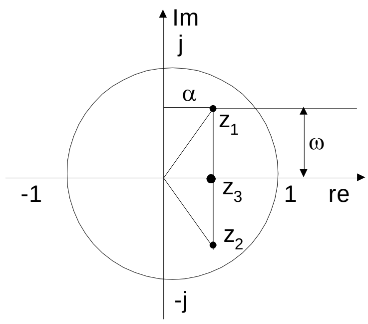
4.2 Characteristic polynomial of the decentralized adaptive controller and of the closed-loop system

In the case of decentralized adaptive controller without integrator, as shown in Eq. (30), M (z^{-1}) has grade 3. The coefficients of this polynomial are determined by pole allocation according to the procedure proposed by Bobál et al. (2005). We choose three poles for the polynomial M (z^{-1}) given by Eq. (45). The proper position of the poles should be selected after several experiments, until the output of links 1 and 2, meets the performance specifications imposed on the system.

$$M(z^{-1}) = (z-\alpha)[z-(\alpha+jw)][z-(\alpha-jw)] \quad (45)$$

The characteristic polynomial M (z^{-1}) from Eq. (45) used in this project, has a pair of complex conjugate poles $z_{1,2} = \alpha \pm j\omega$ inside the unit circle, and a real pole $z_3 = \alpha$, as shown in Fig. 4.

Figure 4. Location of the poles of the characteristic polynomial M (z^{-1})



Source: The Authors

Once the performance specifications are established, a set of poles has been tested to define the matrix M (z^{-1}), so that the links to the outputs meet the imposed specifications. After several attempts made to determine the three poles, the coefficients m_1 = - 0.335, m_2 = -0.0027 and m_3 = 0.04635 were chosen and used in order to obtain the outputs of links 1 and 2, since this polynomial M (z^{-1}) provided the best answers for the links. Therefore, the matrix M (z^{-1}) to be used is given by Eq. (46).

$$M(z^{-1}) = \begin{bmatrix} 1-0{,}335z^{-1}+0{,}04635z^{-2}-0{,}0027z^{-3} & 0 \\ 0 & 1-0{,}335z^{-1}+0{,}04635z^{-2}-0{,}0027z^{-3} \end{bmatrix} \quad (46)$$

5. RESULTS OBTAINED FOR LINKS 1 AND 2 OF THE ROBOT, UNDER ACTION OF THE ADAPTIVE CONTROLLER OF 1 DOF DECENTRALIZED WITHOUT INTEGRATOR

The RLS identification algorithm given by Eq. (1) and the control laws given by Eq. (43) and Eq. (44) were implemented through a computer program, structured in Matlab and Labview platforms.

The system works as follows: the angular positions β_1 (t) and β_2 (t) of the two links are measured by the potentiometers; the output errors are obtained; the parameters of the links are identified by RLS; the parameters of the adaptive controllers are determined, and the control variables u_1(t) and u_2(t) of Eq. (43) and Eq. (44) are determined and sent to the DC motors that drive the joints of the links.

The results obtained with the implementation of adaptive controllers for decentralized 1 DOF without integrators are shown in Figures 5 to 8. Figure 5 and Fig. 6 show the signs of references used and the experimental responses of the positions of links 1 and 2 captured by potentiometers. Figure 7 and Fig. 8 show the output errors of links 1 and 2. Table 1 presents the performance of links 1 and 2, under the action of the adaptive centralized controllers without integrator, following the references shown in Fig. 5 and Fig. 6, in time intervals: 20 to 40s, 40 to 60s, 60 to 80s, 80 to 100s, 100 to 120s, 120 to 140s, 140 to 160s, 160 to 180s and 180 to 200s. The results are presented after the first pulse because the initial instant of the experiment, which corresponds to t = 20s, we used proportional controllers to estimate partially the parameters of links 1 and 2 of the robot and to avoid an inadequate action of adaptive controllers, since the initial parameters of the links have null values, as shown in Tab. 1. After this initial time, the adaptive controllers were automatically triggered.

In addition to initially established performance specifications, the integral absolute error was used, accumulated in absolute mode, calculated by Eq. (47), in each interval of 20s, to evaluate the performance achieved by the links 1 and 2 of the robot. The lower the value of this index, the better the tracking of the trajectory is. These rates are registered in Tab. 2.

$$IAE(v) = \sum_{j=k_{ini}}^{j=k_{fin}} |w_i(j) - v(j)| \qquad (47)$$

where:

wi (j): reference of the i-th link of the robot, at time j;

v (j): position of the i-th link of the robot at time j;

K_{ini}, k_{fin}: moments of first and last time in evaluation of the trajectory.

Table 1. Performance of the links 1 and 2 of the manipulator robot related to the performance of established specifications

Time (s)	Parameters	Link 1		Link 2	
		Mp (%)	ess (%)	Mp (%)	ess (%)
20-40		7.1	0.98	2.0	1.40
40-60		2.44	0.15	5	0.70
60-80	$Mp \leq 10\%$	null	3.14	null	2.4
80-100		null	1.32	3.1	0.70
100-120	$ess \leq \pm 5\%$	null	2.70	null	2.2
120-140		null	0.91	2.24	0.6
140-160		null	3.0	null	2.40
160-180		null	1.16	1.70	1.0
180-200		null	2.93	null	1.9

Source: The Authors

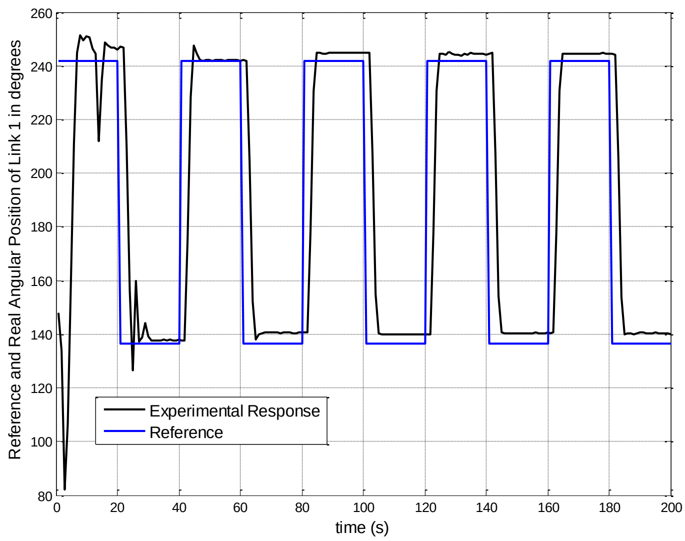
Table 2. Integral Absolute Error (IAE) of links 1 and 2

LINK 1		LINK 2	
Time (s)	**IAE (V)**	**Time (s)**	**IAE (V)**
20-40	3.853	20-40	1.345
40-60	2.828	40-60	1.424
60-80	3.629	60-80	1.663
80-100	3.257	80-100	1.154
100-120	3.703	100-120	1.686
120-140	3.174	120-140	0.951
140-160	3.786	140-160	1.7
160-180	3.203	160-180	1.193
180-200	3.718	180-200	1.611
TOTAL	**31.16**	**TOTAL**	**12.72**

Source: The Authors

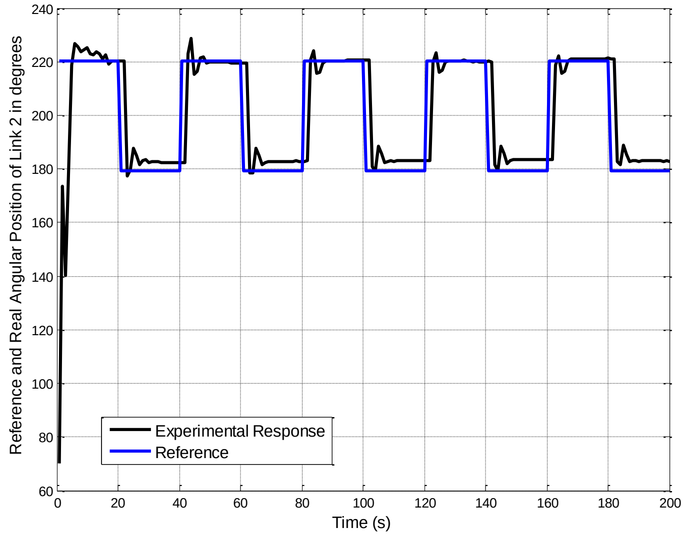
It is observed through Fig. 5 and Fig. 6 that the outputs of links 1 and 2 met the imposed performance specifications, according to Tab. 2, and therefore, with the controllers designed and implemented, the tasks performed by the robot within these specifications will be completely satisfactory. The Integral Absolute Error (IAE) accumulated, obtained by Eq. (47), was of 31.16 V for the link 1, and 12.72 V for the second link; hence, the best performance was related to the second link, because, according to Fig. 5 and Fig. 6, the rise time of the output of link 1 was around 5s while for the link 2, it was around 3s.

Figure 5. Reference and real response of the link 1 under the action of decentralized controller



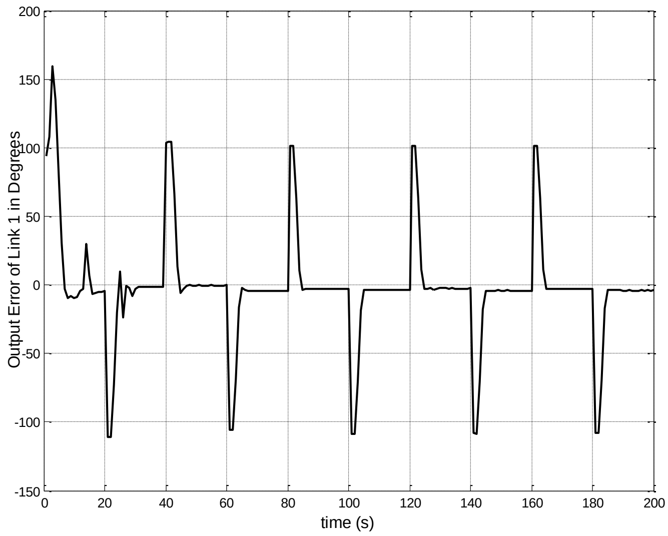
Source: The Authors

Figure 6. Reference and real response of the link 2 under the action of decentralized controller



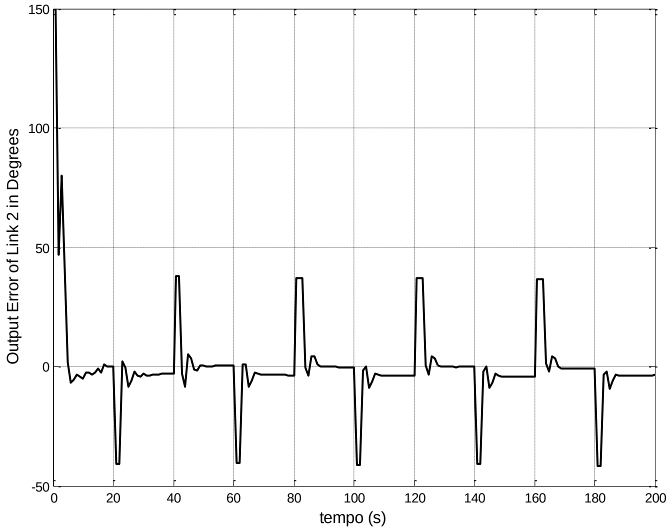
Source: The Authors

Figure 7. Output error of link 1



Source: The Authors

Figure 8. Output error of link 2



Source: The Authors

6. CONCLUSION

This research presented the project and implementation of decentralized adaptive controllers without integrator for two links of a coupled 5 DOF manipulator robot. From the obtained results, it can be verified that with the designed and implemented controllers, the outputs of the links were suitable for the imposed performance specifications; and therefore, it can be concluded that the controllers can be used in tasks to be accomplished by this robot.

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Agência Brasileira ISBN
ISBN: 978-65-85645-05-8