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ADAPTIVE GPC CONTROL OF A PLANAR MANIPULATOR

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Abstract*. This paper aims the development and implementation of the generalized predictive control (GPC) adaptive in in a robot planar manipulator with 2DOF (two-degrees-of-freedom) composed of a rotational link and other prismatic. The rotational link structure has a large U-channel made of aluminum having as actuator a direct current motor, and sensing as a ten turn potentiometer, acting as angular position transducer. The prismatic link is a double acting pneumatic cylinder, and it is fixed inside the rotational link, having as actuator a 5/3-way electro-pneumatic proportional valve, and as sensing a potentiometric rule, which acts as linear position transducer. Obtaining a representative mathematical model of the robot will be through the estimator of recursive least squares (RLS). Simulation results are obtained.*

Keywords: *identification in real time, adaptive controller, position control*

1. INTRODUCTION

This paper presents a simulation of a planar manipulator with 2DOF driven by electromechanical and electro-pneumatic actuators, using the generalized predictive control (GPC) algorithm defined by (Clarke *et al.* 1987), to position the links of the manipulator in a reference trajectory in the horizontal plane, according to pre-established performance specifications.

To perform the simulation of such hybrid system, it will be determined by the black-box modeling, a mathematical model that represents the system in question. The control scheme consists of an online parameter estimator and a control law. Among the many possible combinations, it uses the GPC control law to the algorithm of the recursive least squares (RLS) for online estimation of the parameters of a model type ARX.

To check the efficiency of the controller acting in the system under study, a reference path is set to be followed by the system in question in order to fit predefined performance specifications. The results will be presented through the experimental curves of system performance, control variable, the estimated parameters of the system.

2. SYSTEM DESCRIPTION

The test bench is formed by the 2DOF planar robot manipulator, a personal computer, a data acquisition board, a variable DC voltage supply, and an air compressor.

The computer is responsible for generating control signals and perform real-time identification through the algorithm written in a LabVIEW® platform program with routines written in Matlab® for the robot manipulator. The process of data acquisition and control of the manipulator is accomplished by the acquisition board model NI USB-6009. This board performs through the D/A (digital/analog) and A/D (analog/digital) converters, the interface of identification and control algorithms to the process. Thus, it performs the scanning through the A/D converter of analogue data obtained from the measurements made in the plant, does processing on a digital signal processor and generates output, transforming the digital control signal into analog by a D/A converter. The test bench assembled for this study, four analog channels were used, two input channels (AI O and AI 1) and two output channels (AO 0 and AO 1). Figure 1 shows the block diagram of the test bench.

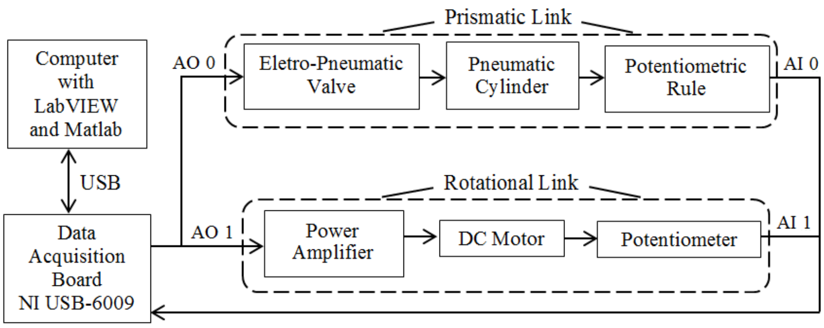

Figure 1 – Block diagram of test bench

The 2DOF manipulator robot planar is composed of two links, one rotational electro-mechanical and one translational electro-pneumatic. The constituent components of the experimental system, as shown in Figure 2.2 are: support base (1), the rotational link, the rotational link, which structure has an aluminum extensive branch in the U-channel (5) having as actuator a DC motor reducer (2), and as sensing which acts as angular position transducer (3) through the use of gears (4). The prismatic link is constituted by a double acting pneumatic cylinder with piston rod (6), having as actuator a proportional electro-valve 5/3 way (8), and as linear position sensor a potentiometric rule (7).

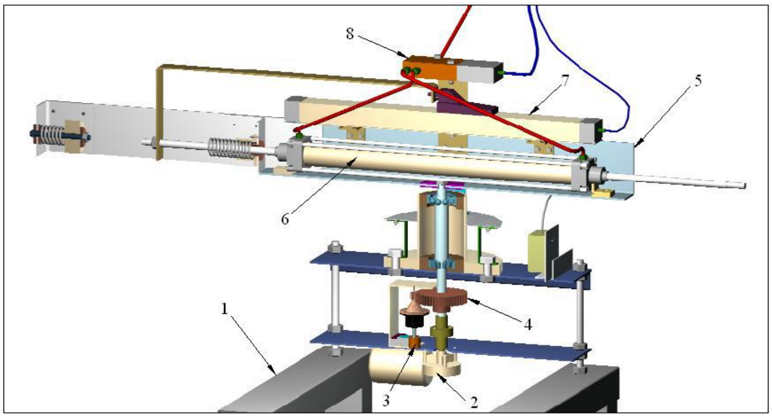

Figure 2. Description of the robot manipulator planar

The rotational link follows a tragetory and to occur its activation is required to receive an analog signal excitation ranging from 0 to 5 V DC. if the received voltage on the rotational link is 2.4 V, the link remains stationary and between 2.42 V to 5 V, it rotates clockwise (return).

The prismatic link has a course of 200 mm. The electro valve is powered by a 24 V DC voltage, and receives analog excitation signal ranging from 0 to 5 V DC, aiming the valve spool reel positioning and thus control the flow of compressed air. The robot when receiving a voltage between 0 V and 2.6 V in prismatic link, it translates in the forward direction. If the incoming voltage is 2.63 V, the translational link remains motionless and receiving between 2.65 V and 5 V, it moves in the return direction.

The study developed by (Régis, 2013) on the rotational link of the robot manipulator under review, served as a guide to select the linear function given by Eq. (1), which relates the value of the joint angle of rotation with the tension in both directions.

$$d_{degree} = 68{,}774 \times V_{RP} - 88.459 \quad (1)$$

Where d_{degree} is the displacement in degrees of the mobile potentiometric cursor e V_{RP} is the voltage in volts measured in the mobile cursor of the rotational potentiometric transducer.

The prismatic link has a range of 200 mm. The electropneumatic valve is powered by a 24V DC voltage and receives analogue excitation signal ranging from 0 to 5 V DC, aiming the valve's spool reel positioning and thus control the flow of compressed air. The robot upon receiving a voltage between 0 V and 2.6 V in the prismatic link, it translates in the forward direction. If the incoming voltage is 2.63 V, the translational link remains motionless and receiving between 2.65 V to 5 V, it moves to return direction.

The study developed by (Régis, 2013) on the prismatic link of the robot manipulator under review, served as a guide to select the linear function given by Eq. (2), which relates the value of the value of linear position potentiometer rule with the tension in both directions.

$$d_{mm} = -42.553 \times V_{PR} + 208.5 \tag{2}$$

Where d_{mm} is the displacement in millimeters at the mobile cursor of the potentiometric rule and V_{PR} is the voltage measured in volts in the mobile cursor potentiometric linear transducer.

3. SYSTEM IDENTIFICATION

System models are obtained using physical laws (white-box model) or using input and output system data (black-box model). The identification of the black box type is used in the mathematical modeling of the manipulator under review, considering its subsequent use in the design and implementation of adaptive controllers. The least squares estimator handles input/output data of a system in iterative and non-iterative forms using non-recursive and recursive algorithms. In this modeling, the algorithm of the recursive least square (RLS) is used in real time. For identification, it is considered a pre-defined structure for the robot (Riul, *et al*, 2010). The manipulator is composed of a rotating link (electro-mechanical) and a prismatic (electro-pneumatic), then the movements are considered independent, then the identification is performed independently for each link. Thus each link of the physical system has an SISO frame (one input and one output) and a disturbance.

The complexity of a mathematical model depends on your purpose and complexity of the system being modeled, however, in the act of choice it is always good to be considered the principle of parsimony and so, opting for simpler models as possible. For these reasons in this paper it will be used the ARX model, which is described by Eq. (1), as follows (Carvalho, 2009).

$$y(t) = \varphi^T(t)\theta(t) + e(t) \tag{3}$$

$$\varphi^T(t) = [-y(t-1) \;\; \dots \;\; -y(k-n_a) \;\; u(k-d) \;\; u(k-d-1) \;\; u(k-d-n_b)] \tag{4}$$

$$\theta^T(t) = [a_1 \;\; a_2 \;\dots a_{n_a} \; b_0 \;\; b_1 \dots \; b_{n_b}] \tag{5}$$

Where $y(t)$ is the system output; $u(t)$ is the system input; $\varphi(t)$ is the vector measures; $\theta(t)$ is the parameters vector of the system; $e(t)$ is the modeling error; a_{n_a} are the system poles; b_{n_b} are the system zeros; n_a is number of system poles; n_b is the number of zeros system; d is the number of system delays.

The RLS is obtained from minimizing a cost dependent function of the forecast error and the estimated answers $\hat{y}_r$ and $\hat{y}_p$ and the forecasting errors ε_r and ε_p are obtained by the following equations.

$$\hat{y}_r = \hat{\theta}_r {\varphi^T}_r \; ; \quad \hat{y}_p = \hat{\theta}_p {\varphi^T}_p \tag{6}$$

$$\varepsilon_r = y_r(t) - \hat{y}_r(t) \; ; \;\; \varepsilon_p = y_p(t) - \hat{y}_p(t) \tag{7}$$

Where $\hat{\theta}$ is the estimated parameters in real time and is given by Eq. (8).

$$\hat{\theta}(t) = \hat{\theta}(t-1) + P(t)\varphi(t)\varepsilon(t) \tag{8}$$

Where $P(t)$ is the covariance matrix given by Eq. (9), that it is the variability of the estimated parameters.

$$P(t) = [\varphi^T(t)\varphi(t)]^{-1} \tag{9}$$

As seen in (Aguirre, 2000), if the order is used for the model is much smaller than the actual order of the real system, the model does not possess the structural complexity required to reproduce the dynamics of the system. On the other hand, if the model order is much greater than necessary, the parameter estimation is likely to be ill-conditioned, leading to cancellation of poles and zeros in the transfer function of the system.

The performance indicators are used to validate the system model structure, which can be calculated by the following equations:

$$SEQ = \sum_{k=1}^{N}[y(k) - \hat{y}(k)]^2 \tag{10}$$

$$R^2 = 1 - \frac{\sum_{k=1}^{N}[y(k)-\hat{y}(k)]^2}{\sum_{k=1}^{N}[y(k)-\bar{y}]^2} \tag{11}$$

$$AIC = N \ln\left[\frac{1}{N}\sum_{k=1}^{N}[y(k) - \hat{y}(k)]^2\right] + 2p_n \quad (12)$$

Where *SEQ* is the sum of squared error; R^2 is the multiple correlation coefficient; *AIC* is the Akaike information. In these equations, N means the number of samples; n is the number of parameters; $\bar{y}$ is the average of N samples on the simulation.

According to the Eq. (10), (11) and (12) on the robot manipulator under review, served as a guide for determining the model order, this analysis proved that the model that best represents the system was the 2nd order with a zero and the transport delay is equivalent to 1.

Following this reference, the values obtained in this study by calculating the corresponding performance indices to the rotational link to a 2º order system were *SEQ* = 3.42649, R^2 = 0.992927 and *AIC* = -4927 and to the translation link the values were *SEQ* = 43.2631, R^2 = 0.976227 and *AIC* = -2675.24. Analyzing the value of the multiple correlation criterion (R^2) for both links can be observed which is a satisfactory value as it is within the corresponding range between 0.9 and 1 (Coelho and Coelho, 2004).

To determine the sample time (T_a), based on the established time of the response to step input applied to both links manipulator robot and Eq. (13), it determined that T_a is 15ms.

$$\frac{t_{95\%}}{15} \leq T_a \leq \frac{t_{95\%}}{5} \quad (13)$$

After performing the identification on the system, it was determined the system parameters. The parameters of the rotational link are $a_1 = -0{,}7$, $a_2 = 0{,}01$, $b_0 = 0{,}3$ e $b_1 = 0{,}3$. The parameters of the prismatic link are $a_1 = -1{,}9$, $a_2 = 0{,}9$, $b_0 = 0{,}05$ e $b_1 = 0{,}02$. The Eq. (14) and (15) represent the discrete transfer function of the rotational (G_r) and prismatic (G_p) link:

$$G_r(z) = \frac{0.3z^{-1} + 0.03z^{-2}}{1 - 0.7z^{-1} + 0.02z^{-2}} \quad (14)$$

$$G_p(z) = \frac{-0.05z^{-1} + 0.02z^{-2}}{1 - 1.9z^{-1} + 0.9z^{-2}} \quad (15)$$

4. SELF-TUNING GENERALIZED PREDICTIVE CONTROL

The GPC controller consists in calculating a sequence of future control actions from the minimization of a cost multi-step function, set within a horizon of prediction. In this cost function it considers the error between the predicted output of the system and a sequence of future known references on a horizon, and the weighting control effort. The GPC control algorithm can be specified in two parts: At first calculates a great predictor for calculating the expected output, as a result of future controls; at the second is a control law which minimizes the cost function (Clarke et al. 1987).

For the calculation of the predictor, the process model is represented by CARIMA (Controlled Auto-Regressive Integrated Moving Average and), which is a model with $A(z^{-1})$, $B(z^{-1})$, $C(z^{-1})$, $\varepsilon(t)$ and Δ, as illustrated in Eq. (16).

$$A(z^{-1})y(t) = B(z^{-1})z^{-d}u(t-1) + \frac{C(z^{-1})\varepsilon(t)}{\Delta} \quad (16)$$

Where:

$$A(z^{-1}) = 1 + a_1 z^{-1} + \ \ldots \ + a_{na} z^{-na} \quad (17)$$

$$B(z^{-1}) = b_0 + b_1 z^{-1} + \ \ldots \ + b_{nb} z^{-nb} \quad (18)$$

$$C(z^{-1}) = 1 + c_1 z^{-1} + \ \ldots \ + c_{nc} z^{-nc} \quad (19)$$

The terms $A(z^{-1})$ $B(z^{-1})$ and $C(z^{-1})$ are polynomials which represent discrete, poles, zeros and disorders, respectively; na, nb and nc represent the number of poles, zeros and delays resulting from disturbances respectively; Δ is the difference operator, which is $\Delta = 1 - z^{-1}$; d is the discrete delay transport of system; z^{-1} is the delay operator, which is: $y(t)z^{-1} = y(t-1)$ and d is the discrete delay transport.

In this paper, for simplicity $C(z^{-1})$ is considered as 1.

The cost function of multiple steps, used to find the control law of the GPC algorithm is represented by Eq. (20).

$$J(u,t) = \sum_{j=N_1}^{N_2}[\hat{y}(t+j) - w(t+j)]^2 + \lambda(j)\sum_{j=1}^{N_u}[\Delta u(t+j-1)]^2 \quad (20)$$

Where N_1 and N_2 are the minimum and maximum forecast cost horizons, respectively, and Nu is the control of the cost horizon; $w(t)$ is the reference signal that the system output must follow and $\lambda(j)$ is a positive constant which weights the relative importance between the two terms (control and tracking error).

To simplify the development of calculation to determinate the control law equation, it is assumed that $N_1 = 1$, $N_2 = N$ and $\lambda(j)= \lambda$. Thus Eq. (20) can be written in matrix form, represented by Eq. (21).

$$J = (G\tilde{u} + f - w)^T + (G\tilde{u} + f - w) + \lambda\tilde{u}^T\tilde{u} \tag{21}$$

Where the vector f is the free response of the control law, that is:

$$f = \begin{bmatrix} f(t+1) \\ f(t+2) \\ \vdots \\ f(t+N) \end{bmatrix} \tag{22}$$

Where $\tilde{u}, w$ and G are:

$$\tilde{u} = \begin{bmatrix} \Delta u(t) \\ \Delta u(t+1) \\ \vdots \\ \Delta u(t+N-1) \end{bmatrix} \tag{23}$$

$$w = \begin{bmatrix} w(t+1) \\ w(t+2) \\ \vdots \\ w(t+N) \end{bmatrix} \tag{24}$$

$$G = \begin{bmatrix} g_0 & 0 & \dots & 0 \\ g_1 & g_0 & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ g_{N-1} & g_{N-2} & & g_0 \end{bmatrix} \tag{25}$$

The control signal is sent to the process is the first element of the vector u, which is expressed by Eq. (26)

$$\Delta u(t) = \bar{g}^T(w - f) \tag{26}$$

Where $\bar{g}^T$ is the first line of $(G^TG + \lambda I)^{-1}G^T$.

The self-tuning GPC controller was implemented on the 2DOF planar robot manipulator using: a microcomputer, the computer programs on LabVIEW® and Matlab®, and the acquisition board data.

5. RESULTS

After the performance of simulation, the graphs were plotted that show the reference and current position on the rotational and prismatic link in closed loop, where in the rotational link the starting point is -90º according to the Eq.(1) and for the prismatic link is 0mm according to the Eq.(2). The graphics is based on the sample numbers, where T_a = 15ms.

Table 1. Sequence of steps

Rotational Link			**Prismatic Link**		
Stage	**Time (s)**	**Ref. (º)**	**Stage**	**Time (s)**	**Ref. (mm)**
1	0 to 10	0	1	0 to 10	0
2	10 to 20	30	2	10 to 20	200
3	20 to 30	60	3	20 to 30	0
4	30 to 40	90	4	30 to 40	200

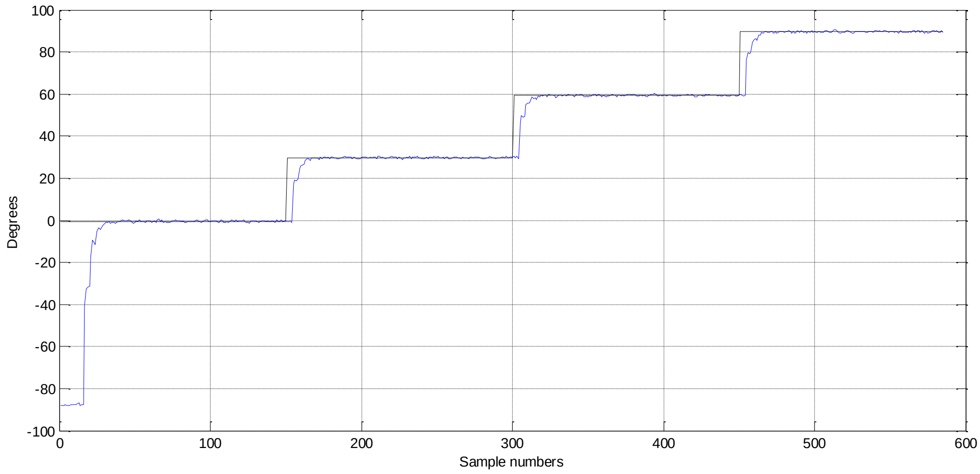

Figure 3. Reference and current position of the rotational link in closed loop

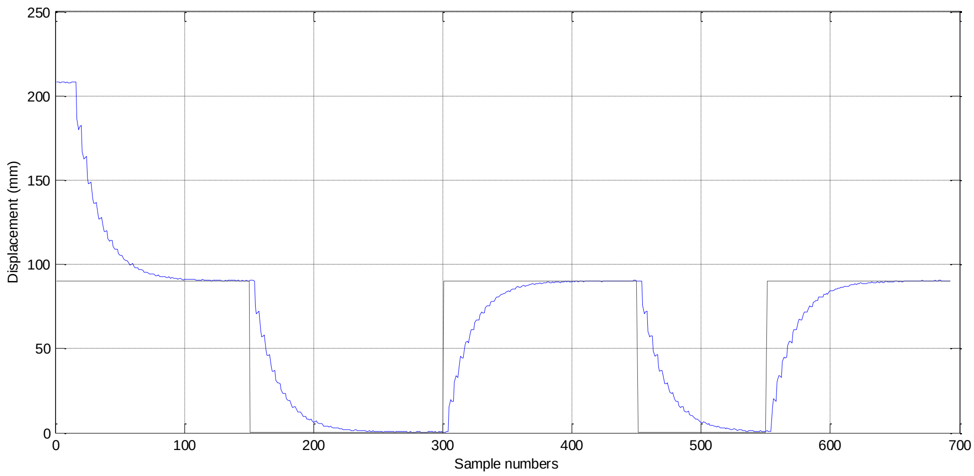

Figure 4. Reference and current position of the prismatic link in closed loop

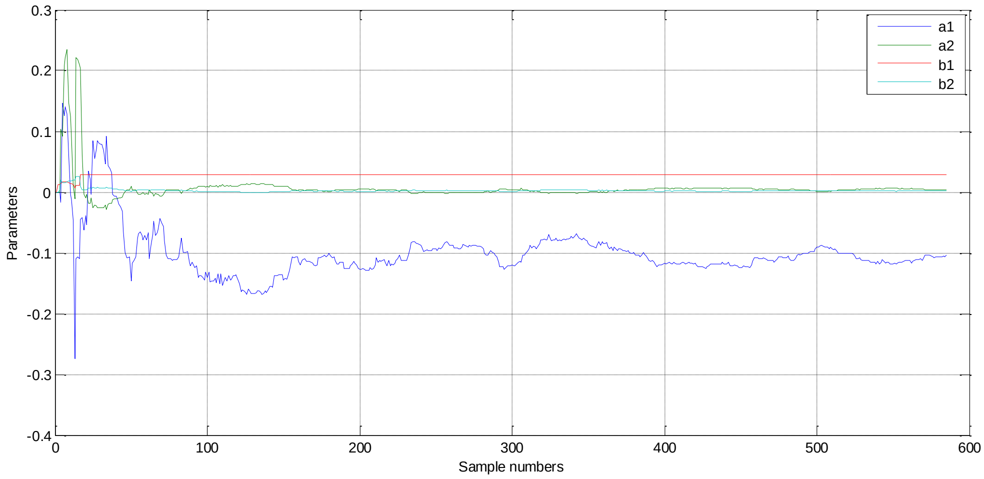

Figure 5. Evolution of the rotational link parameters

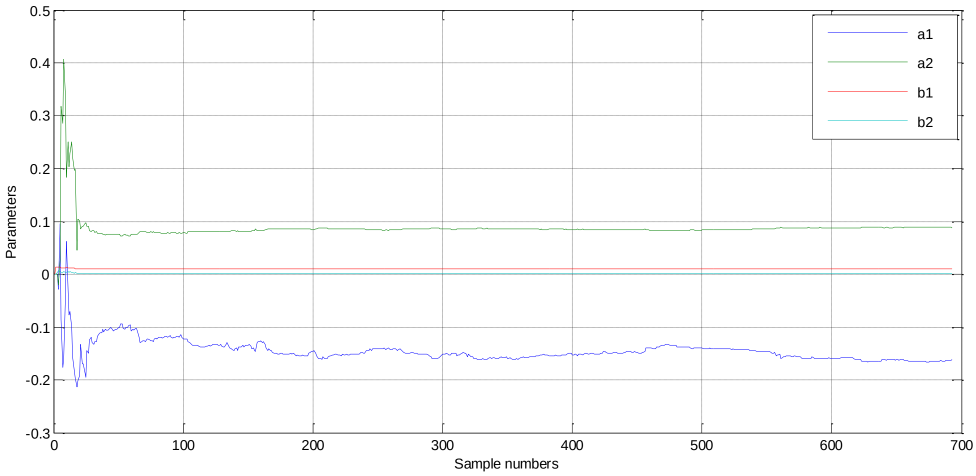

Figure 6. Evolution of the prismatic link parameters

6. CONCLUSION

This work presented the project and implementation of GPC controllers on the 2DOF planar robot manipulator, driven by an electromechanical and electropneumatic system. The simulation results obtained attained the performance specifications imposed on the system, which shows that the projected adaptive controllers were satisfactory for the follow-up of references used.

7. ACKNOWLEDGEMENTS

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