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DESIGN AND IMPLEMENTATION OF A STATE-SPACE CONTROLLER FOR AN AIR PRESSURIZATION PLANT WITH SLOW DYNAMICS AND OUTPUT DELAY

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ABSTRACT

This paper presents the design of a servo-integrator type state-space digital control structure for an air pressurization plant. The plant is characterized by slow dynamics with output delay. To evaluate the performance of the servointegrator controller, two control structures, namely, STR-PID and conventional PID are tuned and implemented. With the results obtained, a comparative analysis is performed based on metrics related to time response and control effort. At the end, it is evidenced that the Servointegrator type state space controller outperformed the other two controllers, demonstrating that it is an effective strategy that allows controlling systems with slow dynamics and dead time in the output.

Keywords: air pressurization plant, state-state controller, slow dynamics, output delay.

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1. INTRODUCTION

Traditional and advanced control techniques are designed based on a model that describes the dynamics of the process. The model can be linear or nonlinear and may be given in continuous or discrete time. The performance of the controller depends on the process model; therefore, the model must have the ability to contain the inherent characteristics of the system, especially those that determine the design conditions of the controller. As more variables are introduced in the process, the complexity of modeling and adjusting the control strategy becomes greater. Also, the delay or dead time present in processes at industrial levels is considered a critical factor for the tuning of controllers, especially those of PID type.

The behavior of the controller is negatively affected by the magnitude of the dead time. In processes with high delays, aggressive controller behavior is inevitable, generating high energy consumption when trying to bring the controlled output to the desired setpoint.

State-space control systems are presented as an alternative that makes the modeling and treatment of process delay more flexible, based on the internal representation of the system. The process model in this case corresponds to mathematical matrix structures, which facilitates the design procedure, since efficient algorithms can be implemented to execute the calculations during the tuning of the strategy, and variables can be estimated from the observed states, without the need to implement sensors for each variable [1]. The problem associated with the process dead time is solved by including a previously tuned observer with design conditions that allows a faster response relative to the actual plant response. In addition, the migration of the design from SISO (*Single Input-Single Output*, SISO) to MIMO (*Multiple Input-Multiple Output,* MIMO) systems can be done quickly, just by resizing the matrices according to the inputs and outputs of the process [2].

The controllers designed in state-space have been used in multiple processes, demonstrating that they are a strategy that presents better results compared to PID type controllers. This can be evidenced in works and research, which highlight the performance of this type of controllers. In [3], two control strategies are presented for a chemical process: PID and state feedback. The results show the simplification of the chemical reaction networks of a chemical process with delay, as a consequence of the effectiveness of the performance of a state feedback control. In [4], an observer was implemented to estimate variables and states of an anaerobic digestion process, showing in the results the efficiency of the observer from the comparison with the experimental data, demonstrating the reliability of the estimation. It is further concluded that the designed observer is potentially useful for the bioprocess control strategy. A PID controller and a state space controller oriented to dynamic systems such as level, temperature and pressure are presented in [5]. A PLC is used to control and monitor the processes. Plant data are acquired and the systems are identified to obtain the mathematical models. Comparative results between the two controllers indicate 100% performance for the state-space controller and 98% for the PID controller. In [6], a detection system that generates an alarm when an abnormal state appears in an aircraft control system is used. A servo-integrator type controller is designed, obtaining the plant model by means of excitation at the input with step-type signals of random magnitudes. Radial-based classifiers are used, which are trained and validated for the detection of anomalous behaviors that may occur in aircraft stability. Both the classifier and controller demonstrated good performance in the aircraft flight tests. The contribution of model-based controllers for systems with delay is presented in [7]. The delay or dead time is described as a challenging feature for control engineering. The dead time present in industrial processes causes unwanted and oscillatory behaviors, affecting both the controlled output and the control action. The contribution includes controlin state-space as a strategy that presents good performance for systems with dead time.

This paper presents the results of the implementation of an integrating servo controller by state feedback and the comparison with the performance of a conventional PID controller and an STR controller, tuned for an air pressurization plant with high delay. The rest of the paper is organized as follows: Section 2 describes the proposed methodology. Section 3 presents the tests and results with the proposed controllers; finally, Section 4 presents the conclusions derived from the work.

2. METHODOLOGY

In this section the design procedure of the controllers is presented, starting from the continuous model of the system and its representation in the discrete time state space, to the obtaining of the control law and the implementation of each strategy on the air pressurization plant.

2.1 Air Pressurization Plant

As previously mentioned, the plant used for the implementation of the controllers is characterized by high dead time and slow dynamics. The plant consists of an air pressurization prototype that allows measuring the pressure in a storage tank. The prototype has electronic systems and measurement and instrumentation systems for its regulation, data acquisition, control, conditioning and monitoring of the process [8].

To obtain the plant model, a system identification approach was implemented. A modeling strategy based on experimental data of the plant was used [9]. Open-loop system information was obtained by exciting the system with step-type inputs of different magnitudes. The response information of the plant i.e., the final pressure in the storage tank, was stored in a text file. The time vector and the vector of the inputs applied to the plant were also stored.

The system data were used to estimate the parameters of the selected structure: System of First Order with Delay (SFOD). Then, the linear regression method was implemented, obtaining as a result the SFOD model of the air pressurization plant. The model obtained is as indicated by equation (1).

$$Gp(s) = \frac{1.0572e^{-2.778s}}{84.55s+1} \tag{1}$$

2.2 Plant Discretization

To discretize the model in continuous time, the closed-loop Transfer Function (TF) Equation (2) is found and the equivalent time constant of the system is obtained. Subsequently, the sampling period (T) is selected using the equivalent Tao criterion τ_{eq}.

$$Gp(s)_{LC} = \frac{Gp(s)}{1+Gp(s)} \tag{2}$$

The interval for the selection of T, is obtained by implementing equation equation (3):

$$0.2(Teq + \theta) \leq Tm \leq 0.6(Teq + \Theta) \tag{3}$$

$$T = 17.5s \tag{4}$$

Discretizing the continuous model yields the discrete-time FT:

$$HG_p z = \frac{0.1689z+0.02871}{z^2-0.8131z} \tag{5}$$

2.3 Design Conditions

The design conditions are those specifications that the controller must meet. Some conditions are given by time response characteristics, for example: Settling Time t_{ss}, Maximum Over Impulse Mp, Damping Factor ξ, and Natural Frequency ω_n. In order to establish the design parameters, knowledge of the time behavior of the system must be available. The above can be obtained from off-line simulation with the plant model. The simulated responses allow defining the working range and the subsequent assignment of the design conditions, taking into account the dynamic characteristics of the plant [10].

2.4 Servointegrator Type State-Space Controller

The state feedback control techniques seek to obtain a control law using negative feedback of the states for subsequent regulation. This is implemented by means of the assignment of desired poles in closed loop, i.e., poles that will establish the design conditions for the controller [11]. To improve the performance of the system, an additional integrator is used, which also allows to properly stabilize the controller and improve the accuracy [12]. Figure-1 shows the complete block diagram of a servo integrator type control system with state feedback.

During controller tuning, two design specifications were chosen: $\xi = 0.9$ and $t_{ss} = 300s$. Thenthe desired poles were found and the desired equation $Q_d(z)$ was defined.

The magnitude of $|z|$ was found with equation (6) and the angle with equation (7).

$$|z| = e^{-\xi W_n T} = 0.792 \tag{6}$$

$$\Theta = 57.3 W_n T\sqrt{1-\xi^2} = 6.46° \tag{7}$$

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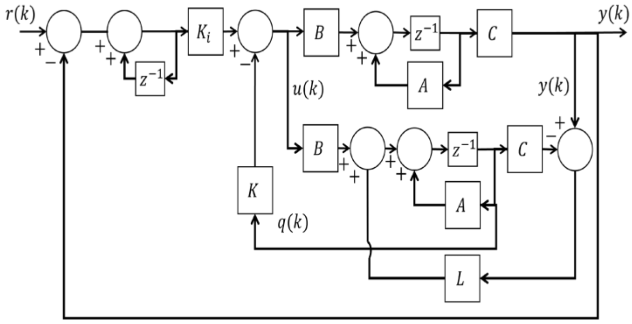

Figure-1. Servointegrator block diagram.

To obtain $Qd(z)$ equation (8) was implemented:

$$Q_d(z) = z_{1,2} = |z| * [cos\theta \pm jsen\theta] \quad (8)$$

The $Q_d(z)$ is:

$$Q_d(z) = z_{1,2} = 0.7869 \pm 0.0891j \quad (9)$$

The state space representation of the system uses the matrix structures equation (10) and equation (11).

$$x(k+1) = Ax(k) + Bu(k) \quad (10)$$

$$y(k) = Cx(k) + Du(k) \quad (11)$$

$$A = \begin{bmatrix} 0.8311 & 0 \\ 1 & 0 \end{bmatrix} \quad (12)$$

Where:
$x(k)$: State vector
$y(k)$: Output Vector
$\mu(k)$: Input Vector
A: Status matrix
B: Input matrix
C: Output matrix
D: Direct transmission matrix.

The state space representation of the air pressurization plant in the canonical controllable form (CCF) is shown in equations (13) and (14).

$$\begin{bmatrix} x1(k+1) \\ x2(k+1) \end{bmatrix} = \begin{bmatrix} 0.8311 & 0 \\ 1 & 0 \end{bmatrix} \begin{bmatrix} x1(k) \\ x2(k) \end{bmatrix} + \begin{bmatrix} 1 \\ 0 \end{bmatrix} u(k) \quad (13)$$

$$y(k) = [0.1689 \; 0.02871] \begin{bmatrix} x1(k) \\ x2(k) \end{bmatrix} \quad (14)$$

Equation (15) was used to calculate the matrices corresponding to the integrator (K_i) and the feedback matrix (K_1).

$$[K_1 \; \vdots \; K_i] = \left[\widehat{K} \; + [0 \; \vdots \; Im\,]\right] \left(\frac{A - I_n}{CA} \frac{B}{CB}\right)^{-1} \quad (15)$$

Where:

$$\widehat{K} = [0\;0\;\cdots\;1][\hat{B}\;\;\hat{A}B\;\;\hat{A}^2\hat{B}\;\cdots\;\hat{A}^{\,n-1}\hat{B}]^{-1}\phi(\hat{A}\,) \quad (16)$$

$$\phi(\hat{A}) = \hat{A}^{\,n} + \alpha_1\hat{A}^{\,n-1} + \alpha_2\hat{A}^{\,n-2} + \cdots . \alpha_n I \quad (17)$$

The results obtained from matrices K_i and K_1 are shown in equations (18) and (19):

$$[K_1 \; \vdots \; K_i] = [0.2117 \; -0.2745 \;\; 0.27029\,] \quad (18)$$

$$[K_1] = [\,0.2117 \; -0.2745]; \; [K_i] = [0.27029] \quad (19)$$

$\alpha_1, \alpha_2, .., \alpha_n$ corresponds to the coefficients of the desired characteristic equation, represented in equation (17). Matrices $\hat{A}$ and $\hat{B}$ are obtained from equations (20) and (21).

$$\hat{A} = \begin{bmatrix} A & B \\ 0 & 0 \end{bmatrix} \quad (20)$$

$$\hat{B} = \begin{bmatrix} 0 \\ I_m \end{bmatrix} \quad (21)$$

The observer's matrix L is obtained from equation (22).

$$L = \varphi(A)[C\;CA\;CA^2\;\vdots\;CA^{n-1}]^{-1}[\,0\;00\;\vdots\;1\,] \quad (22)$$

$$L = [-1.51757\;0.617079] \quad (23)$$

Where $\varphi(A)$ refers to the polynomial generated from the design conditions for the observer.

2.5 STR Controller

In general, a dynamic system can be expressed as a discrete-time transfer function of the form:

$$HG_p(z) = \frac{B(z^{-1})}{A(z^{-1})} z^{-d} \quad (24)$$

Where:

$$B(z^{-1}) = b_1z^{-1} + b_2z^{-2} + \cdots b_mz^{-m} \quad (25)$$

$$A(z^{-1}) = 1 + a_1z^{-1} + a_2z^{-2} + \cdots b_mz^{-m} \quad (26)$$

For the system shown in equation (24), a controller of the following form can be set up:

$$D(z) = \frac{U(z)}{E(z)} = \frac{Q(z^{-1})}{P(z^{-1})} \quad (27)$$

Where:

$$Q(z^{-1}) = q_0 + q_1z^{-1} + q_2z^{-2} + \cdots q_vz^{-v} \quad (28)$$

$$P(z^{-1}) = 1 + p_1z^{-1} + p_2z^{-2} + \cdots p_uz^{-u} \quad (29)$$

The controller transfer function depends on the control law $u(k)$and the control error $e(k)$. The objective is to find the parameters p_i, q_i, and the degrees v, u of the polynomials, so that the system meets the conditions established during the controller design.

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The desired characteristic equation for the closed-loop system is:

$$Q(z) = 1 + HGp(z)D(z) \tag{30}$$

That is:

$$\Delta(z^{-1}) = 1 + \alpha_1 z^{-1} + \alpha_2 z^{-2} + \cdots \alpha_l z^{-l} \tag{31}$$

Where:

$$l = (m + u, m + d + v) \tag{32}$$

According to the desired characteristic equation (30), the system will generate l simultaneous equations that when solved will determine the controller coefficients. However, to guarantee $e_{ee} = 0$, an integrator must be integrated, which in turn increases in $l + 1$ equations. The controller coefficients are obtained by solving equation (31) by implementing equation (32) [13-15].

$$\begin{bmatrix} p_1 \\ p_2 \\ \vdots \\ p_{m+d} \\ q_1 \\ q_2 \\ \vdots \\ q_m \end{bmatrix} = \begin{bmatrix} 1 & 0 & \dots & 0 & 0 & 0 & \dots & 0 \\ a_1 & 1 & \dots & 0 & 0 & 0 & \dots & 0 \\ a_2 & a_1 & \dots & 0 & b_1 & 0 & \vdots & 0 \\ \vdots & \vdots & \vdots & 0 & b_2 & b_1 & \vdots & 0 \\ a_m & a_{m-1} & \vdots & 0 & \vdots & \vdots & \vdots & b_1 \\ 0 & a_m & \vdots & 0 & b_m & \vdots & \vdots & \vdots \\ \vdots & \vdots & \vdots & a_m & 0 & b_m & \dots & b_m \\ 1 & 1 & \dots & 1 & 0 & 0 & 0 & 0 \end{bmatrix} [\vartheta] \tag{32}$$

$$\vartheta = \begin{bmatrix} \alpha_1 - a_1 \\ \alpha_2 - a_2 \\ \vdots \\ \alpha_{m-} a_m \\ \alpha_{m+1} \\ \vdots \\ \alpha_{2m+d} \\ -1 \end{bmatrix} \tag{33}$$

The FT of the STR controller for the pressure plant is:

$$D(z) = \frac{1.21918z^2 - 0.9488z}{z^2 - 0.9664z - 0.0335} \tag{34}$$

2.6. PID Controller

The FT of a conventional discrete-time controller is:

$$D(z) = \frac{M(z)}{E(z)} = \frac{q_0 z^2 + q_1 z + q_2}{z(z-1)} \tag{35}$$

The characteristic equation of the controller is calculated by equation (36).

$$Q(z) = 1 + Hgp(z)D(z) \tag{36}$$

Equating the characteristic equation $Q(z)$ with the desired equation $Qd(z)$ equation (37), the controller parameters (q_0, q_1, q_2) are obtained.

$$Q(z) = Qd(z) \tag{37}$$

The equation $Qd(z)$ is the result of the desired pole assignment. The FT of the PID controller for the pressure plant is:

$$D(z) = \frac{1.1049z^2 - 0.7947z + 0.00934}{z(z-1)} \tag{38}$$

3. TESTS AND RESULTS

The different responses of the implemented controllers and the numerical results of the performance metrics used to evaluate the controllers are presented below.

The controllers are implemented by obtaining the difference equation of the conventional STR-PID and PID controller equation (39).

$$q(k) = q_0 e(k) + q_1 e(k-1) + \cdots + q_n e(k-n) \tag{39}$$

$$p(k) = p_1 m(k-1) + \cdots + p_r m(k-r) \tag{40}$$

$$m(k) = q(k) + p(k). \tag{41}$$

For the Servointegrator type controller with state feedback, the control law was programmed from equation (42) as indicated below, where $x(k)$are the states of the observer.

$$m(k) = -kx(k) + k_i\big(e(k) - e(k-1)\big) \tag{42}$$

The three controllers Servointegrator, STR-PID and Conventional PID were implemented under the same conditions and at the same operating point.

Figure-2 shows the response of the Servointegrator controller implemented on the pressure plant. It is observed that the control law follows a path free of oscillation, stabilizing at a constant value of 40%. As a consequence of the above, there is no over-peak in the controlled output. It can be verified that the control action evolves with smooth movements protecting the final control element.

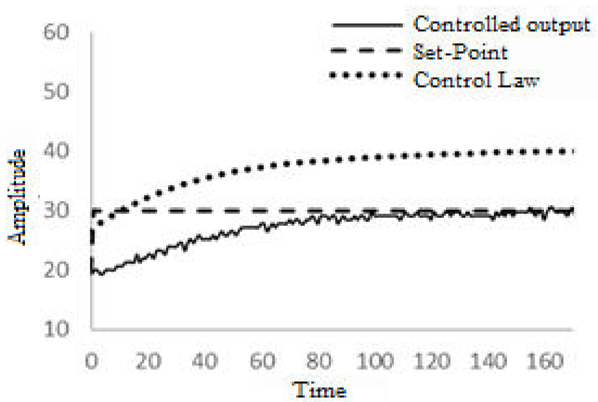

Figure-2. Servointegrator type controller.

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Figure-3 shows the response of the conventional PID controller by pole assignment; and Figure-4 shows the response of the STR-PID controller. Both figures correspond to the graphical responses obtained as a result of the implementation of the two control strategies on the pressure plant. It can be verified that in both responses there is a high consumption of the control law, causing a peak that exceeds 50% of the maximum capacity of the manipulated variable. The control law in both controllers is located after 20s in a sustained oscillation with an amplitude equivalent to 40%. Likewise, the controlled output presents overshoot in both systems as a consequence of the delay and the slow dynamics of the plant.

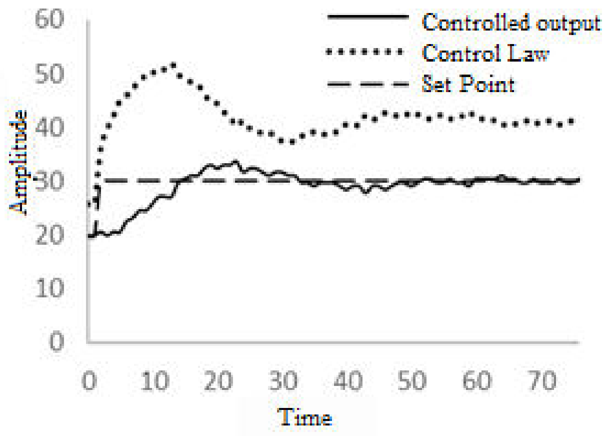

Figure-3. PID controller by pole assignment.

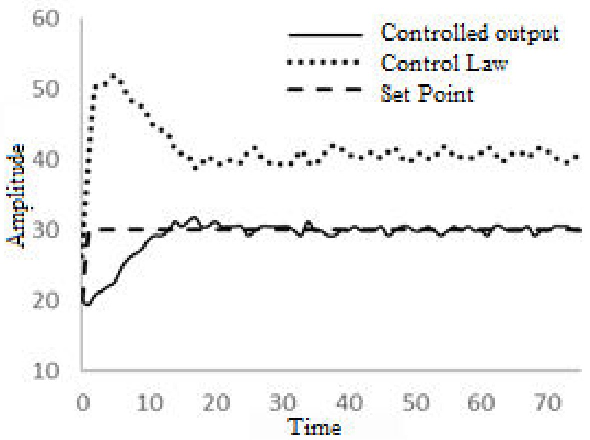

Figure-4. STR Controller.

Metrics related to temporal response equations (43) and (44), and a metric to evaluate control effort equation (45) were used to evaluate the controllers.

Maximum Overshoot:

$$M_p = \frac{y_{max} - y_{ee}}{y_{ee}} * 100\% \quad (43)$$

Steady state error:

$$e_{ee} = Set\ Point - y_{ee} \quad (44)$$

Control effort:

$$TV = \sum_{k=1}^{\infty} m(k+1) - m(k) \quad (45)$$

Table-1 shows the numerical results of the evaluated metrics. It is evident that the Servointegrator controller outperforms the conventional PID and STR-PID controllers in the metrics M_p, e_{ee}, and TV. Regarding the settling time, the Servointegrator controller does not outperform the other two controllers, since the evolution of the control law presents non-critical and oscillation-free movements, protecting the final control element. The state-space controller also met the design specifications, exceeding the established requirements, while generating a control action with lower energy consumption compared to the other controllers.

Table-1. Performance metrics.

Performance Metrics	Controllers		
	Servo	PID	STR-PID
M_p	0	12.0373	6
e_{ee}	0.00152	0.0912	0.0039
TV	13.627	14.6673	14.645
t_{ss}	80	50	30

4. CONCLUSIONS

Three types of controllers were implemented in this paper for an air pressurization plant characterized by slow dynamics with delay. From the results obtained, it was verified that of the three control structures tuned and implemented, namely: Servointegrator by state feedback, STR-PID and conventional PID; the Servointegrator type state-space controller outperformed the other two controllers, demonstrating that it is an effective strategy to control systems with slow dynamics and dead time at the output.

The results of the implementation showed that the Servointegrator type state-space controller generated a control action characterized by smooth movements, free of oscillation, allowing reducing the energy load and the critical evolution of the control law, which translates into the conservation of the useful life of the final control element.

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