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On-line identification and control of pneumatic servo drives via a mixed-reality environment  
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On-line identification and control of pneumatic servo drives via a mixed-reality environment

This paper presents a method to identify and control electro-pneumatic servo drives in a real-time environment. Acquiring the system's transfer function accurately can be difficult for nonlinear systems. This causes a great difficulty in servo-pneumatic system modeling and control. In order to avoid the complexity associated with nonlinear system modeling, a mixed-reality environment (MRE) is employed to identify the transfer function of the system using a recursive least squares (RLS) algorithm based on the auto-regressive moving-average (ARMA) model. On-line system identification can be conducted effectively and efficiently using the proposed method. The advantages of the proposed method include high accuracy in the identified system, low cost, and time reduction in tuning the controller parameters. Furthermore, the proposed method allows for on-line system control using different control schemes. The results obtained...
from the on-line experimental measured data are used to determine a discrete transfer function of the system. The best performance results are obtained using a fourth-order model with one-step prediction.

31 Keywords separated by ' - '
On-line identification - Auto-regressive moving-average - Pneumatic servo drive
- Mixed-reality environment

32 Foot note information
On-line identification and control of pneumatic servo drives via a mixed-reality environment

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Abstract This paper presents a method to identify and control electro-pneumatic servo drives in a real-time environment. Acquiring the system’s transfer function accurately can be difficult for nonlinear systems. This causes a great difficulty in servo-pneumatic system modeling and control. In order to avoid the complexity associated with nonlinear system modeling, a mixed-reality environment (MRE) is employed to identify the transfer function of the system using a recursive least squares (RLS) algorithm based on the auto-regressive moving-average (ARMA) model. On-line system identification can be conducted effectively and efficiently using the proposed method. The advantages of the proposed method include high accuracy in the identified system, low cost, and time reduction in tuning the controller parameters. Furthermore, the proposed method allows for on-line system control using different control schemes. The results obtained from the on-line experimental measured data are used to determine a discrete transfer function of the system. The best performance results are obtained using a fourth-order model with one-step prediction.

Keywords On-line identification · Auto-regressive moving-average · Pneumatic servo drive · Mixed-reality environment

1 Introduction

Pneumatic servo drives play an important role in industrial mechatronic systems. This is due to their cost-effectiveness, easy maintenance, and clean operating conditions. However, pneumatic actuators are characterized by high-order time-variant dynamics, nonlinearities due to the compressibility of air, internal and external disturbances, and payload variations. In turn, it is difficult to build an accurate...
dynamic model for describing pneumatic servo-drive behavior. Therefore, in order to design controllers that are reliable and easy to understand in practice, simplified plant models are obtained by linearization around operating points [1–4].

In practical applications, one often does not have available values for the model parameters and/or part of the model structure. Therefore, one tries to obtain these parameters and/or structural elements using experimental data from the real process. Researchers developed various parameter-identification methods and applied them to many engineering systems. Carducci et al. [5] presented the identification of viscous friction coefficients for a pneumatic system model using optimization methods. Their work focused on developing a mathematical model of a pneumatic actuator driven by two on/off two-way valves based on the identified friction parameters. They reported that pneumatic systems are not only nonlinear, but also involve several tuning parameters. Daw et al. [6] employed a genetic algorithm in order to identify the dynamic friction parameters along the pneumatic cylinder. The evaluation function has been conducted using the statistical expectation of the mean squared error (MSE). Further study has been conducted by Wang et al. [7] to improve the convergence rate and the accuracy of the algorithm. Their work concentrated on measuring the friction parameters of the cylinder rather than a complete system. Ziae and Sepehr [8] discussed some practical issues concerning the identification of electro-hydraulic actuators using discrete-time linear models. They considered a discrete-time linear model and estimated its unknown parameters. Other researchers used neural networks to identify system parameters. Angerer et al. [9] used a structured recurrent neural network to identify the physically relevant parameters and nonlinear characteristics of a nonlinear two-mass system with friction and backlash. None of the above researchers identified the transfer function of a servo-pneumatic system. Rather, they concentrated in their research on identifying certain nonlinear parameters within their plant model.

In order to identify the transfer function of a plant, several researchers have employed auto-regressive moving-average (ARMA) models. ARMA models are based on difference equations that involve the system’s inputs and outputs. Söderström and Stoica [10] and Ljung [11] have worked on system-identification methods using ARMA models and recursive algorithms since the 1980s. Their work became a cornerstone in system identification. Many other researchers have employed ARMA models and recursive algorithms in their work. Yan et al. [12] used a recursive prediction error method based on an ARMA model to identify the transfer function of a CNC milling machine in order to apply combined self-tuning adaptive control and cross-coupling control to retrofit the machine with DC motors instead of stepper motors. Östring et al. [13] identified the behavior of an industrial robot in order to model its mechanical flexibilities, while Johansson et al. [14] used a state-space model to identify the robot manipulator dynamics. Tutunji et al. [15] and, later, Abdrabbo and Tutunji [16] used a recursive least squares (RLS) algorithm to identify gyroscopic system behavior and examine a hydrostatic transmission system, respectively. Their results showed that an RLS algorithm based on ARMA models provides a reasonably accurate transfer function of the systems under study.

In this work, ARMA models and RLS algorithms were utilized within a mixed-reality environment (MRE) in order to identify and control the servo-pneumatic system transfer function on-line. Transfer function identification is considered as one of the crucial issues that influence the control design of pneumatic servo systems. MATLAB/Simulink is devised to facilitate the realization of the proposed method in order to identify the system model on-line. The developed platform also provides an excellent environment to support design, simulation, and emulation of servo-pneumatic control systems.

The rest of the paper is organized as follows. Section 2 provides the nonlinear model of the pneumatic servo drive system. ARMA models and the recursive estimation algorithm is presented in Sect. 3. Section 4 introduces the concept of a mixed-reality environment (MRE). The experimental setup is provided in Sect. 5 and, finally, the obtained results are discussed in Sect. 6.

2 Nonlinear model of the pneumatic servo drive system

The system under consideration consists of an electro-pneumatic position control servo drive and a pneumatic actuator with a load as shown in Fig. 1. The cylinder (pneumatic actuator) represents a variable chamber which contains a variable mass of gas. The present model was established considering the following assumptions: the air flow media is a perfect gas, pressure and temperature within the system components are homogenous, and the process is polytropic.

2.1 Cylinder chamber model

The governing equations of the pneumatic cylinder dynamic behavior rely entirely on the study of the charging and discharging processes of air to the controlled volume in the cylinder chambers. The traditional approach on the analysis is based on linearization, which makes the analysis valid only for small perturbations about an operating point [17–19]. Therefore, a nonlinear analysis was used in this research. The following analysis refers to the double-acting
asymmetric cylinder, which can be generalized to include symmetric cylinders (by assigning the bore diameter to zero). Figure 1 illustrates diagrammatically the relationship of the cylinder’s chambers and the inlet connections. The time derivative of the chamber pressure and flow rates can be written for the inlet side (a) and the outlet side (b) as:

\[
\frac{dP_a}{dt} = \frac{kRT_s}{X_{ao}} \left[ \frac{\dot{m}_a(P_a, P_s, P_e, X_a)}{A_a} - \frac{\dot{m}_l(P_a, P_b)}{A_a} - \frac{P_a}{RT_s} X \right]
\]

\[
\frac{dP_b}{dt} = \frac{kRT_s}{X_{bo}} \left[ \frac{\dot{m}_b(P_b, P_s, P_e, X_b)}{A_b} - \frac{\dot{m}_l(P_a, P_b)}{A_b} - \frac{P_b}{RT_s} X \right]
\]

where:

\[
X_{ao} = L_o + X
\]

\[
X_{bo} = L_o - X
\]

\[
L_o = \text{half stroke length} + \text{inactive length}
\]

\[
\dot{m}_a = C_d W X_a f(P_a, P_s, P_e)
\]

\[
\dot{m}_b = C_d W X_b f(P_b, P_s, P_e)
\]

2.2 Leakage mass flow rate

The leakage mass flow rate between the cylinder chambers is given by [1]:

\[
\dot{m}_l(P_a, P_b) = \begin{cases} 
\frac{f(P_a)}{P_a} P_a & \text{if} \ P_a \geq P_b \\
\frac{f(P_b)}{P_b} P_b & \text{if} \ P_a < P_b 
\end{cases}
\]

2.3 Payload

For the payload, the inputs are the pressures in the chambers (\(P_a\) and \(P_b\)) and the outputs are the piston’s position and velocity, as shown in Fig. 1. Hence, the load equation is given by the following expression:

\[
m \ddot{X} = P_a A_a - P_b A_b - \mu_d \dot{X} - F_r(X)
\]

where \(\mu_d\) is the dynamic friction coefficient and \(F_r(X)\) is the position-dependent resistance force. According to Eqs. 1–4, the following states are defined:

\[
X_1 = X
\]

\[
X_2 = V
\]

\[
X_3 = P_a
\]

\[
X_4 = P_b
\]
If the valve displacements are given by $U_1=X_a$ and $U_2=X_b$, then the system nonlinear model in the state equations form can be written as:

$$\dot{X}_1 = X_2$$

$$\dot{X}_2 = \frac{1}{m} [A_bX_3 - A_bX_4 - \mu_aX_2 - F_1(X_1)]$$

$$\dot{X}_3 = \frac{kRT_s}{L_0 + X} \left[ -f\left(\frac{X_4}{X_3}\right) \frac{X_3}{A_a} - \frac{X_2X_3}{RT_s} \right] + \frac{C_dW}{A_a} f(X_3, P_5, P_e)U_1$$

$$\dot{X}_4 = \frac{kRT_s}{L_0 + X} \left[ f\left(\frac{X_4}{X_3}\right) \frac{X_4}{A_b} + \frac{X_2X_4}{RT_s} \right] + \frac{C_dW}{A_b} f(X_4, P_5, P_e)U_2$$

Obviously, it is not easy to accurately derive and simulate the mathematical model of a nonlinear system. Furthermore, it is extremely difficult to acquire the system parameters, such as component dimensions, dynamic friction parameters, and internal leakage coefficients, accurately once the servo system is assembled. This causes a great difficulty in system modeling and control. Therefore, many researchers adopted system identification methods in order to approximate the desired system model using input/output measurements [8]. The basic concept of the proposed method is to deal with the physical system as a “black box,” where the input and output variables can be measured in a series of experiments on the system. The following section will explain the ARMA model-identification algorithm which was employed in this research.

3 ARMA models and recursive estimation algorithms

System identification is the field of modeling dynamic systems from measured data using mathematical algorithms. These algorithms use a “black box” model and assume no prior knowledge of the system physics [10].

Discrete-time signals are resulted from A/D sampling and are represented as $y(nT_s)=y(n)$. Here, $T_s$ is the sampling time and $n$ is an integer value that represents the sample number. The model structure used to identify the system dynamics for a single-input-single-output is given by:

$$\hat{y}(n) = g(u(n) \cdots u(n-p), y(n-1) \cdots y(n-q), a_1, \ldots, a_q, b_0, \ldots, b_p)$$

Equation 9 shows that the estimated output sample $\hat{y}(n)$ is a function of the present input $u(n)$, past inputs $u(n-p)$, past outputs $y(n-q)$, and parameters $a_j$, $b_i$.

For linear models, the function $g$ becomes a linear multiplier and, therefore, the output can be represented as an ARMA model [20]:

$$\hat{y}(n) = \sum_{j=1}^{q} a_j y(n-j) + \sum_{i=0}^{p} b_i u(n-i)$$

The goal is to find a linear system model that gives an output $\hat{y}$ equal to the real output $y$. The least square error between the actual and the modeled output is given by:

$$\text{error} = \frac{1}{2} \sum_{n=1}^{N} (\hat{y}(n) - y(n))^2$$

Input-output patterns $(u, y)$ are available. They are used in Eq. 10 to calculate $\hat{y}$. The parameters $a_j$ and $b_i$ are updated to minimize the least square error, as shown in Fig. 2.

In vector format, the following vectors are defined:

$$\Phi^T(n) = [y(n-1) \cdots y(n-q) u(n) \cdots u(n-p)]$$

$$\theta^T = [a_1 \cdots a_q b_0 \cdots b_p]$$

RLS, in vector format, gives the following equations [10]:

$$\theta = \theta - Qe$$

$$e = \Phi^T \theta - y$$

$$Q = \rho \Phi$$

where $P$ is a positive definite matrix initialized to be $cl$ ($I$ is the identity matrix, $100 < c < 10,000$) and $\lambda$ is the forgetting factor $(0.95 < \lambda < 0.99)$. The equations in Eq. 12 are used in a
A recursive algorithm, where the parameter vector $\theta$ is updated at every iteration until convergence.

Once the parameters are identified, the Z-transform of the ARMA ($p$, $q$) model is calculated to yield the estimated transfer function of the model, which is given by:

$$
Z\left\{y(n) - \sum_{j=1}^{q} a_j y(n - j)\right\} = Z\left\{\sum_{i=0}^{p} b_i u(n - i)\right\}
\Rightarrow H(z) = \frac{Y(z)}{U(z)} = \frac{b_0 + b_1 z^{-1} + \ldots + b_p z^{-p}}{1 - a_1 z^{-1} - \ldots - a_q z^{-q}}
$$

The disadvantage of off-line system identification is the need to acquire a sufficient set of experimental test data of the system, which may require a long time and large efforts. Furthermore, this approach cannot be adopted as a general analysis or configuration for modular servo-pneumatic systems, since the model is created for a particular actuator with certain dimensions. Therefore, a new data collection and training procedure should be conducted if any modification on the system is applied. This was the main motivation to develop a new method in order to identify the system on-line. MRE was employed in order to facilitate system identification and control on-line control. On-line identification saves time in data collection and improves the model accuracy and reliability. Moreover, any change in the system structure and/or components will be reflected on the system model without the need to data recollection.

4 The concept of a mixed-reality environment

Generally, mechatronic systems comprise of a controller, actuators, and sensors. The controller generates an output...
according to the feedback signal from the sensors and sends it to the actuator, which performs a certain task. According to the above situation, some of the hardware components, such as the controller, can be substituted by its model and simulated in real time. The simulated component(s) can be run in conjunction with real components under the same environment. This environment can be regarded as an MRE. Figure 3 shows the concept of the proposed environment.

The MRE is an environment whereby virtual components can be applied on real systems’ components. From the control perspective, working with an MRE should include control system synthesis off-line (or under a simulation environment) and then apply the simulated model on the real system under the MRE. Off-line simulation will normally take place before moving onto the real system, where the system should be tested and the controller should be tuned or optimized. Then, the optimized virtual controller will be applied on the real system.

This environment should allow the system to be controlled with different control schemes by simply replacing the “controller” component according to the application requirements. Furthermore, the MRE gives the capability to monitor the system’s behavior by observing the output signals, such as speed and position signals. These signals can be utilized to identify the real system using one of the system-identification methods. In the context of this research work, the ARMA model was employed for on-line system identification using the MRE. The following sections give an overview of the experimental setup of the system.

Fig. 5 MRE Simulink block

![MRE Simulink block](image)

Fig. 6 Variation of the on-line actual output, third-order predicted model with one-step prediction, and the error verses time

![Variation of the on-line actual output, third-order predicted model with one-step prediction, and the error verses time](image)
5 Experimental setup

Figures 1 and 4 show the schematic and a photograph, respectively, of the experimental setup used to validate the proposed method. The main feature of the test rig is to perform integrated components of mechanical, electronics, and computer interface structure, with high computational capacity and good software programmability. It is also designed to resemble the basic pneumatic circuit of various applications. The pneumatic unit consists of a pneumatic power supply, which includes a compressor with an air conditioning unit, lubricating unit, and manifold.

The servo-pneumatic valve was an 1/8-inch port and had an operating voltage from zero to 10 V, while the pneumatic...
actuator had a piston diameter of 27 mm, rod diameter of 8 mm, and stroke length of 100 mm. A rotary potentiometer has a resistance range from 2 to 12 kΩ, with a voltage source of 10 V, and is fixed on the cylinder, which is used for measuring the position of the piston and providing the position feedback. All signals were sent to a computer via a National Instruments (NI) DAQ card 1036E through an A/D converter terminal. The DAQ card had 16 analog inputs, two analog outputs, a sampling rate of 200 kS/s, and an input voltage range of ±10 V. The final signals were used to activate an analog input block in MATLAB’s real-time windows target (rtwt).

The input signal of the valve was the controlled voltage from the analog output block of MATLAB (rtwt) to the D/A converter of the DAQ card and, finally, to the servo valve. The change of input voltage from zero to 5 V produces the change of air flow through the valve to control the motion of the piston of pneumatic actuator.

### 6 Results and discussion

In order to examine the plant characteristics and obtain its model, a group of experiments were performed on the test rig outlined in the previous section. First, on-line identification using the ARMA model was obtained using the impulse response of the real system. Figure 5 shows the Simulink block diagram of on-line system identification that was interfaced to the real system through the DAQ card. The input signal was applied to the servo drive via an analog output block.

<table>
<thead>
<tr>
<th>Transfer function order</th>
<th>Signal</th>
<th>Statistical criteria</th>
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<tbody>
<tr>
<td></td>
<td></td>
<td>Min.</td>
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<tr>
<td>Third order</td>
<td>Actual output</td>
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<tr>
<td></td>
<td>Predicted model output</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Error</td>
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<tr>
<td>Fourth order</td>
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<tr>
<td></td>
<td>Predicted model output</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Error</td>
<td>-0.2052</td>
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<tr>
<td>Fifth order</td>
<td>Actual output</td>
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<tr>
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<tr>
<td></td>
<td>Error</td>
<td>-0.1818</td>
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Table 1 Comparison of the statistical error analysis of different orders with one-step prediction

![Fig. 9](image_url) Variation of the on-line actual output, fourth-order predicted model with five-step prediction, and the error versus time.
analog output block (DAQ output). The response of the pneumatic actuator (piston displacement) was measured and sent back to the computer through the analog input block (DAQ input).

To find the proper model structure, different prediction strategies were performed with a 6-bar supply pressure, 2-bar back pressure (load), and 1-ms sampling time.

6.1 Effect of prediction orders

Based on the mathematical model presented in Sect. 2 and the state equations presented in Eqs. 5–8, the servo-pneumatic system under study has four state variables, namely, load position, load velocity, and pressures in both chambers. Therefore, it was predicted that it can be best modeled by a fourth-order ARMA model. Consequently, a set of experiments using third, fourth, and fifth orders were conducted to show the effect of the identification orders with a one-step prediction strategy. Figure 6 shows the on-line actual output and third-order predicted model with one-step prediction. The square error was 7.09e−5 cm, with a standard deviation of 0.008468 cm. Referring to the ARMA model detailed in Sect. 3, the identified system parameters vector ($\theta$) was $[1.3857 - 0.073178 - 0.320960.0082979 - 0.0154160.020473]^{T}$, and, therefore, the resulting transfer function is:

$$G_p = \frac{0.0082979 - 0.015416z^{-1} + 0.020473z^{-2}}{1 - 1.3857z^{-1} + 0.073178z^{-2} + 0.32096z^{-3}}$$  \quad (14)$$

Figure 7 represents the on-line actual output and the fourth-order predicted model with one-step prediction. The square error was 3.22e−5 cm with a standard deviation of 0.00571 cm and $\theta = [1.9827 - 1.2989 0.43504 - 0.12436 0.0070699 - 0.017738 0.019649 0.00027783]^{T}$. The corresponding transfer function is depicted as:

$$G_p = \frac{0.0070699 - 0.017738z^{-1} + 0.019649z^{-2} + 0.00027783z^{-3}}{1 - 1.9827z^{-3} + 1.2989z^{-2} - 0.43504z^{-3} + 0.12436z^{-4}}$$  \quad (15)$$
Figure 8 shows the results of the on-line actual output and the fifth-order model with the same conditions. The square error was $3.397 \times 10^{-5}$ cm with a standard deviation of 0.005861 cm. The identified corresponding transfer function was:

$$G_p = \frac{0.0075351 - 0.017093z^{-1} + 0.013851z^{-2} + 0.012393z^{-3} - 0.0075649z^{-4}}{1 - 1.9622z^{-1} + 1.2423z^{-2} - 0.2243z^{-3} - 0.22505z^{-4} + 0.17458z^{-5}}$$  \hspace{1cm} (16)$$

Table 1 shows a comparison of the statistical analysis of the ARMA predicted output with different orders and one-step prediction. As expected, the fourth-order model resulted in the minimum square error and, therefore, was adopted as the system model for the controller design. It is worth noting that, since the ARMA model converges to a local minimum, the identified transfer functions in Eqs. 14–16 are not unique.

6.2 Effect of step predictions

To explain the effect of step size prediction, a number of experiments were performed using the fourth-order model and different step size predictions. Figures 7, 9, and 10) show the on-line actual output and predicted model outputs with different prediction step sizes (one step, five steps, and ten steps, respectively). It can be observed that the best
result was the one-step prediction. This is because, in pneumatic systems, which are highly nonlinear systems, one-step prediction succeeded in tracking the changes in the system behavior, while five- and ten-step predictions introduced delay in the samples, which prevented the model from following the transient system response accurately.

6.3 Implementation of a PID control scheme

A desired speed profile was prepared to be used as a reference input signal for both simulated and real systems. The software block of a proportional-integral-derivative (PID) servo controller was designed to control the position and speed of the pneumatic actuator. The challenge in PID controller design is to tune the values of the proportional gain $K_p$, integral gain $K_i$, and derivative gain $K_d$. Tuning work is usually performed manually by trying out different tuning parameter combinations on-line until satisfactory or, at least, acceptable results are achieved. This method is laborious, time-consuming, unsafe, and does not always give the best possible solution. The effects of varying the PID controller parameters are shown Table 2 [21].

This was the motivation to tune the controller parameters under a simulation environment (off-line tuning) using an established tuning technique, such as the Ziegler-Nicholas method.
method, to avoid the drawbacks of a manual tuning method. The practical steps used to tune the virtual PID controller are:

Step 1: The tuning was started by applying a small value to the proportional gain ($K_p$) and then increasing $K_p$ until the system oscillated. Fifteen percent (15%) of the total value of $K_p$ was decreased.

Step 2: Once the proportional gain ($K_p$) was set, the integral gain ($K_i$) was increased by a small value until the minimum error was achieved. Twenty-five percent (25%) of the total values of $K_i$ and $K_p$ was decreased.

Step 3: After increasing the integral gain $K_i$, $K_p$ was increased until the system oscillated again to enhance the stability of the system. Then, 15% of the total value of $K_p$ was decreased.

Step 4: Steps 1 to 3 were repeated, adjusting each gain value carefully to achieve better system performance.

7 Conclusions

In this research, a method to identify and control electro-pneumatic servo drives in a real-time environment was proposed and implemented. In order to avoid the great difficulty associated with servo-pneumatic system modeling and control, a mixed-reality environment (MRE) was employed to identify the system using the recursive least squares (RLS) algorithm based on the auto-regressive moving-average (ARMA) model. On-line system identification was performed effectively and efficiently using the proposed method. The advantages of the proposed method include high accuracy in the identified system, low cost, and reduction in the tuning time required of the controller parameters.

The results showed a reasonably good match between the simulated and real system behaviors. This implies that the accuracy of the system model obtained through on-line identification is high and that the developed MRE is appropriate for different virtual control scheme applications on real systems. Furthermore, the proposed method used to control the pneumatic system showed good performance in tracking the demand positions of multiple profiles with different widths.
References


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