OPTIMAL CONTROL OF PNEUMATIC MANIPULATORS FOR CONSTRUCTION APPLICATION

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Abstract: problems of pneumatic manipulators positioning in angle trajectories and in long linear trajectories for construction applications are discussed. Optimal positioning of a pneumatic manipulator of angle trajectories with minimum control energy consumption is solved. An implementation of the control system is presented. A control algorithm for a pneumatic manipulator of long linear trajectories based on a two-phase movement of the end-effector is investigated. Experimental results are shown.

Keywords: automation in construction, pneumatic manipulators, positional accuracy, angle trajectory, linear trajectory, optimal control, experimental optimisation.

1. INTRODUCTION

Advantages of pneumatic manipulators for construction applications are high speed and force capabilities and smaller sizes, compared to electric driven manipulators. Pneumatic manipulators have a high payload-to-weight ratio that is especially important for their usage with wall climbing robots to fulfill different construction operations [1,2]. An essential application limitation of industrial pneumatic manipulator is the difficulty to change a given program for the end-effector trajectories during motion and a limited number of discrete positions.

A hierarchical feedback control for pneumatic manipulators was proposed in [3]. However, it is difficult to compensate payload and supply pressure variation in such way. A pneumatic manipulator control based on recursive identification is described in [4]. A stability of this controlled motion is not guaranteed. It was concluded in [5] that the third-order control provides a practical choice for effective control of industrial pneumatic manipulators. Sometimes, in practice, it is impossible to measure a full phase vector because of design parameters of the manipulator [6]. A problem of minimising of sensors number for optimal control is important in this case [7].

The task of flexible positioning system design applying a sensor block in a feedback loop is discussed for a widespread type of industrial robots with an angle manipulator drive of two double-acting pneumatic power cylinders.

Some building inspection operations require working in long linear trajectories with good position accuracy. This may be carried out by means of long cylinders with necessary technological equipment connected to an end-effector. The main difficulties in this case are to combine velocity during the motion with high accuracy at the desired positioning.

Those problems of the pneumatic manipulators positioning for construction applications are considered.

2. POSITIONING OF A PNEUMATIC MANIPULATOR IN ANGLE TRAJECTORIES

2.1 Description of the system

A diagram of the manipulator drive is presented in Figure 1.

The manipulator 1 of a length L and a gripper with an object 2 of mass m, is actuated by double-acting pneumatic power cylinders 3 through a gear 4 with a lever l. The considered drive system with pressure variation in pneumatic power cylinders [8], is described by a non-linear differential equations of the third order

$$\begin{aligned} \ddot{\varphi} &= p\frac{2F_n l}{mL^2} - f(\dot{\varphi}) \\ \dot{p} &= -\frac{2PF_n l}{V}\dot{\varphi} + \frac{RT}{V}g \end{aligned}; \qquad (1)$$

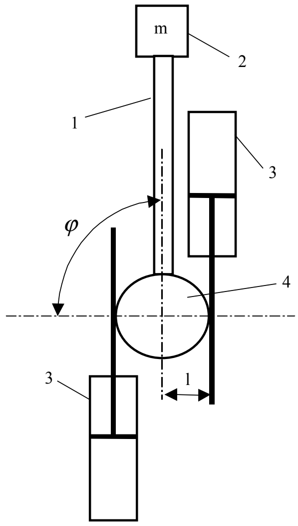

Figure. 1. Diagram of the manipulator drive

where φ - angular position of the manipulator gripper, p - current pressure difference in pneumatic cylinder volumes, F_n – cross-section of the cylinder piston, l - lever of acting force, R - gas constant, T - absolute temperature of working gas, V – full volume of the pneumatic cylinder, P - pressure in the volumes of the cylinder in an equilibrium position of a cylinder piston, g - molar gas consumption in pneumatic cylinder volumes, $f(\dot{\varphi})$ - summand taking into account a friction force of the drive system. The force of inertia for rather large values of mass m considerably exceeds friction force in the drive system. In this case it is possible to transform a system (1) as follows

$$\begin{aligned} \dot{x}_1 &= a_{13}x_3 \\ \dot{x}_2 &= x_1 \\ \dot{x}_3 &= -a_{31}x_1 + u \end{aligned} \quad ; \qquad (2)$$

where

$$\begin{aligned} & x_1 = \dot{\varphi},\ x_2 = \varphi,\ x_3 = p, \\ & a_{13} = \frac{2F_n l}{mL^2},\quad a_{31} = \frac{2PF_n l}{V}, \\ & u = \frac{RT}{V} g . \end{aligned} \qquad (3)$$

Thus, phase coordinates of the system are an angular position and angular velocity of the manipulator gripper and pressure in pneumatic power cylinders. A control parameter is the gas consumption.

A problem of minimization of positioning coordinates of the system (2) and simultaneously of control energy consumptions should be solved. It is possible to solve this optimal control task by means of the following quadratic functional

$$I = \int_0^\infty \left(r_2 x_2^2 + r_3 x_3^2 + \rho u^2 \right) dt, \qquad (4)$$

where $x_2 = \varphi$, $x_3 = p$, $u = \frac{RT}{V} g$, and r_2, r_3, ρ - coefficients depending on construction task. The control of the system is carried out by means of a gas consumption valve. Information about a current system state is obtained from the sensor block.

2.2 Synthesis of the control system

For the considered stationary system, we can use the equation [9]

$$R_1 - PBR_2^{-1}B'P + AP + PA = 0, \qquad (5)$$

where the matrixes A and B are determined according to [7], and

$$R_1 = \begin{bmatrix} 0 & 0 & 0 \\ 0 & r_2 & 0 \\ 0 & 0 & r_3 \end{bmatrix}; \quad R_2 = \rho;$$

$$P = \begin{bmatrix} P_{11} & P_{12} & P_{13} \\ P_{21} & P_{22} & P_{23} \\ P_{31} & P_{32} & P_{33} \end{bmatrix}. \qquad (7)$$

An optimal control of the system (2), (4) can be written as following

$$\begin{aligned} u_o &= -R_2^{-1}B'PX = \\ &= -\rho^{-1}(P_{31}x_1 + P_{32}x_2 + P_{33}x_3) \end{aligned}, \qquad (8)$$

where the elements i = 1, 2, 3 are amplifying coefficients in the feedback loop of the control system.

The problem of the optimal control is reduced to a determination of necessary elements of the matrix P, which can be obtained from the equation (5). For such a purpose a solution algorithm of the equation (5) for stationary systems with infinite time of observation [9] can be used.

Let us introduce the following matrix

$$R = \begin{bmatrix} -A & BR_2^{-1}B' \\ R_1 & A' \end{bmatrix} \tag{9}$$

and an expression for a matrix

$$\lambda I - R, \tag{10}$$

where I - identity matrix, λ - eigenvalue of the matrix (9). A determinant of the matrix (10) is

$$det(\lambda I - R) =$$
$$= \lambda^3(\lambda^3 - \lambda\frac{r_3}{\rho} + \lambda a_{13}a_{31}) + \lambda a_{13}a_{31}(\lambda^3 + \lambda a_{13}a_{31})$$
$$+ \frac{a_{13}}{\rho}(-r_2 a_{13}).$$

Let

$$\lambda^2 = \alpha, \tag{11}$$

then, rewriting expression for $det\ (\lambda I - R)$ with using of (11) and equating it to zero, we have

$$\begin{aligned} &\alpha^3 + \alpha^2(a_{13}a_{31} - \frac{r_3}{\rho}) + \alpha^2 a_{13}a_{31} \\ &+ \alpha(a_{13}a_{31})^2 - \frac{a_{13}}{\rho} r_2 a_{13} = 0 \end{aligned}. \tag{12}$$

It is possible to solve the equation (12) using equations (3) and defining $\lambda_1, \lambda_2, \lambda_3$ that lye to the left of an imaginary axis.

We can introduce the determinant of the matrix (10) as

$$\det(\lambda I - R) = (-1)^n \Delta(\lambda)\Delta(-\lambda), \tag{13}$$

where $\Delta(\lambda)$ - scalar polynomial of power n. Thus,

$$\Delta(\lambda) = (\lambda - \lambda_1)(\lambda - \lambda_2)(\lambda - \lambda_3). \tag{14}$$

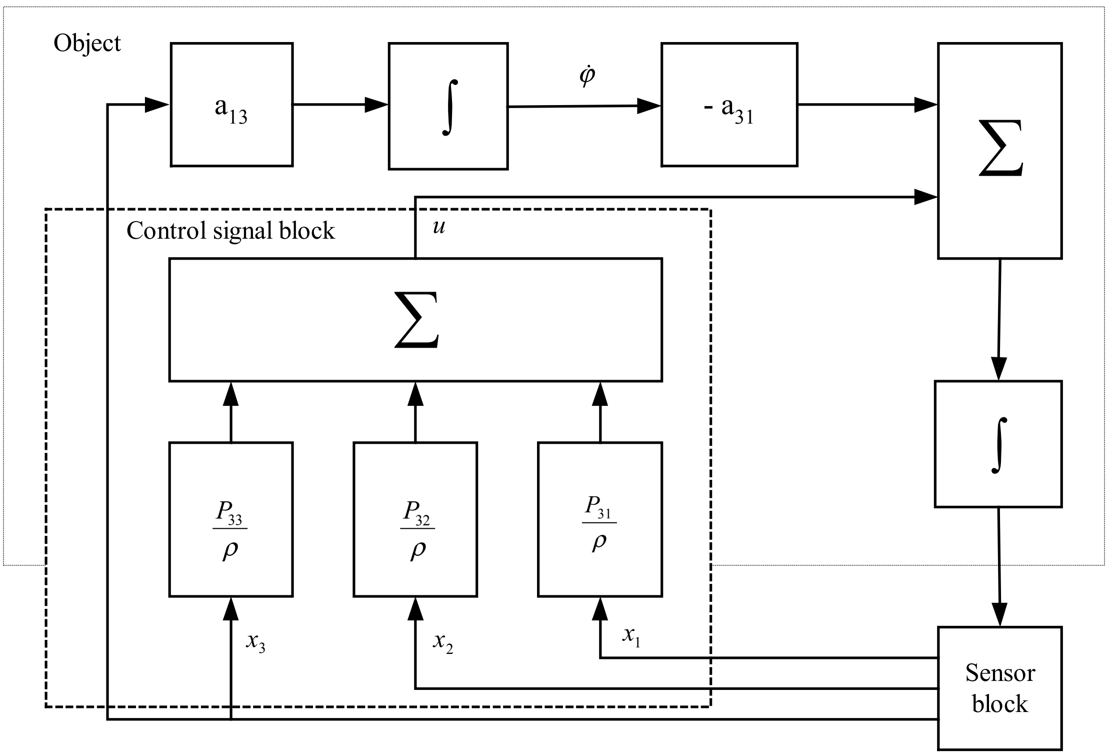

Figure 2. Implementation of the optimal control

Substituting values $\lambda_1, \lambda_2, \lambda_3$ in equation (14), we can obtain a numerical value for $\Delta(\lambda)$. Then, making a substitution λ and *R*, we form a matrix

$$\Delta(R) = \begin{bmatrix} R_1 & R_2 \\ R_3 & R_4 \end{bmatrix}. \tag{15}$$

The matrix R is defined by the equation (9) and can be presented as

$$R = \begin{bmatrix} 0 & 0 & -a_{31} & 0 & 0 & 0 \\ -1 & 0 & 0 & 0 & 0 & 0 \\ a_{31} & 0 & 0 & 0 & 0 & \rho^{-1} \\ 0 & 0 & 0 & 0 & 1 & -a_{31} \\ 0 & r_2 & 0 & 0 & 0 & 0 \\ 0 & 0 & r_3 & a_{13} & 0 & 0 \end{bmatrix}. \tag{16}$$

Now it is possible to get values R_2 and R_4 from equations (15) and (16). According to [9],

$$P = R_4 R_2^{-1}. \tag{17}$$

Necessary elements of the matrix *P* are defined from the equation (17). Using them in the equation (8), we obtain the optimal control as

$$u_o = -\rho^{-1}(P_{31}\dot{\varphi} - P_{32}\varphi - P_{33}p). \tag{18}$$

The system by the optimal control (18) is asymptotically stable. Experimental results with a manipulator of the robot "Tsiclon" [7] show that all disturbances are converged to zero in an exponential manner. Response time is about 1 second.

An implementation of the optimal control (18) with a simulation of the object (2) is shown in Figure 2.

3. POSITIONING OF A PNEUMATIC MANIPULATOR IN LONG LINEAR TRAJECTORIES

3.1 Description of the system

Some building inspection operations require working in long linear trajectories with good positional accuracy. This may be carried out by means of long cylinders with necessary technological equipment connected to an end-effector. The main difficulties in this case are to combine velocity during the motion with high accuracy at the desired positioning.

A rodless pneumatic manipulator can be applied to fulfil the described task. A diagram of the manipulator is shown in Figure 3.

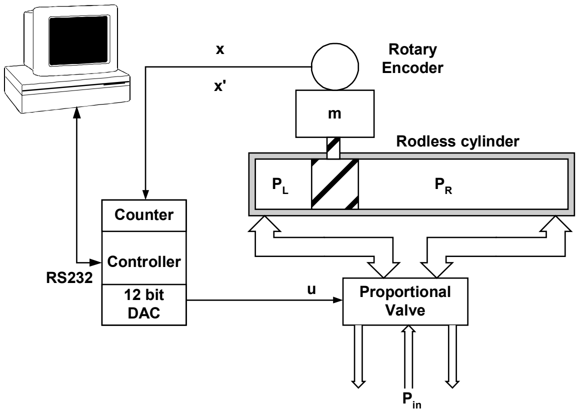

Figure 3. Diagram of the linear pneumatic manipulator

The manipulator has a rodless pneumatic cylinder with the piston connected to the tool of the mass M to be moved. The tool position is measured by an incremental optical encoder. The air flow in cylinder chambers is controlled by a current commanded proportional valve. The control algorithm is run by means of a microcontroller that interfaces to the encoder and to the valve through a 12 bit digital-to-analog converter (DAC). The system is monitored by a PC connected by a RS232 serial interface to the controller.

The general view of the system is shown in Figure 4.

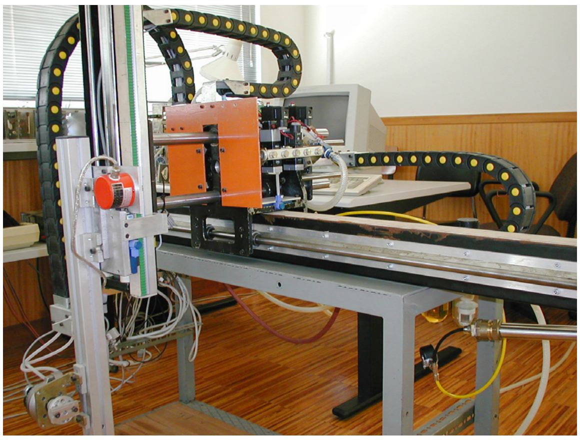

Figure 4. General view of the long linear trajectory manipulator

The system has five degrees of freedom. There are three degrees of freedom related to transporting motion (x, y, z), rotation motion of the gripper, and gripping motion. X motion is performed by a linear stage composed by an Origa P210 rodless cylinder with 1200 mm stroke and 25 mm piston diameter. The payload moved by this cylinder is 46 *kg* and the medium static friction is 3.5 *kgf*. The end-effector position is measured with 20 *μm* accuracy by a rotary incremental encoder toothed to the fixed structure. The airflow is controlled by a Martonair SQPB1898 5/3 proportional valve. The current through the valve solenoid defines five working zones: from 0 to 300 *mA* the valve is completely open in one direction (say A); from 300 to 500 *mA* the flow in direction A changes linearly; from 500 to 600 *mA* the valve is closed; from 600 to 800 *mA* the flow changes linearly in the other direction (say B); above 800 *mA* the valve is completely open in direction B. The valve electrical current is controlled with a 12 bits accuracy DAC. The working pressure is 6 *bar* and the connecting nylon tubes of 4 *mm* interior diameter. In order to deal with the solenoid hysteresis, the command current is summed with a 50 *Hz* sinusoidal current. In order to not disturb the system, the frequency of the summed signal was chosen much higher then the frequency of the system (less then 2 *Hz* depending on the command amplitude).

The dynamics of pressure P_i in the *i*-th chamber can be described by the following equation

$$\dot{P}_i = \frac{f_i}{x} S_i - k \frac{P_i}{x} \dot{x}, \qquad (19)$$

where S_i is the valve cross-sectional area, k is the ratio of specific heats, x is the piston position,

$$f_i = \frac{kT_i}{A_i} \sqrt{\frac{2R}{T_i}} P_u . Y\left(\frac{P_d}{P_u}\right), \qquad (20)$$

where T_i is absolute temperature, R is the universal gas constant, P_u and P_d are upper and lower pressures correspondingly and Y is a constant coefficient [12],

$$S_i \cong k_v u_i, \qquad (21)$$

where k_V is the valve proportional constant and u_i is the valve input signal.

The system dynamics can be modeled by the following equation

$$M\ddot{x} + B\dot{x} + L = A(P_L - P_R) \qquad (22)$$

where M represents the moving mass, B is the viscous-damping coefficient, L represents disturbances because of static and Coulomb friction, A is the piston area and P_L and P_R are the pressures in left and right chambers correspondingly.

Experimental research of the rodless pneumatic manipulator shows that friction has essential influence on a control algorithm of this system. From the other side, friction has a stochastic character sometimes.

In this case, one of the most reliable solutions to control the system is an experimental approach.

3.2 Experimental optimisation

To achieve high accuracy and high velocity at the same time, with minimum overshoot and settling time, it could be used a control algorithm based on a two-phase movement of the end-effector [10]. Figure 5 shows the valve control signal.

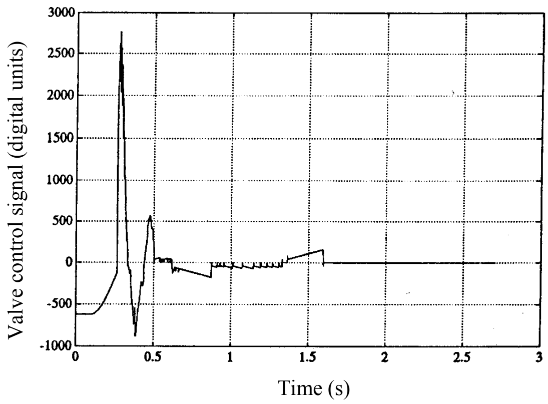

Figure 5. Command signal versus time in seconds

Figure 6 shows the output position in time for a 125 mm long trajectory experiment.

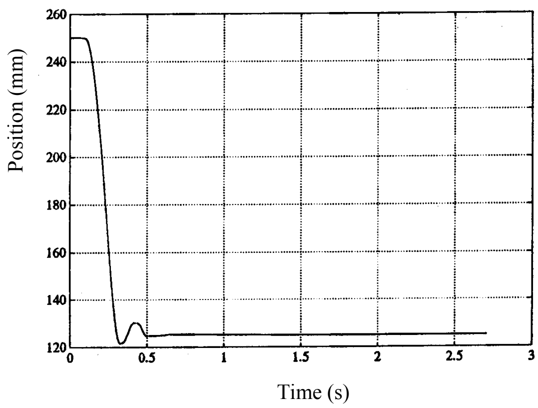

Figure 6. Position versus time in seconds

At the first phase, the motion is carried out with high velocity till the end-effector reaches 80% length of the trajectory. This phase is done with a high gain proportional controller.

The second phase is the approaching phase. It is carried out with a PI controller with small proportional gain [11].

The achieved results using experimental optimisation were satisfactory, with a maximum steady state position error of 0.3 *mm.* As can be seen from Fig. 6, the system stabilizes in less then 0.5 seconds.

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