Sliding mode controller for a 2 dof fully pneumatic parallel kinematic manipulator

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ABSTRACT

Sliding mode controller approach (SLM) was used in pick and place position control of a fully pneumatic parallel robot in this paper. The SLM approach could be used to overcome the nonlinearities associated with pneumatic systems and non-Cartesian kinematic. The paper shows the control law design procedure and includes simulation result to evaluate the performance achieved by the control algorithms in terms on positioning error. In order to prove the stability of the control law we tested it changing the payload moved by the robot end-effector.

1. INTRODUCTION

Mechanical industries are showing a growing interest to devices based on parallel kinematics, because these architectures often provide excellent performances in terms of stiffness/weight ratio if compared to traditional serial robots [8]. Another advantage of parallel architectures is that, in most cases, actuators can be placed on the truss, hence allowing the design of very light moving parts. This is a significant advantage, especially when powerful and huge motors are adopted. Indeed, the parallel kinematic arrangement of the links provides higher stiffness and lower moving masses that reduce inertia effects.

In many industrial applications, like the food and manufactory industry, very high precision positioning is not required. In these cases pneumatic actuators afford the opportunity to design a simple and low cost positioning system.

Pneumatic cylinders could be hardly used for serial robots, but they can be easily employed in a parallel device because cylinders and accessories would be simply fixed to the truss, thus achieving a limited weight for the moving parts. Moreover pneumatic cylinders may be directly coupled with a load without needing a transmission system. Unlike hydraulic actuators they are clean, reliable and they are inexpensive. Pneumatic cylinders have several advantages as high compactness, high acceleration capability, high robustness and reliability. Moreover pneumatic drive systems need low maintenance and thanks to the high standardization degree and to the ease of assembly they allow to realize modular systems.

Main limits are related to the difficulty of controlling the position and therefore the accuracy and repeatability of movements [2]: the pneumatic actuators have a non-linear behaviour due to the mechanical stick-slip friction and air compressibility that makes difficult and expensive the positioning control [11]. In fact, in the industrial fields the pneumatic actuators are mainly used in open-loop configuration. This allows fixed point positioning of the pay-load by means of mechanical end-stroke stops. Fully pneumatic systems with multi-degrees of freedom are therefore not used in industrial applications [9]. The characteristics of the parallel robots joined to the servo-pneumatic cylinders allow new solutions for industrial automation.

This paper has two main parts: in the first one we present the design and the mathematical model of a fully pneumatic 2 Dof robot. The robot is designed to carry out pick and place operations in industrial environments. This robot is a device based on parallel kinematic scheme [7] and it is built with 2 double acting rodless pneumatic cylinders placed in a planar frame. Pneumatic actuators are regulated by two 5/3 pneumatic proportional valves. The mathematical model of the pneumatic actuators dynamic and of the air flow through the inlet and outlet valves is based on elliptical approximation of non linear behaviour of pneumatic devices [1]. Friction and sticking phenomena are considered too.

The second part of the work relates the position control algorithm developed and the evaluation of its performances when applied to a multibody model of the manipulator. The control algorithm we used to control the piston position is a sliding mode control a kind of variable structure control [3]. Sliding mode control (SLM) has several benefits such as fast response and low sensitivity to disturbance and system parameter variations. SLM has been promoted as a solution to overcome the non-linearity associated with air compressibility in pneumatic positioning systems [10], [4]. One observe, the continuous form of sliding mode control (CLSM) does not require a mathematical model of the system to be controlled.

This feature makes the CSLM very useful to control complex and nonlinear systems like as that one we studied. Indeed the fully pneumatic parallel robot shows a non-Cartesian kinematic structures and a nonlinear actuation system. The paper shows the control law design procedure and it includes simulation result to evaluate the

Table 1: Nomenclature

Symbol	Description
q_1, q_2	Position of cylinder sliders
l	Link length
α	Angular link position
P_x, P_y	End-effector translating coordinates
P_x^*, P_y^*	End-effector coordinates
P_{ai}, P_{bi}	Cylinder chamber pressure
G_{ai}, G_{bi}	Mass air flow
P_0	Pressure in standard condition
ρ_0	Air density in standard condition
A	Cylinder useful section
P_v	Downstream pressure
P_m	Upstream pressure
C	Sonic conductance
β	Critical pressure ratio

performance achieved by the CSLM control algorithms in terms on positioning error. In order to prove the stability of the control law we tested it changing the payload moved by the robot end-effector. Symbols used in the exposition are described in table 1.

2. ROBOT DESCRIPTION

A 2 dof robot has been designed to carried out pick and place operations for industrial applications. Figure 1 shows the kinematic model of the developed parallel kinematic manipulator. It consists on two rigid links, each one connected to a slider at one side and to the other link on the other side through revolute joints. Sliders are driven by pneumatic rodless actuators placed in a planar frame. The linear drive is a FESTO DGPL-32-1200-PPVA-B-KF-GK-SV commercial cylinder. The pneumatic positioning system is realized by a 5/3-way proportional directional flow control valve (FESTO, model MPYE-5-1/8-HF-010-b). The mechanical characteristic of the valves and cylinder are estimated in [5]. Such a manipulator is able to reach a point in the plane xy inside the workspace. The orientation of the end effector is maintained thanks to an auxiliary link connected both to the end effector and one of the two sliders. Figure 1 shows the kinematic scheme of the manipulator under study. The end effector position (P^*) is described through its cartesian coordinates (P_x^*, P_y^*), while the displacements of the two pneumatic cylinders actuating the sliders are respectively q_1, q_2.

Kinematic analysis

The kinematic analysis of the robot can be carried out considering the system as shown in Fig.1. Since the end effector (P^*) can only translate, its velocity and acceleration are the same of the ones related to the point $P(P_x, P_y)$. The end effector position can be expressed as a function of the actuator displacement as:

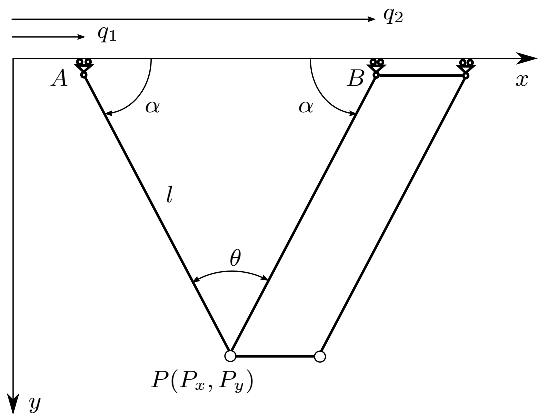

Figure 1: Kinematic robot scheme

$$\begin{cases} q_1 + le^{i\alpha} = P_x + iP_y \\ q_2 - le^{i\alpha} = P_x + iP_y \end{cases} \tag{1}$$

Projecting the first equation of (1) respectively on real and imaginary axis one gets:

$$\begin{cases} q_1 + l\cos\alpha = P_x \\ l\sin\alpha = P_y \end{cases} \tag{2}$$

and then:

$$\sin\alpha = \frac{P_y}{l}; \qquad \cos\alpha = \frac{1}{l}\sqrt{l^2 - P_y^2}$$

Equations (1) can be rewritten and finally it is possible to solve the inverse kinematic using equations (3):

$$\begin{cases} q_1 = P_x + \sqrt{l^2 - P_y^2} \\ q_2 = P_x - \sqrt{l^2 - P_y^2} \end{cases} \tag{3}$$

Deriving equations (3) with respect to time, one can obtain the values of the actuators velocities as a function of the end effector position (P_x, P_y) and velocity ($\dot{P}_x$, $\dot{P}_y$):

$$\begin{cases} \dot{q}_1 = \dot{P}_x + \dfrac{P_y\dot{P}_y}{\sqrt{l^2 - P_y^2}} \\ \dot{q}_2 = \dot{P}_x - \dfrac{P_y\dot{P}_y}{\sqrt{l^2 - P_y^2}} \end{cases} \tag{4}$$

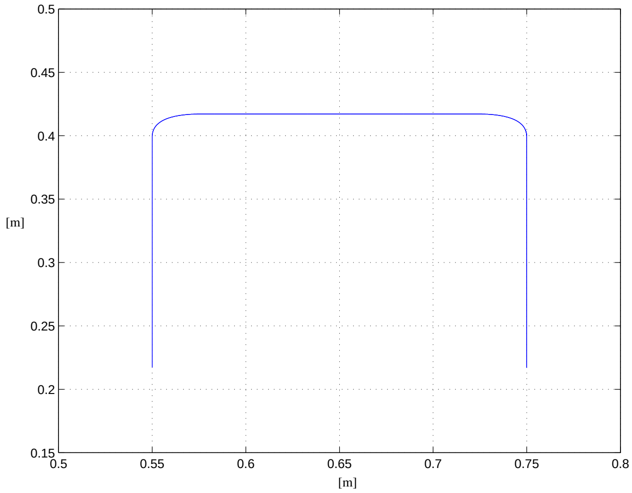

Figure 2: Trajectory in the xy plane

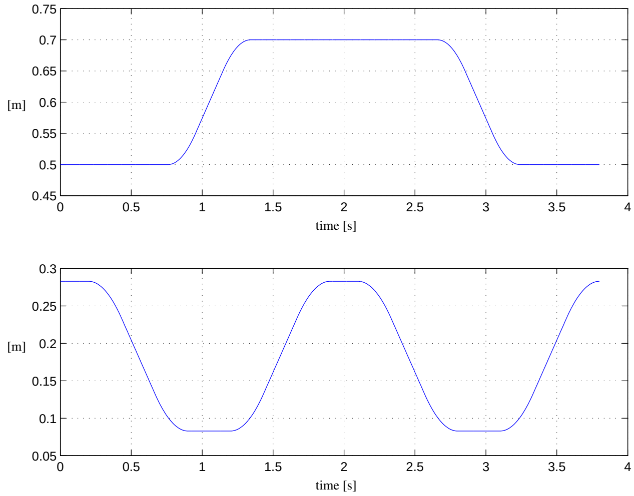

Figure 3: Motion law along the two axis x, y.

The same can be done for accelerations:

$$\begin{cases} \ddot{q}_1 = \ddot{P}_x + \dfrac{1}{\sqrt{l^2 - P_y^2}} \left[\dot{P}_y^2 + P_y \ddot{P}_y + \dfrac{\left(P_y \dot{P}_y\right)^2}{(l^2 - P_y^2)} \right] \\ \\ \ddot{q}_2 = \ddot{P}_x - \dfrac{1}{\sqrt{l^2 - P_y^2}} \left[\dot{P}_y^2 + P_y \ddot{P}_y + \dfrac{\left(P_y \dot{P}_y\right)^2}{(l^2 - P_y^2)} \right] \end{cases} \quad (5)$$

Once the inverse kinematic problem is solved, it is possible to define a trajectory to be followed in the workspace (Fig.2) and the motion law to perform the movement along each axis. Figure 3 shows the designed law of motions along x, y axes. In this case constant symmetrical acceleration profiles have been chosen for both the axes.

Using equations (3), (4), (5) it is possible to calculate how to move the two sliders. These motion laws represent the reference of the controller needed to move the two pneumatic cylinders (Fig.4).

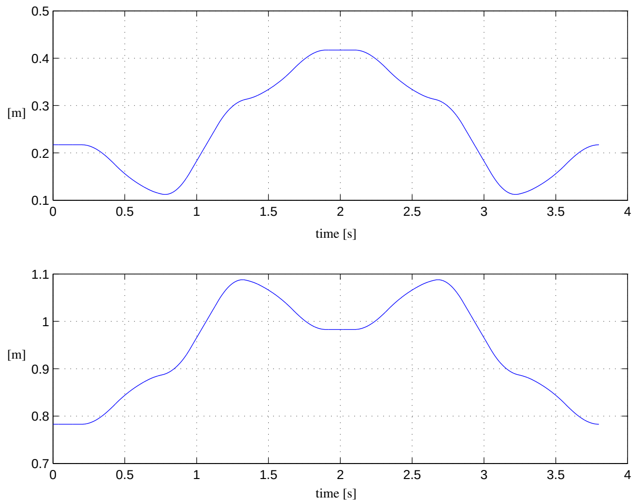

Figure 4: Motion law of each pneumatic actuator q_1, q_2.

3. DYNAMIC MODEL

The mathematical model of the system is composed by 3 main subsystems: the mechanical part describing the dynamic behavior of the manipulator, the pneumatic part concerning the dynamic of actuators and distribution circuitry and the controller that allows the end effector to reach the desired position.

Mechanical model

The mechanical model is very simple and it is constituted by two sliders whose position, velocity and acceleration can be measured. Two forces, representing the action of the two pneumatic cylinders, are applied on the sliders. Such forces are calculated by the pneumatic subsystem. Rigid links are characterized by their inertial properties and are connected to the sliders as shown in Fig. 5. End effector position, velocity and acceleration is measured and it will be used by the controller to perform the desired movement.

Pneumatics model

To complete the system study it is necessary to consider the equations of the pressure dynamics in the piston chambers and the equation of the mass air flow through the valves. With reference to equations [1], for every cylin-

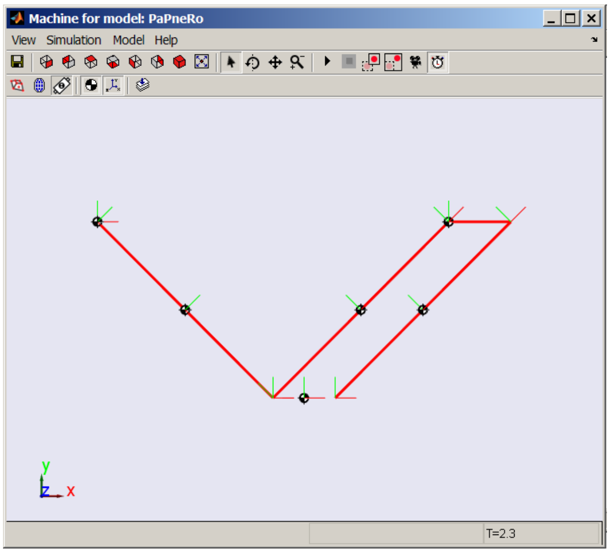

Figure 5: SimMechanics robot layout

der we have:

$$\begin{cases} \dot{P}_{ai} = \left[G_{ai} - \rho_0 \left(\dfrac{P_{ai}}{P_0} \right) A\dot{d}_i \right] \dfrac{P_0}{\rho_0 A q_i} \\ \dot{P}_{bi} = \left[G_{bi} + \rho_0 \left(\dfrac{P_{bi}}{P_0} \right) A\dot{d}_i \right] \dfrac{P_0}{\rho_0 A (c_i - q_i)} \end{cases} \tag{6}$$

where P_{ai} and P_{bi} are the pressures in the two chambers of i-th piston, G_{ai} and G_{bi} are the air flows entering in the two chambers by means of the valve, and A is the useful section of the cylinder. The air flow according to the elliptic approximation can be expressed by the following relation:

$$G = \rho_0 C P_m \Phi \left(\frac{P_v}{P_m}, \beta \right) \tag{7}$$

were the function Φ is defined as:

$$\Phi = \begin{cases} 1 & \text{for } \dfrac{P_v}{P_m} \leq \beta \\ \sqrt{1 - \left[\dfrac{\frac{P_v}{P_m} - \beta}{1 - \beta} \right]^2} & \beta < \dfrac{P_v}{P_m} \leq 1 \end{cases} \tag{8}$$

where C and β are respectively the conductance and the critical pressure ratio (these are empiricist parameters which define the behavior of valves; in order to their characterization it is possible to use the following regulation [1]) while P_m and P_v are the upstream and downstream pressure regarding to the air flow direction.

4. Continuous Sliding Mode Controller

The implemented control scheme is based on the variable structure control theory, in particular on sliding mode control. It is easy to demonstrate that servo-pneumatic system is a third-order servosystem. In fact the dynamic equation of a symmetric pneumatic cylinder can be written as:

$$M\ddot{x} + \gamma\dot{x} + f = A(P_a - P_b) \tag{9}$$

where M is the load mass, γ is a friction coefficient, x is a piston position, $P_{a,b}$ are the chamber pressures and f is an external force applied to the system. Taking differentiation on both sides we get:

$$M\dddot{x} + \gamma\ddot{x} + \dot{f} = A(\dot{P}_a - \dot{P}_b) \tag{10}$$

Substituting the derivative of chamber pressure 6 in equation 10 and equation of mass air flow 7 in equation 6, we could introduce the control input in servosystem dynamic. Indeed the conductance C, shown in equation 7, depends on valve command signal. We have shown that the servo-pneumatic system is a third-order, but the precise knowledge of term $\dot{f}$, γ is normally unavailable furthermore the approximations introduced on chamber pressure dynamics make inaccurate the mathematical description of the system. Luckily, one of the attractions of a CSLM is intended to be the ability to design a controller without the perfect system knowledge. This feature is very useful because we can design the controllers for every cylinder in a decoupled manner. The CSLM controller is based on the switching function s expressed by:

$$s = m_1 e + m_2 \dot{e} + \ddot{e} \tag{11}$$

where m_1 and m_2 are the coefficients that define the sliding surface, as the terms e, $\dot{e}$ and $\ddot{e}$ are respectively the position, velocity and acceleration errors. The control law for CSLM can be given [3] as:

$$u = K \cdot X + V \cdot \text{sign}(s) \tag{12}$$

with K and X as gain and state vectors respectively; V is the maximum supply voltage to the proportional valve. The first term ($K \cdot X$) is often ignored in the applications where the problem is not reaching the sliding surface but staying on the sliding surface. The second term, causing the function sign(s), may generate an excessive chattering in u once the sliding surface is reached. It is important to reduce chattering phenomena when one uses a 5/3 way proportional pneumatic valve. One common technique to do this is to modify the basic control law of equation 12 to include a *boundary layer* [6]:

$$u = V \cdot \text{sat}(s) \tag{13}$$

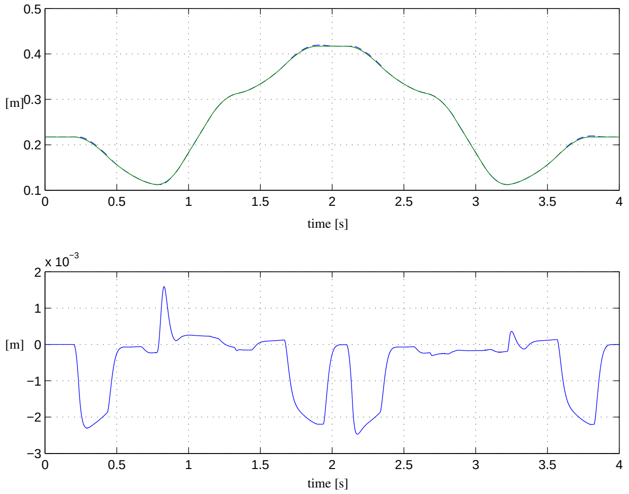

Figure 6: Comparison between the reference and the actual position q_1 (up) and the error between them (down).

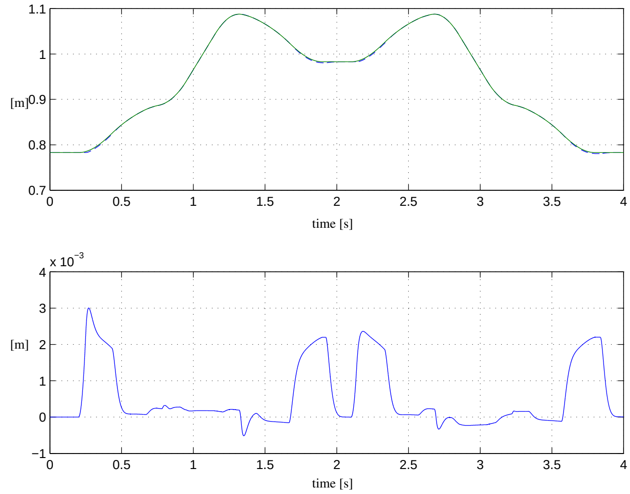

Figure 7: Comparison between the reference and the actual position q_2 (up) and the error between them (down).

where

$$\mathrm{sat}(s) = \begin{cases} \mathrm{sign}(s/\phi) & \text{when} \quad |s| > \phi \\ s/\phi & \text{when} \quad |s| \leq \phi \end{cases}$$

where ϕ is the parameter to define the boundary layer. It must be found to provide the proper balance between minimal chattering and acceptable accuracy.

5. RESULTS

The control action is tested on pick and place task shown in figures 2, 3 and 4. The payload is varied four time: 0.5 [kg], 2.5 [kg], 5.0 [kg] and 10.0 [kg] respectively. The controller parameters are tuned considering the small load and they remain the same during the different payload tests. In particular the sliding surface was defined by $m_1 = 2304$, $m_2 = 80$ moreover the boundary layer parameter was $\phi = 1.5$. The performance of the manipulator can be analyzed comparing the actual displacement of the two actuators with their reference values. Figures 6, 7 show the comparison between the reference and the actual position (up) and the error between them (down) respectively for joint coordinates q_1 and q_2 when the payload is 0.5 [kg]. The maximum position error is about 3mm, it is important to highlight that such error is limited to the motion phase, where it is not so important to exactly follow the desired trajectory. Errors in points where pick and place operations are carried out are very small.

Figure 8 shows the air pressures inside the two chambers of each cylinder while figure 9 shown the supply voltage to the two servovalve (in this case the maximum value is 5 [V]).

We can observe the smoothing effect due to boundary layer action. Figure 10 shows the effect of changing payload value on CLSM performance in terms of position error and supply voltage to the servovalve for one of sevopneumatic system in the first 1.5 [s] of the motion. The controller is robust when the mass is varied from 0.5 [kg] to 10 [kg].

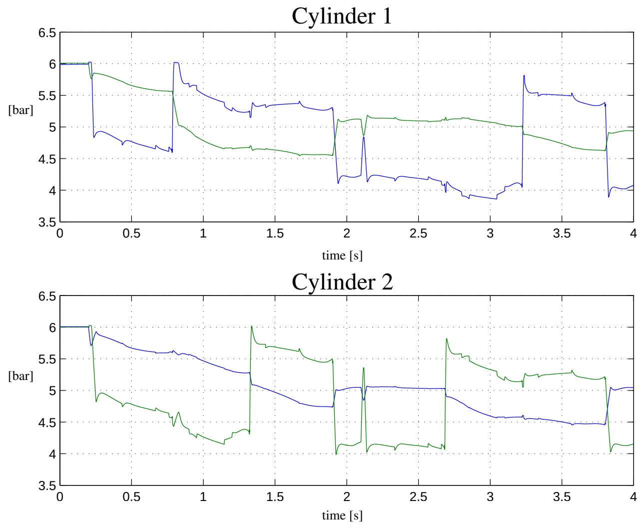

Figure 8: Air pressures inside the two chambers of each cylinder.

6. CONCLUSION

Pneumatic technology in parallel kinematics structures allows to develop new solutions to be proposed in industrial field which are characterized by ease of implementation, low cost and performance appropriate to the requirements of the industry. The CSLM controller is able to maintain

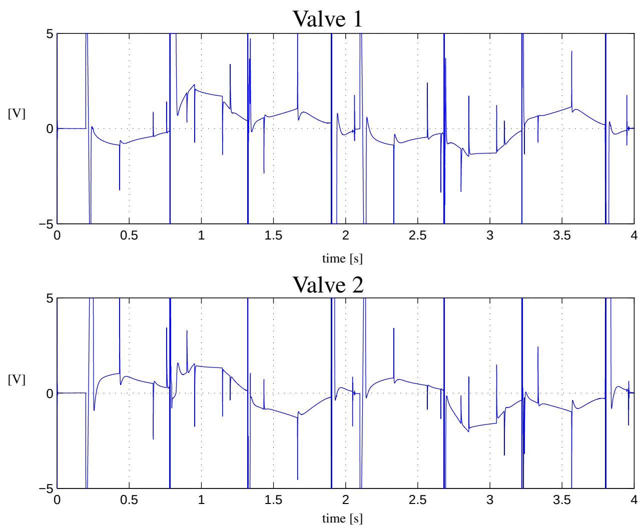

Figure 9: Supply voltage to the two servovalve.

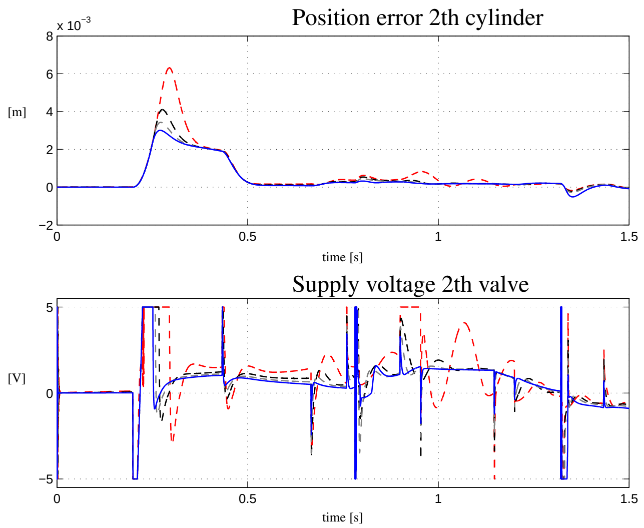

Figure 10: Effect of changing payload value on CLSM performance.

performance when the load mass is varied. This is a very good feature in a pick and place task because normally in the first part of the task, the robot ed effector moves with a full load while, in the second part, it returns empty.

Though the sliding mode control approach does not need an explicit mathematical model of the system only the knowledge of the system dynamics is required to select better sliding surface. Furthermore the control implementation is very easy and does not require an expensive hardware. The good result presented here suggest to further investigate the use of this technology (Parallel pneumatic robot - Continuous sliding mode controller) in industrial applications.

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