Robust Sliding Mode Controller Design for the Electro-Pneumatic Nonlinear Stewart System (6 DoF)

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ABSTRACT:
In this paper, the design of a controller for a nonlinear electro-pneumatic system of six degrees of freedom Stewart is discussed. Since the Stewart’s mechanism is a nonlinear system, nonlinear control methods should be used to control it and, in this paper, the sliding mode control (SMC) is used. In this method, at first a sliding surface is defined so that the dynamics of the system are restricted to it. In the next step, feedback control law is defined so that the paths outside the sliding surface to reach sliding surface in a limited time and stay on them. Thus, the closed loop system of SMC is robust against uncertainties and external disturbances. Finally, through computer simulation in the matlab software, the desired performance of the designed controller is shown.

KEYWORDS: Parallel Robot, Stewart Mechanism, Dynamic Modeling of Mechanism, Dynamics of Actuator’s System, Sliding Mode Controller.

1. INTRODUCTION
The advantages of parallel link arms depending on their type series, which are known as the Stewart platform, have recently been explained by numerous researchers around the world. The parallel mechanism first to propose by gough england’s governing board, as the system ground-testing machine was used. This plan was later developed by the doctor Stewart as a flight simulator. This phenomenon broad range of applications utility of this plan was followed in the future. Current industry initiatives developed Stewart platform for applications such as Automation, defense and security industry, transport and development tools used in the shipbuilding industry [1]. Pneumatic actuators are still widely being used in the process of automation. These Actuators the driver the equipment is light and small dimensional systems with relatively high weight load index used. On the average, the use of pneumatic actuators Compared to the hydraulic and electrical them due to the low cost of manufacturing technology in industrial applications preferred. So that the cost of making them, around 20% is, lower than the electric or hydraulic. The Simple installation and maintenance, the availability of a wide range, clean, non-flammable, and less sensitive to temperature changes the most important reasons for using these systems are compare to electrical and mechanical type [2]. Although desired characteristics of pneumatic systems, control is difficult. When these systems, as the actuators in the nonlinear systems and multivariate like Stewart mechanism is used. To control this type of system, various control methods are used. However, control schemes that the desired control in against disturbances and model uncertainties to contain is limited. In the Many of studies to conduct in this field, the dynamic model of the Stewart structural to considered, but the dynamics of system actuator is not considered. The focus of this paper is the robust control approach for control of the Stewart mechanisms that pneumatically driven incentives with taking into account the dynamics of the system drive. In the second section of this paper, In order to extract the dynamic model of the system Lagrange classic dynamics method is used. In this method, the dynamic behavior system to base on the work and the energy stored in it is expressed and promiscuity forces the intruder automatically deleted. In the third section, the pneumatic system with its components is the described and its dynamics is extracted. In the fourth section, for the control purposes, the dynamic equations are derived from both systems the equations are the integrated into
a single category. In the fifth section, the control method of the sliding mode control of system for the removal of nuisance factors such as external disturbances acting on the system and non-model dynamics and uncertainty to designed. With the simulation of the designed controller, optimal performance of the external perturbation of the system and its uncertainties is the show.

2. MODELING OF THE STEWART SYSTEM

In this section, the servomechanism electro- pneumatic of the Stewart platform dynamic model with six degrees of freedom is presented. Various approaches have been used to derive dynamic equations. In this paper, In order to extract the dynamic model of the system Lagrange classic dynamics method is used. In this method, the dynamic behavior of the system to base on the work and the energy stored in it is the expressed and promiscuity forces the intruder automatically deleted. Lagrange equation is expressed in the following form:

\[ L = T - U \]  

In equation (1), \( T \) is the kinetic energy and the \( U \) is potential energy of the system that is calculated from the following equation:

\[ T = \frac{1}{2} \text{mv}^2 + \frac{1}{2} \text{Iw}^2 \]  

\[ U = \text{mgh} \]  

\[ \frac{d}{dt} \left( \frac{\partial L}{\partial \dot{q}} \right) - \frac{\partial L}{\partial q} + \frac{\partial D\cdot E}{\partial \dot{q}} = Q \]  

In equation (4), the parameters \( q, D, E \) and \( Q \) are respectively the vector of generalized coordinates, vector of friction forces, and damper vector of generalized forces are calculated using the principle of virtual work, there. By letting equation lagrange in the equation of motion dynamical systems, the dynamic equation can be expressed in the following form:

\[ M(q)\ddot{q} + C(q, \dot{q})\dot{q} + G(q) + F_{fr}(q) = \tau \]  

In equation (5), the parameters \( M, C, G, F_r \) and \( \tau \) are respectively: the positive definite mass matrix of the order of \( 6 \times 1 \), the vector of forces and torques generated to provider of centrifugal forces and carioles acceleration of the order of \( 6 \times 1 \), the vector of the provider torques caused by the gravitational pull of the order of \( 6 \times 1 \), the vector provider torque caused by the friction forces of the order of \( 6 \times 1 \) and the vector of the generalized forces applied are of the order of \( 6 \times 1 \).

In equation (5), can to be vector of the generalized moments terms enforcement forces to the driving mechanism to be rewritten in the following form:

\[ \tau = J^TF_p \]  

In equation (6), the parameters \( J \) and \( F_p \) respectively: the jacobian matrix in the order to \( 6 \times 6 \) and the vector of the driving forces in the order to \( 6 \times 6 \) are presented. The vector of the driving forces is defined in the following form:

\[ F_p = [F_{p,1}, F_{p,2}, ..., F_{p,6}] \]  

Using inverse kinematics mechanism and equation (5), we have:

\[ M^*(q)\ddot{q} + C^*(q, \dot{q})\dot{q} + G^*(q) + F_{fr}^*(d) = F_p \]  

In equation (8), the Parameters \( d, M^*(q), C^*(q), G^*(q) \) and \( \tau \) are respectively: the length vector of the mechanism actuators, the mass positive definite matrix of order \( 6 \times 6 \), the carioles and centrifugal force vector provider of order \( 6 \times 1 \), the vector of gravitational forces of the order of \( 6 \times 1 \) and the vector provider of the friction forces in the joint of the space of in order to \( 6 \times 1 \). In equation (7), the term \( M^*(q) \) and \( C^*(q) \) and \( G^*(q) \) can to be calculated using the following equations:

\[ M^*(q) = [J(q)^T]^{-1}(M(q)J(q)^{-1}) \]  

\[ C^*(q, \dot{q}) = [J(q)^T]^{-1}[C(q, \dot{q}) - M(q)J(q, \dot{q})\cdot \dot{q}] \]  

\[ G^*(q) = [J(q)^T]^{-1}G(q) \]  

It is the mentioned that in this paper, the term friction joint space due to greater complexity, system dynamics is neglected [3].

3. ACTUATOR MODELING

In this section, we derive the dynamic model of the pneumatic system will be discussed. The system consists of several main parts, which are:

- Cylinder: using to create motion in the system.
- Servo- valve: That cylinder used to supply the power needed.
- Power supply: compressed air is contained.
- The control unit that controls the motion of the cylinder stroke is responsible.

In pneumatic systems, force necessary to produce linear motion actuators embedded in the system comes from the source of compressed air. To use compressed air, it is necessary to install a device in between the two units, to input and output cylinder stroke linear motion actuators schedule defined for the control. In fact, this device is the same servo-valve that to act in the accordance with orders issued Switching the control unit performs. Servo- valve used, Is a solenoid valve (electric) that the input voltage is applied, Switch operation input/output cylinder offers. In Figure 1, how servo-valve with is a hydraulic cylinder is the show. It should be noted that about 80% of hydraulic and pneumatic systems are similar [4].
The equations of pneumatic system can be expressed as follows:

\[
\begin{align*}
\dot{p}_p &= \frac{\gamma_1 A_p p_n}{v_n} \dot{x}_{pos} - k_v \frac{\gamma_1 R_g T_s}{v_n} V \\
\dot{p}_p &= -\frac{\gamma_1 A_p p_p}{v_p} \dot{x}_{pos} + k_v \frac{\gamma_1 R_g T_s}{v_p} V \\
\dot{x}_{pos} &= \frac{A_p p_p - A_n p_n}{M_p} - \frac{F_{fr}}{M_p} \dot{x}_{pos}
\end{align*}
\]

The pneumatic system parameters as shown in table 1 are:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Name</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_s$</td>
<td>Temperature</td>
<td>300 k</td>
</tr>
<tr>
<td>$\gamma_1$</td>
<td>Ratio of specific heat</td>
<td>1.4</td>
</tr>
<tr>
<td>$F_{fr}$</td>
<td>Friction forces</td>
<td>47 N.s/m</td>
</tr>
<tr>
<td>$R_g$</td>
<td>Universal gas constant</td>
<td>284 J/kg.k</td>
</tr>
<tr>
<td>$K_v$</td>
<td>Servo valve constant</td>
<td>0.0023 kg/s.v</td>
</tr>
<tr>
<td>$M$</td>
<td>Piston mass</td>
<td>0.2 kg</td>
</tr>
<tr>
<td>$A_p$</td>
<td>Piston area (chamber p)</td>
<td>5.72×10^{-4} m²</td>
</tr>
<tr>
<td>$A_n$</td>
<td>Piston area (chamber n)</td>
<td>4.94×10^{-4} m²</td>
</tr>
<tr>
<td>$P_p$</td>
<td>Nominal pressure in chamber p</td>
<td>2.5×10^{7} pa</td>
</tr>
<tr>
<td>$P_n$</td>
<td>Nominal pressure in chamber n</td>
<td>2.5×10^{7} pa</td>
</tr>
<tr>
<td>$V_p$</td>
<td>Nominal volume in chamber p</td>
<td>5.683×10^{-5} m³</td>
</tr>
<tr>
<td>$V_n$</td>
<td>Nominal volume in chamber n</td>
<td>5.285×10^{-5} m³</td>
</tr>
</tbody>
</table>

**Table 1. Pneumatic system parameters [4]**

4. INTEGRATION OF THE SYSTEM STATE-SPACE EQUATIONS

For control purposes, it is necessary to integrate the equations of Stewart platform and pneumatic systems written and the inputs and outputs of the system are characterized. Where the system is a multi-variable, it is best to the equations of systems to be written in state-space form. To do this, the state space equations are derived for each system individually adapted. It should be noted that for simplicity of writing equations, the asterisk (*) in the final parameters of our relationship apart. However, equation (8) in terms of the second derivative when the actuators are arranged:

\[
\ddot{d} = M^{-1}(C + F_{fr})\dot{d} - M^{-1}[G(q) - F_p]
\]

We define the variables of the system into the following form:

\[
\begin{align*}
\dot{z}_1 &= y \\
\dot{z}_2 &= A_2 \ddot{z} + B_2 \dot{u} \\
\end{align*}
\]

As a result, the equation of state of Stewart platform system comes in the form below:

\[
\begin{align*}
\dot{z}_1 &= \begin{bmatrix} 0 \\ 0 \end{bmatrix} + \begin{bmatrix} I \\ -M^{-1}(C + F_{fr}) \end{bmatrix} \begin{bmatrix} \dot{z}_1 \\ \dot{z}_2 \end{bmatrix} \\
\dot{z}_2 &= \begin{bmatrix} 0 \\ -M^{-1} \end{bmatrix} \begin{bmatrix} G(q) + F_p \end{bmatrix} \\
\end{align*}
\]

4.1. Extraction Pneumatic System State-Space Equations

If we consider the same cross-sectional area of the inner cylinder and the pressure difference between the two cylinders, $p_d$ we consider that:

\[
\begin{align*}
\{A_p = A_n = A_{pn} \\
P_{p} - P_{n} = P_{d}
\end{align*}
\]

Then, the state-space equation of the pneumatic system can be expressed in the following form:
\[
\begin{bmatrix}
\dot{p}_d \\
\dot{x}_{pos} \\
\ddot{x}_{pos}
\end{bmatrix}
= \begin{bmatrix}
0 & 0 & a-b \\
0 & 0 & I \\
A_{pn} & 0 & -F_{fr}
\end{bmatrix}
\begin{bmatrix}
p_d \\
x_{pos} \\
\dot{x}_{pos}
\end{bmatrix}
+ \begin{bmatrix}
c-d \\
0 \\
\dot{x}_{pos}
\end{bmatrix}
+ \begin{bmatrix}
0 \\
0 \\
0
\end{bmatrix}
V
\] (20)

\[y_{pos} = \left[ \begin{array}{c}
p_d \\
x_{pos} \\
\dot{x}_{pos}
\end{array} \right] D = 0
\]

That in the equation (20), we have:
\[
a = -\gamma M_p p_p
\] (21)

\[b = \gamma A_{pn} p_n
\] (22)

\[c = k_v
\] (23)

\[d = -k_v
\] (24)

Now, integrated equations of the entire system by selecting the appropriate state variables, we derive the form below. For this first, the pneumatic system state variables will change as follows:
\[
\begin{align*}
x_1 &= p_d \\
x_2 &= x_{pos} \\
x_3 &= \dot{x}_{pos} \\
x_4 &= \ddot{x}_{pos} \\
y &= x_2
\end{align*}
\] (25)

Derivative of equation (25) with respect to time we get:
\[
\begin{align*}
\dot{x}_1 &= \dot{p}_d = (a-b)x_3 + (c-d)V \\
\dot{x}_2 &= x_3 \\
\dot{x}_3 &= \frac{A_{pn}}{M_p} x_1 - \frac{F_{fr}}{M_p} x_3 \\
\dot{x}_4 &= \dot{x}_3 = \ddot{x}_{pos} \\
\end{align*}
\] (26)

Moreover, in equation (26), by letting \( \dot{x}_1 \) and \( \dot{x}_3 \) in terms of \( \dot{x}_4 \), we have:
\[
\begin{align*}
\dot{x}_4 &= \frac{A_{pn}}{M_p} (a-b)x_3 + \frac{A_{pn}}{M_p} (c-d)V - \frac{F_{fr} A_{pn}}{M_p^2} x_1 + \frac{F_{fr}}{M_p} x_3 \\
\end{align*}
\] (27)

The state-space equations of the pneumatic system can be rewritten in the following matrix form:
\[
\begin{bmatrix}
\dot{x}_1 \\
\dot{x}_2 \\
\dot{x}_3 \\
\dot{x}_4
\end{bmatrix}
= \begin{bmatrix}
0 & 0 & (a-b) & 0 \\
0 & 0 & I & 0 \\
\frac{A_{pn}}{M_p} & 0 & -F_{fr} & 0 \\
-\frac{F_{fr} A_{pn}}{M_p^2} & \frac{F_{fr}}{M_p} & \frac{A_{pn}}{M_p} (c-d) & 0
\end{bmatrix}
\begin{bmatrix}
x_1 \\
x_2 \\
x_3 \\
x_4
\end{bmatrix}
+ \begin{bmatrix}
0 \\
0 \\
0 \\
1
\end{bmatrix}
\] (28)

Now, the variables of the Stewart platform system rewrite the terms of the new state variables:
\[
\dot{x}_5 = x_6
\] (30)

\[
\dot{x}_6 = -M^{-1}(c + F_{fr}) x_6 - M^{-1}[G(q) - F_p]
\] (31)

Therefore, integration of the system state-space equations can be expressed in the following form:
\[
\dot{x} = Ax + Bu
\] (32)

\[y = Cx
\] (33)

\[
\begin{bmatrix}
\dot{x}_1 \\
\dot{x}_2 \\
\dot{x}_3 \\
\dot{x}_4 \\
\dot{x}_5 \\
\dot{x}_6
\end{bmatrix}
= \begin{bmatrix}
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
\frac{A_{pn}}{M_p} & 0 & 0 & 0 & 0 & 0 \\
-\frac{F_{fr} A_{pn}}{M_p^2} & \frac{F_{fr}}{M_p} & \frac{A_{pn}}{M_p} (c-d) & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0
\end{bmatrix}
\begin{bmatrix}
x_1 \\
x_2 \\
x_3 \\
x_4 \\
x_5 \\
x_6
\end{bmatrix}
+ \begin{bmatrix}
0 \\
0 \\
0 \\
0 \\
0 \\
1
\end{bmatrix}
\] (34)
5. DESIGN OF SLIDING MODE CONTROLLER

The inaccuracy in the model may result from uncertainties in the plan (e.g., unknown parameters of the plan), or due to selecting the targeted for a simplified representation of the system dynamics (e.g., modeled as a linear friction, or cancel the modes of the structure in a rigid mechanical system). From the perspective of control, the lack of precision in the modeling can be classified into two main types:

- Structural uncertainties (parametric)
- Non-structural uncertainties (not model dynamics)

The first type relates to inaccuracy in the statement is actually in the model, While second-order uncertainty in the system (lower estimate) is concerned. As already mentioned, the inaccuracies in modeling nonlinear systems can have severe adverse effects. Thus, in any practical design, must be considered explicitly them. The two main and complementary methods to deal with the uncertainties of the model are robust control and adaptive control. A robust controller is composed of a portion of a nominal; that is similar to the feedback linearization or invers control law and the additional statements directed to deal with the model uncertainties. Adaptive controllers have a similar structure, but add to this fact that when the model is updated based on the measured performance [5]. During recent decades, the design of robust control systems, control engineers have been highly regarded; among the different methods of robust control, sliding mode control (SMC) plays a major role. Because this controller, in addition to the stabilization of specific systems and the systems with uncertainty, disturbance rejection capability as well. In addition, this controller has a low sensitivity to changes in system parameters. The sliding mode control of nonlinear systems is one of the most powerful methods for control. Since this controller has good consistency in dealing with uncertainty is and is classified as resistant controls, so in many nonlinear systems with uncertainties are used. Moreover mentioned, a simple approach to robust control is the sliding mode control where in this paper it is used as system controller. This method is based on the point that the first-order control systems (systems that are described by the differential equations of first order), much easier are to control my order n general systems (systems that are described by the differential equation of n order). Therefore, the introduction of a simple symbol that actually allows you to have problems with the order n of the first to be replaced. Then, it can be seen as a simple turned issues, full performance can be provided by applying the optional uncertain of the parameter. However, such action, the control activities to obtained for very high prices. This may in the contrast to other sources of the modeling uncertainty, for example, off from the presence of these dynamics, may stimulate a lot of the activity control. This leads us towards the regulatory the control reform. Therefore, with having acceptable control activities, these rules have been modified to obtain a compromise between performance tracking and parameter uncertainties paid. However, in some of the special applications, the especially those involving the electrical motor control, the unmodified control rules can be directly applied.

Design of sliding mode controller is composed of two components. First, a sliding surface is defined that is supposed to be limited the dynamics of the system. Then, the feedback control law is defined as the paths outside the sliding surface in a finite time to reach sliding surface and stay on it. Thus, the closed loop system (SMC) is robust against uncertainties and external disturbances [6-8]. To this end, we define the sliding surface as follows:

\[ s = \left( \frac{d}{dt} + \lambda \right)^{n-1} e(t) \]  

(35)

In equation (28), parameters \( s \), \( e \) (t) and \( n \), are respectively: sliding surface, the error signal of the system and \( \lambda \) is the positive strictly constant. The movement system on the sliding surface can be an interesting geometric interpretation, such as the grade point average of system dynamics on both sides. In the case of dynamics are in the sliding mod, they can be written as follows:

\[ \dot{s} = 0 \]  

(36)

By solving the above equation for arbitrary control input, we find an expression for \( V \) that called is the equivalent control \( V_{eq} \) and it can be considered as an interpretation of a continuous control law. Moreover, if the dynamics are known, it is keeps. Thus, the control input can be expressed as follows:

\[ V_{eq} = M^{-1} \left( \frac{A_{pn}}{M_p} (c - d) \right) \]  

(37)

To this end, we define the sliding surface as follows:

\[ s = \left( \frac{d}{dt} + \lambda \right)^{n-1} e(t) \]  

By the switching control actions to overcome the uncertainty, the control signal will be obtained as follows:
\[ V_{eq} = \left[ M^{-1} \frac{A_{pn}}{M_p} (c - d) \right]^{-1} \]
\[ \begin{bmatrix} -\ddot{y}_d - 2\lambda\dot{x} + x^2 \dot{\dot{x}} + M^{-1} \left( \frac{F_{fr}A_{pn}}{M_p^2} \right)x_1 \\ -M^{-1} \frac{A_{pn}}{M_p} (a-b) + \left( \frac{F_{fr}}{M_p} \right)^2 x_3 \\ + M^{-1} CM^{-1} x_4 + (M^{-1} C)^2 x_6 \end{bmatrix} + K \text{sgn}(s) \]

Where, the sign function is defined as follows:
\[
\text{sgn}(s) = \begin{cases} 
+1 & , s > 0 \\
0 & , s = 0 \\
-1 & , s < 0 
\end{cases}
\]

6. COMPUTER SIMULATION AND THE RESULTS OF THE SIMULATION

To simulate the system in the MATLAB software, primarily in Simulink software, the system has been implementing the initial conditions and values of the system load. Simulation steps performed in this paper consist of three stages that have been studied in order to evaluate each of them:

6.1. First Step: Check the Performance of Controller Designed Without Considering the Uncertain and External Disturbances

The control gains of the sliding mode controller system from the dynamic error equation are calculated and were included in the simulation. Figure (2), the steady state error of the system diagram illustrates the use of sliding mode controller:

Fig. 2. Diagram of the system’s steady-state error in the application of the sliding mode controller

Therefore, that is noticeable, the dynamic response to system error in steady state reached within approximately 300 milliseconds. Therefore, it is highly desirable to control the speed of response. It should be noted that in the above graphs, the horizontal axis represents the time axis is in seconds and the vertical axis represents the amount of error is the basis of mechanism. In addition, in all charts, colored lines represent the error of the base (system drivers), and faded black horizontal lines, the optimal values of the reference input signal.

6.2. Second Step: Evaluation of the Performance of the Designed Controller Against Disturbance Inputs Actions Step

At this stage, to evaluate the ability of the controller to the annoying, constant disturbance is the applied at the input to our system. So again, examine the results of the simulation. In figure 3, the diagram of steady-state error of the system is presented.

Fig. 3. Diagram of the system’s steady-state error a constant perturbation, when the sliding mode controller is used

According to the diagram of figure 3, see the sliding mode controller for the case when the disturbances applied to the system have good performance. As a result, the system output, input without steady-state error will follow.

6.3. Third Step: Evaluation of the Performance of Controller Designed With the Consideration of Structural Uncertainty

This step involves two phases. In the first phase, the cylinder mass change and the behavior of the system with the designed controller to look at. At this stage the mass of the cylinder is increased by as much as 10%, and simulates the actions of an unspecified doing this. This output is in figure (4), is shown.
In figure 4, see the sliding mode controller is robust against uncertainties and good performance of the control system. In the second phase, the friction force between piston and cylinder wall will rise to 10% and then we do the simulation. In figure 5, the output of the simulation by applying the uncertainty, when the sliding mode controller is used to control the system, is shown.

Figure 5 shows that the sliding mode controller, with the uncertainty the type of friction, while the sliding mode controller is used.

7. CONCLUSION AND SUGGESTIONS
In this paper, a robust control strategy for the control of mechanism Stewart with pneumatic actuators offered. Results of the simulation, the performance of the optimal controller design shows. To better illustrate the performance of the sliding mode controller, in the first phase, the system input, constant perturbation was the applied and observed that the sliding mode controller favorably of turbulence in the exhaust removed and the ability to control the system and the system is stable. In the second phase, the efficiency of the controller design is studied in the presence of uncertain and observed that the sliding mode controller, as well as resistance against an unspecified and good control performance to their shows. As the firstly, Increased by 10 percent the mass of the cylinder as first the uncertainty parameter was considered. Moreover, it was observed that the sliding mode controller is robust against uncertain. In the next step, a 10 percent increase friction force between piston and cylinder wall as the next parameter was uncertain terms and at this stage, it was observed that the designed controller is to apply the uncertainty has always been resistant and output of the system no steady-state error, follow the reference input. For further researches, the adaptive control techniques for the control system are proposed.

REFERENCES