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Modeling, Simulation and Robust Control of a Parallel Robot Electro- Pneumatic Gough- Stewart (6dof)

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Abstract. In this paper, modeling, simulation, and control of a six-degree of freedom Gough- Stewart robust parallel robot driven by pneumatic drivers are discussed. The robot modeling is performed based on the classical Lagrangian approach and a comprehensive dynamic model by taking into account the dynamics of the system in addition to the driving rigid dynamics are presented. Robust control strategy and Sliding mode control were used in order to control the robot. In this approach, the feedback control law presented such that the closed loop system defined by the SMC is robust against uncertainties and external disturbances. To demonstrate the appropriateness of the designed controller, its performance was compared with a feedback linearization controller and finally the computer simulation using MATLAB/Simulink validated the optimal performance of the designed controller.

Keywords: Parallel Robot, Gough- Stewart Platform, Lagrangian Dynamic, Feedback Linearization, Sliding Mode Control

1. INTRODUCTION

The advantages of parallel robots, today known as Gough/Stewart platform (see Figure 1), in comparison with their series counterparts are the main reasons for their widespread use in industry. Including such advantages due to their closed physical structure is the ability to carry heavy loads, high accuracy and rigidity, as well as low inertia. Parallel mechanism was first proposed by Gough, England's governing board member, as a testing system of car wheel. Afterwards, Dr. Stewart improved the plan as a flight simulator resulted in various applications. Current industry make use of developed Stewart platform in applications such as separate platforms, endoscopic, simulating vehicles, flying simulation systems, rotary radio telescopes, and six-axis machine tools [1, 2].

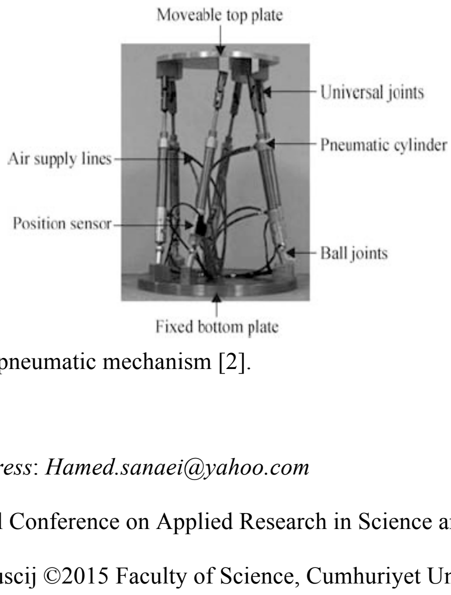

Figure 1. Gough- Stewart electro- pneumatic mechanism [2].

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Despite their favorable properties, it is difficult to control parallel robots. To control this type of systems, a variety of control methods have been utilized. However, the control schemes with good control capabilities against model's disturbances and uncertainties are scarce. In most of the reported research in this field the Stewart structural dynamic model was taken into account but the dynamics of system operator is not considered [3]. The main focus of this paper is to provide a robust control method for controlling the Stewart mechanism driven by pneumatic drivers with regard to driving system dynamics in addition its rigid dynamics.

The remaining parts of this paper are organized as follows. In Section II, classic Lagrangian dynamic model is used to derive dynamic model of system. Afterwards, pneumatic system was described along with its dynamic equations and its dynamic is extracted. In Section III, for the control purposes, the derived dynamic models from both systems are integrated into one set of equations. Section IV introduces the feedback linearization control and final control law is briefly described [4]. Here, the method of sliding mode control system was designed to control the system against elimination of nuisance factors such as external disturbances acting on the system and non-modeled dynamics as well as designed uncertainties [5]. In Section V, by the simulation of designed controller for optimal performance in the face of external disturbances applied to the system and the uncertainties in comparison with performance feedback linearization controller is shown. This paper is concluded in Section VII in while suggestions are given to develop control systems.

2. SYSTEM MODELING

2.1. Stewart Platform Dynamics

In this section, the dynamic model of electro-pneumatic Stewart platform servomechanism with six degrees of freedom based on classical Lagrangian dynamics is presented. Lagrangian equation is defined as follows [6, 7]:

$$L = T - U \tag{1}$$

Where in equation (1), T is the kinetic energy and U is the potential energy of the system calculated from the following relationship:

$$T = \frac{1}{2}mv^2 + \frac{1}{2}Iw^2 \tag{2}$$

$$U = mgh \tag{3}$$

$$\frac{d}{dt}\left(\frac{\partial l}{\partial \dot{q}}\right) - \frac{\partial l}{\partial q} + \frac{\partial D \cdot E}{\partial \dot{q}} = Q \tag{4}$$

Where in equation (4), the parameters q, D.E, and Q are the vector of generalized coordinates, friction and damper forces vector, and the generalized forces vector respectively, which are calculated using the principle of virtual work. By placing Lagrangian equation into motion equation of a dynamic system, dynamic equation can be expressed in the following form [8]:

$$M(q)\ddot{q} + C(q,\dot{q})\dot{q} + G(q) + F_{fr}(\dot{q}) = \tau \tag{5}$$

Where in equation (5), the parameters M, C, G, Ffr, and τ indicate positive definitive mass matrix with the order of 6*1, forces and torques generated by the vector provider of centrifugal forces and Carioles acceleration with the order of 6*1, vector provider of torque caused by the gravitational pull with the order of 6*1, vector provider of torque caused by the friction forces with the order of 6*1, and the vector of generalized forces applied with the order of 6*1, respectively.

In equation (5), generalized torques vector can be rewritten in terms of applied forces of the mechanism drives:

$$\tau = J^T F_p \tag{6}$$

Where in equation (6), parameters J and Fp are Jacobian matrix of the system with the order of 6*6 and vector of driving forces with the order of 6*6, respectively. The driving force vector is defined as:

$$F_p = [F_{p,1}, F_{p,2}, \ldots, F_{p,6}] \tag{7}$$

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

$$M^*(q)\ddot{d} + C^*(q,\dot{q})\dot{d} + G^*(q) + F^*_{fr}(\dot{d}) = F_p \tag{8}$$

Where in equation (8), parameters d, M*(q), C*(q, $\dot{q}$), G*(q), and $F^*_{fr}(\dot{d})$ are the vector of mechanism lengths drivers, definitive mass matrix with the order of 6*6, vector provider of centrifugal forces and Carioles with the order of 6*1, vector provider of torque caused by the gravitational pull with the order of 6*1, vector provider of friction forces in the joint space with the order of 6*1, respectively. In equation (8), the terms M*(q), $C^*(q,\dot{q})$ and G*(q) can be calculated using the following relationship:

$$M^*(q) = \left[J(q)^T\right]^{-1} M(q)J(q)^{-1} \tag{9}$$

$$C^*(q,\dot{q}) = \left[J(q)^T\right]^{-1}\left[C(q,\dot{q}) - M(q)\dot{J}(q,\dot{q}) \cdot \dot{q}\right] \tag{10}$$

$$G^*(q) = \left[J(q)^T\right]^{-1} G(q) \tag{11}$$

2.2. Pnuematic System Dynamics

In this section, the pneumatic system dynamic model will be derived. Figure 2 depicts the pneumatic system along with its components.

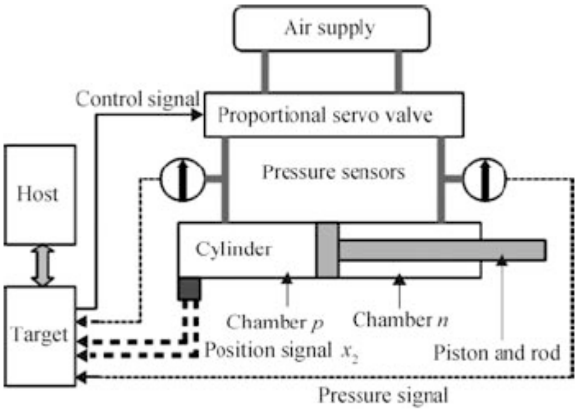


Figure 2. Pneumatic system [2].

Equations of pneumatic system (see Figure 2) can be expressed as [2]:

$$\dot{p}_n = \frac{\gamma_1 A_n p_n}{v_n} \dot{x}_{pos} - k_v \frac{\gamma_1 R_g T_s}{v_n} V \tag{12}$$

$$\dot{p}_p = \frac{-\gamma_1 A_p p_p}{v_p} \dot{x}_{pos} + k_v \frac{\gamma_1 R_g T_s}{vp} V \tag{13}$$

$$\ddot{x}_{pos} = \frac{A_p p_p - A_n p_n}{M_p} - \frac{F_{fr}}{M_p} \ddot{x}_{pos} \tag{14}$$

The pneumatic system's parameters are presented in Table 1:

Table 1. Parameters of pneumatic system [2].

parameter	Name	Value	Parameter	Name	Value
T_s	Temperature	300 K	A_n	Piston area (Chamber n)	4.94×10^{-4} m^2
γ_1	Ratio of specific heat	1.4	A_p	Piston area (Chamber p)	5.72×10^{-4} m^2
F_f	Friction forces	47 N.s/m	P_p	Nominal pressure in chamber p	2.5×10^5 Pa

R_g	Universal gas constant	287 J/kg.K	P_n	Nominal pressure in chamber n	2.5 × 105 Pa
K_v	Servo valve constant	0.0023 kg/s.V	V_p	Nominal volume in chamber p	5.683×10^{-5} m^3
M	Piston mass	0.2 kg	V_n	Nominal volume in chamber n	5.285×10^{-5} m^3
		System input pressure	4 bar		

3. INTEGRATION of SYSTEM STATE EQUATIONS

For control purposes, it is necessary to present integrated system of equations of Stewart platform and pneumatic system; meanwhile the input and output of the system are determined. Since the system is a multivariate system, the system of equations should be written in state-space form. To do this, the state-space equations are derived for each system individually. It should be noted that for the simplicity of relationships, the asterisk (*) on top of the final parameters is ignored [9].

3.1. Stewart Constract State- Space Model

In order to derive a state-space model of Stewart platform, equation (8) is sorted based on the second time derivative of the drivers' lengths:

$$\ddot{d} = M^{-1}(C + F_{fr})\dot{d} - M^{-1}\left[G(q) - F_p\right] \tag{15}$$

$$\begin{bmatrix} \ddot{d}_1 \\ \ddot{d}_2 \\ \ddot{d}_3 \\ \ddot{d}_4 \\ \ddot{d}_5 \\ \ddot{d}_6 \end{bmatrix} = M^{-1}(C + F_{fr})\begin{bmatrix} \dot{d}_1 \\ \dot{d}_2 \\ \dot{d}_3 \\ \dot{d}_4 \\ \dot{d}_5 \\ \dot{d}_6 \end{bmatrix} - M^{-1}\left[G(q) - F_p\right] \tag{16}$$

The system state variables are defined as:

$$if \begin{cases} z_1 = y \\ \dot{z}_1 = z_2 \\ \dot{z}_2 = \ddot{z}_1 \end{cases} \Rightarrow \begin{cases} \dot{z} = Az + Bu \\ y = Cz + Du \end{cases} \tag{17}$$

Thus, the state space equation of Stewart platform system is obtained as:

$$\begin{cases} \begin{bmatrix} \dot{z}_1 \\ \dot{z}_2 \end{bmatrix} = \begin{bmatrix} 0 & I \\ 0 & -M^{-1}(C + F_{fr}) \end{bmatrix} \begin{bmatrix} z_1 \\ z_2 \end{bmatrix} \\ \qquad + \begin{bmatrix} 0 \\ -M^{-1} \end{bmatrix} \begin{bmatrix} G(q) + F_p \end{bmatrix} \\ y = \begin{bmatrix} I & 0 \end{bmatrix} \begin{bmatrix} z_1 \\ z_2 \end{bmatrix} \end{cases} \tag{18}$$

3.2. EXTRACTİON OF PNEUMATİC SYSTEM STATE- SPACE EQUATİONS

If the cross-sectional area between two inner sections of the cylinder are assumed equal, and the pressure difference between the cylinders is considered as Pd, thus:

$$if \begin{cases} A_p = A_n = A_{pn} \\ p_p - p_n = p_d \end{cases} \tag{19}$$

The pneumatic system state- space equation can be expressed as:

$$\begin{cases} \begin{bmatrix} \dot{p}_d \\ \dot{x}_{pos} \\ \ddot{x}_{pos} \end{bmatrix} = \begin{bmatrix} 0 & 0 & a-b \\ 0 & 0 & I \\ \dfrac{A_{pn}}{M_p} & 0 & \dfrac{-F_{fr}}{M_p} \end{bmatrix} \begin{bmatrix} p_d \\ x_{pos} \\ \dot{x}_{pos} \end{bmatrix} + \begin{bmatrix} c-d \\ 0 \\ 0 \end{bmatrix} V \\ y_{pos} = \begin{bmatrix} 0 & I & 0 \end{bmatrix} \begin{bmatrix} p_d \\ x_{pos} \\ \dot{x}_{pos} \end{bmatrix}, D = 0 \end{cases} \tag{20}$$

In equation (20), we have:

$$a = -\frac{\gamma_1 A_{pn} p_p}{v_p},\ b = \frac{\gamma_1 A_{pn} p_n}{v_n},\ c = k_v \frac{\gamma_1 R_g T_s}{v_p},\ d = -k_v \frac{\gamma_1 R_g T_s}{v_n}$$

3.3. System State- Space Model

In this section, the integrated equations of the total system are derived by selecting the appropriate state variables. First, the pneumatic system state variables will be changed as follows:

$$\begin{cases} x_1 = p_d \\ x_2 = x_{pos} \\ x_3 = \dot{x}_{pos} \\ x_4 = \dot{x}_3 = \ddot{x}_{pos} \\ y_{pos} = x_2 \end{cases} \tag{21}$$

By taking derivatives of equation (21) with respect to time, we have:

$$\begin{cases} \dot{x}_1 = \dot{p}_d = (a-b)x_3 + (c-d)V \\ \dot{x}_2 = x_3 \\ \dot{x}_3 = \dfrac{A_{pn}}{M_p} x_1 - \dfrac{F_{fr}}{M_p} x_3 \\ \dot{x}_4 = \ddot{x}_3 = \dfrac{A_{pn}}{M_p} \dot{x}_1 - \dfrac{F_{fr}}{M_p} \dot{x}_3 \end{cases} \tag{22}$$

And placing $\dot{x}_1$ and $\dot{x}_3$ into $\dot{x}_4$ relation, thus:

$$\begin{aligned} \dot{x}_4 &= \frac{A_{pn}}{M_p}(a-b)x_3 + \frac{A_{pn}}{M_p}(c-d)V - \frac{F_{fr}A_{pn}}{M_p^2} x_1 + \left(\frac{F_{fr}}{M_p}\right)^2 x_3 \\ &= -\frac{F_{fr}A_{pn}}{M_p^2} x_1 + \left\{\frac{A_{pn}}{M_p}(a-b) + \left(\frac{F_{fr}}{M_p}\right)^2\right\} x_3 + \frac{A_{pn}}{M_p}(c-d)V \end{aligned} \tag{23}$$

The pneumatic system state- space equations can be rewritten in matrix form as:

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \\ \dot{x}_4 \end{bmatrix} = \begin{bmatrix} 0 & 0 & (a-b) & 0 \\ 0 & 0 & I & 0 \\ \dfrac{A_{pn}}{M_p} & 0 & \dfrac{-F_{fr}}{M_p} & 0 \\ \dfrac{-F_{fr}A_{pn}}{M_p^2} & 0 & \dfrac{A_{pn}}{m_p}(a-b) + \left(\dfrac{F_{fr}}{M_p}\right)^2 & 0 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix} + \begin{bmatrix} (c-d) \\ 0 \\ 0 \\ \dfrac{A_{pn}}{M_p}(c-d) \end{bmatrix} V \tag{24}$$

$$F_p = \begin{bmatrix} 0 & 0 & 0 & M_p \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix} \tag{25}$$

Stewart platform variables based on the new state variables of new system can be rewritten as:

$$\dot{x}_5 = x_6 \tag{26}$$

$$\dot{x}_6 = -M^{-1}(c + F_{fr})x_6 - M^{-1}[G(q) - F_p] \tag{27}$$

Thus, the integrated system's state space equations can be expressed in the following form:

$$\begin{cases} \dot{x} = Ax + BV \\ y = Cx \end{cases} \tag{28}$$

$$\left\{ \begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \\ \dot{x}_4 \\ \dot{x}_5 \\ \dot{x}_6 \end{bmatrix} = \begin{bmatrix} 0 & 0 & (a-b) & 0 & 0 & 0 \\ 0 & 0 & I & 0 & 0 & 0 \\ \frac{A_{pn}}{M_p} & 0 & \frac{-F_{fr}}{M_p} & 0 & 0 & 0 \\ \frac{-A_{pn}F_{fr}}{M_p^2} & 0 & \frac{A_{pn}}{M_p}(a-b) + \left(\frac{F_{fr}}{M_p}\right)^2 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & I \\ 0 & 0 & 0 & -M^{-1} & 0 & -M^{-1}(c+F_{fr}) \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \\ x_5 \\ x_6 \end{bmatrix} + \begin{bmatrix} (c-d) \\ 0 \\ 0 \\ \frac{A_{pn}}{M_p}(c-d) \\ 0 \\ 0 \end{bmatrix} V \right.$$

$$y = \begin{bmatrix} 0 & 0 & 0 & 0 & I & 0 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \\ x_5 \\ x_6 \end{bmatrix} \tag{29}$$

5. CONTROLLER DESİGN

5.1. Feedback Linearization

The main idea of this method is that the dynamics of nonlinear systems (completely or partially) to be linear such that the linear control methods are used to control them. Further, how to use this method for the control of Stewart system will be expressed. Firstly, the error signal is defined as [9, 10]:

$$e = y_d - y \tag{30}$$

Where in equation (30), the parameters e, y_d, and y represent the error signal, the input reference signal, and the output signal of system, respectively. From equation (21), we have:

$$y = cx \Rightarrow y = x_5 \tag{31}$$

Thus, according to equation (31), equation (30) can be rewritten in the following form:

$$\dot{e} = \dot{y}_d - \dot{x}_5 \tag{32}$$

Taking double derivation of equation (32) with respect to time, we have:

$$\ddot{e} = \ddot{y}_d - \ddot{x}_5 \tag{33}$$

Now, by placement of the equation (27) into equation (33) we have:

$$\ddot{e} = \ddot{y}_d + M^{-1}(c + F_{fr})x_6 + M^{-1}x_4 \tag{34}$$

In order to write the control law, for simplicity, the friction term in equation (34) is neglected. Again, we take derivative of the relationship with respect to time and we have:

$$\ddot{e} = \ddot{y}_d - \ddot{x}_6 \tag{35}$$

Equating the variable P and v, we have:

$$p = \ddot{x}_6 = -M^{-1} c\dot{x}_6 - M^{-1}\dot{x}_4 \tag{36}$$

Here, by placement of equations (23) and (27) into equation (36), we have:

$$p = -M^{-1}C[-M^{-1}Cx_6 - M^{-1}x_4] - M^{-1}[-\frac{F_{fr}A_{pn}}{M_p^2}x_1 + \left(\frac{A_{pn}}{M_p}(a-b) + (\frac{F_{fr}}{M_p})^2\right)x_3 + \frac{A_{pn}}{M_p}(c-d)V]$$

$$= -M^{-1}[-\frac{F_{fr}A_{pn}}{M_p^2}x_1 - \left(\frac{A_{pn}}{M_p}(a-b) + (\frac{F_{fr}}{M_p})^2\right)x_3] + M^{-1}CM^{-1}x_4 + (M^{-1}C)^2 x_6 - M^{-1}(\frac{A_{pn}}{M_p}(c-d))V \tag{37}$$

Equation (37) can be rewritten in terms of the input signal V:

$$V = [M^{-1}(\frac{A_{pn}}{M_p}(c-d))]^{-1}[-p + M^{-1}(\frac{F_{fr}A_{pn}}{M_p^2})x_1$$

$$-M^{-1}(\frac{A_{pn}}{M_p}(a-b) + (\frac{F_{fr}}{M_p})^2)x_3 + M^{-1}CM^{-1}x_4 + (M^{-1}C)^2 x_6$$

The dynamic error equation, i.e. the equation (33), is rewritten in terms of P:

$$\ddot{e} = \ddot{y}_d - \ddot{x}_6 = \ddot{y}_d - p \tag{39}$$

Then the equation P is defined in terms of the dynamic error as:

$$p = \ddot{y}_d + K_1\ddot{e} + K_2\dot{e} + K_3 e \tag{40}$$

By inserting equation (40) into equation (39), the dynamic error equation is obtained as follows:

$$\ddot{e} + K_1\ddot{e} + K_2\dot{e} + K_3 e = 0 \tag{41}$$

Thus, the final control law is obtained by the placement of the equation (40) into equation (38) as follows

$$V = [M^{-1}(\frac{A_{pn}}{M_p}(c-d))]^{-1}[-\ddot{y}_d - K_1\ddot{e} - K_2\dot{e} - K_3 e + M^{-1}(\frac{F_{fr}A_{pn}}{M_p^2})x_1$$

$$-M^{-1}(\frac{A_{pn}}{M_p}(a-b) + (\frac{F_{fr}}{M_p})^2)x_3 + M^{-1}CM^{-1}x_4 + (M^{-1}C)^2 x_6 \tag{42}$$

4.2. Sliding Mode Controller Design

Among the various methods for robust control, sliding mode control (SMC) plays a fundamental role. Because in addition to the stabilization of certain systems and systems with uncertainties, this controller has also the ability of disturbance rejection. Moreover, this controller has a low sensitivity to changing system parameters. For the designing purpose of this controller, at first the sliding surface is defined as follows [10]:

$$s = \left(\frac{d}{dt} + \lambda \right)^{n-1} e(t) \tag{43}$$

Where in equation (43), the parameters s, e(t), and n are sliding level, error signal, and system order respectively; and λ is strictly positive constant. Dynamics when they are in sliding mode can be written as follows:

$$\dot{s} = 0 \tag{44}$$

By solving the above equation for conventional control input, we find an expression for V called the equivalent control V_{eq} which can be expressed as a continuous control law maintaining $\dot{s} = 0$ if dynamics are defined. Thus, this control input can be expressed as:

By employing the switching control to overcome uncertainties, the control signal is obtained as follows:

Where, sgn is the sign function defined as follows:

$$\text{sgn}(s) = \begin{cases} +1 & , \quad s \rangle 0 \\ 0 & , \quad s = 0 \\ -1 & , \quad s \langle 0 \end{cases} \tag{47}$$

5. SIMULATION RESULTS

In this section, the implementation of control systems designed in MATLAB/Simulink is discussed and simulation process is completed with the inclusion of appropriate amounts of control gains. In Figure 3, the control system of Gough/Stewart platform is shown. The simulations carried out in this paper consist of three stages, each of which is discussed.

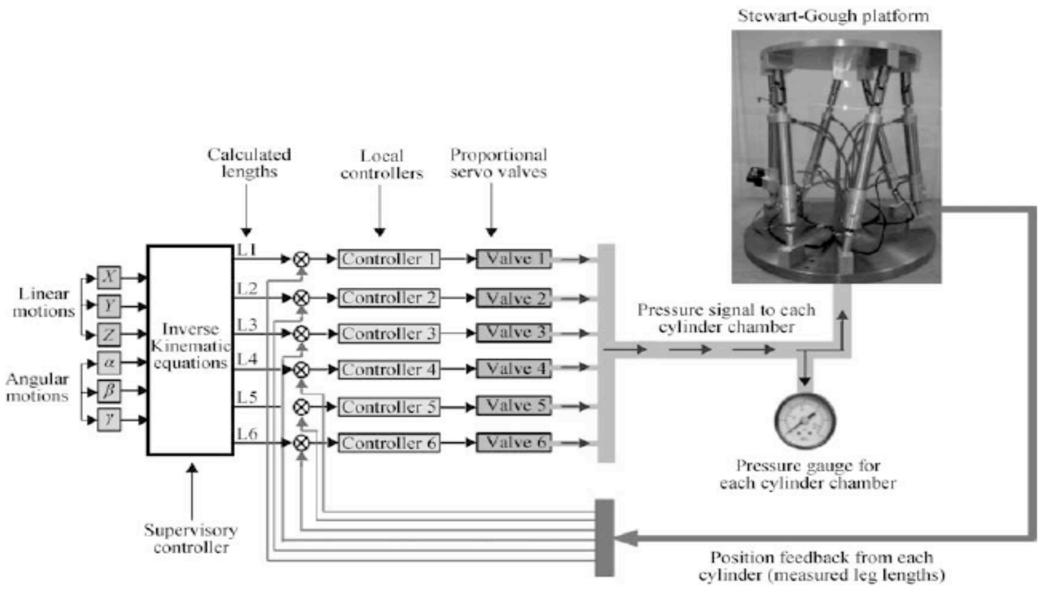
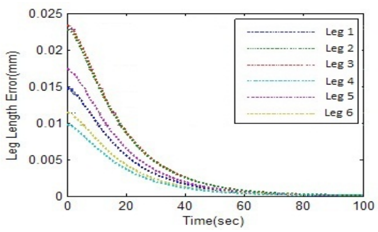
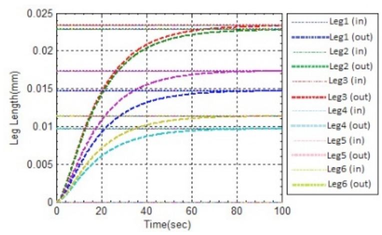


Figure 3. Gough- Stewart platform control system [2].

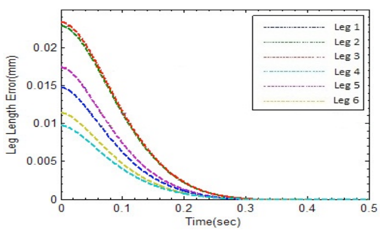
5.1. Phase I: Evaluate Of the Performance of Controller Designed Without Considering the Uncertain and External Disturbances

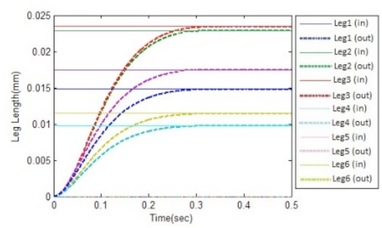
In this section, the performance of control systems designed in normal conditions (absence of external disturbances and uncertainties) is examined. Figure (4- a) illustrates the feedback linearization control system response. Figure (4- c) shows a sliding mode control system. As it is noticeable in both figures, the outputs of the model are completely consistent with the corresponding inputs, and the steady-state error of the system is zero according to the Figures (4- b) and (4- d). As a result, the controlled system in the application of both controllers is always stable and the output of the system follows corresponding inputs without error.





(b) **(a)**



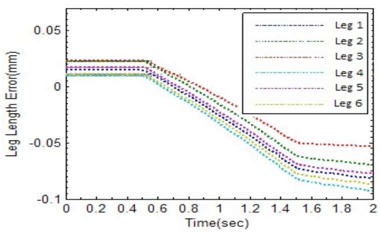


(d) **(c)**

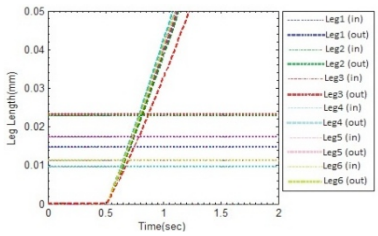
Figure 4. Dynamic response of the control systems with steady- state error diagram in normal conditions

5.2. Phase II: Evaluation of the performance of the designed controller against disturbance input actions

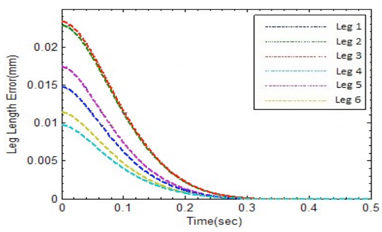
In this section, the performance of designed control systems is examined by employing disturbances of the unity impulse. Figure (4- a) depicts the feedback linearization control system response. Figure (4- c) shows a sliding mode control system. When feedback linearization control system is used, a disturbance in the form of impulse is inserted at the time delay of 0.5 second. It was noticed that this disturbance leads to the instability of system and steady state error is infinite (see Figure (4- b)). Further, in the case of using sliding mode control system, this disturbance is inserted at the time delay of 0.2 second during the simulation exercise, but in this case the outputs of the model is completely consistent with the corresponding inputs and the steady-state error of the system as shown in Figure (4- d) is equal to zero. Thus, the system is stable when uses this controller.



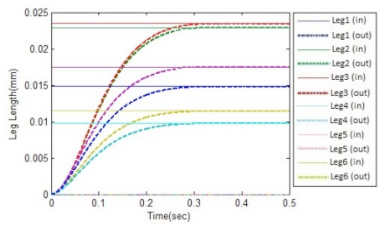
(b)



(a)



(d)

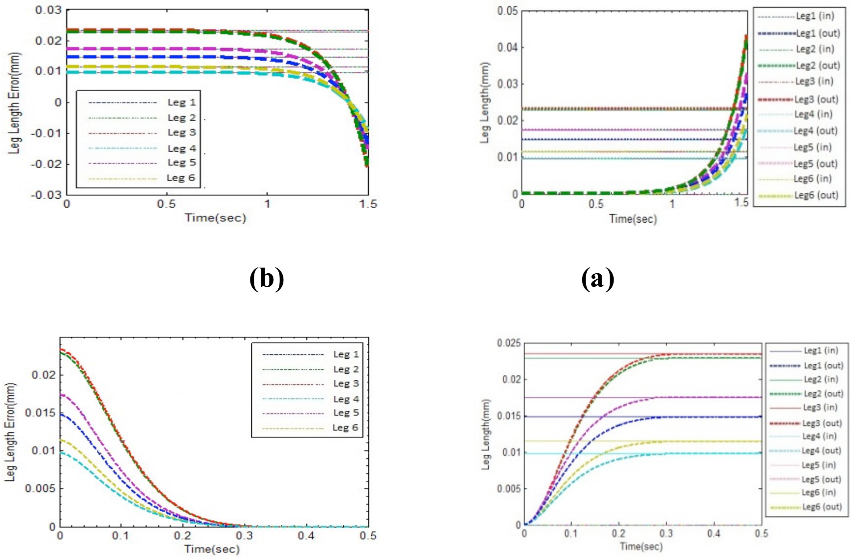


(c)

Figure 5. Dynamic response of the control systems with steady-state error diagram with disturbance

5.3. Phase III: Evaluation of the controller designed, by considering the uncertainly of the structural

In this section, the performance of the designed control system is examined by applying uncertainty in the mass quantity of the cylinder which is a kind of structural uncertainty. Figure (4- a) illustrates the feedback linearization control system response. While, Figure (4- c) shows a sliding mode control system. Given the 10 percent increase of the cylinder mass quantity as an uncertain parameter, it was found that sliding mode controller system has been resistant against uncertainties and the output of the system follows the reference input without steady-state error (see Figure 4-d). However, the feedback linearization controller has not the ability to control the system and the system was unstable (see Figure 4- b).



(b) **(a)**

(c) **(d)**

Figure 6. Dynamic response of the control systems with steady-state error diagram with uncertain of mass

6. CONCLUSIONS

In this paper, a robust control strategy was proposed in order to control the six degrees of freedom Gough/Stewart parallel robot with pneumatic drivers. Results of the simulation verified the performance of the optimal controller design. As in the first phase, the disturbance of impulse type was inserted into the input of the system and it was observed that the sliding mode controller optimally removed the disturbance effect on the input and the system remained stable. Whereas applying feedback linearization controller system resulted in unstable condition.

In the second phase, the designed controller performance was assessed in the presence of uncertainty such that the increase in mass of the cylinder by 10 percent was considered as an uncertainty parameter. It was observed that the sliding mode control system is robust in the face of uncertainty and system output had no steady-state error, following the reference input appropriately. However, the feedback linearization controller has no ability to control the system and the system was unstable. For the future research, adaptive control method is proposed to control the system.

REFERENCES

[1] Chin, J.H.and Suna, Y. H. and Chengb, Y.M. (2011), “Force Computation and Continuous Path Racking for Hydraulic Parallel Manipulators”, Department of Mechanical Engineering, National Chiao-Tung University, Hsinchu, 300, Taiwan, ROC
[2] Singh, k. and Dixon, R. and Pearson, J. (2012), “LQG Controller Design Applied to a Pneumatic Stewart-Gough Platform”, International Journal of Automation and Computing, 9 February, pp45-53.
[3] Sanaei, H. and dalaliyan, P. and Giasi, A. R. (2014), “Kinematic and Jocobian Analysis of a Stewart Mechanism with Pneumatic Actuators”, Proc of the 6th International Conf on Electrical Engineering, Gonabad, (in Persian).
[4] Sanaei, H. and Dalaliyan, P. and Giasi, A. R. (2014), “Dynamic Analysis of a Stewart Mechanism with Pneumatic Actuators”, Proc of the 1th International Conf on Electrical and Computer Engineering, Anzali, (in Persian).
[5] Sanaei, H. and Dalaliyan, P. and Giasi, A. R. (2014), “Sliding Mode Control Design for Stewart Mechanism”, Proc of the 6th International Conf on Electrical Engineering, Gonabad, (in Persian).
[6] Li, D. and Salcudean, S.E. (2000), “Modeling, Simulation, and Control of a Hydraulic Stewart Platform”, Department of Electrical Engineering, University of British Columbia Vancouver, BC, V6T 1Z4, Canada.
[7] Bai, X and Turner, J.D. and Junkins, J.L. (2006), “Dynamic Analysis and Control of a Stewart Platform Using A Novel Automatic Differentiation Method”, AIAA/AAS Astrodynamics Specialist Conference and Exhibit, Keystone, Colorado.
[8] Ioann, D. and Evangelos, P. (2007), “A Model-Based Impedance Control of a 6Dof Electrohydraulic Stewart Platform”, Proceedings of the European Control Conference, Kos, Greece, July 2-5.
[9] Sedigh, A. K. (2012), “Modern Control Systems”, 9 edition, published by the Institute of Tehran University, (in Persian).
[10] Slotine, J. J. and Lee, W. (1991), “Applied Nonlinear Control”, Prentice Hall.