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Research Article

DESIGNING AND SIMULATION OF A SLIDING MODE CONTROLLER FOR A CABLE-DRIVEN PARALLEL-PLANAR ROBOT

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ABSTRACT
Primitive robots consisted of some spinal arms connected by joints. However, deficiencies of these serial mechanisms led to the emergence of parallel robots. To eliminate these deficiencies, spinal arms were substituted by cables in the structure of parallel robots. Applying cables in parallel robots introduced new challenges including designing appropriate controlling algorithms for the cable-driven parallel robots. In the current study we designed a controller for these robots. Therefore, first the dynamic model of a cable-driven parallel robot was extracted and then the desirable sliding mode controller was designed. Results of the above-mentioned controller established it as a more efficient detection instrument and demonstrated that the output followed the input so desirably. Also the input-output error was less and the time period that output reached to the desirable amount of input showed improvements. Considering the results of cables' stretching torque and oscillation, we understood that chattering was the major problem of this controller and increasing the portion of k led to a growing in the amplitude which was undesirable.

Keywords: *Cable-driven Parallel Robots, Sliding Mode Controller, Endeffector, KNTU Cable Robot*

INTRODUCTION
Designing mechanical transportation systems is one of the major and fundamental issues in robotics. The first generation of modern industrial robots composed of spinal arms connected by several successive joints similar to the structure of a serial robotic arm. These robots are the most common mechanisms used in industry. The growing application of robots in industry highlights a critical need for designing mechanisms without the restrictions and drawbacks of serial robots. Therefore, mechanisms were designed with high degree of accuracy, velocity and ability of load transportation which were called **parallel robots**. However, the above-mentioned mechanisms had some deficiencies. Work place restriction was one of the deficiencies of parallel robots. So, new approaches have been adopted regarding designing and manufacturing parallel robots since three decades ago. Besides eliminating deficiencies, these approaches aimed to decrease the cost of design and construction. In the modern structure of parallel robots, cable is used instead of common spinal arm. Applying this new parallel structure, we can design parallel robots with a large work space and less weight comparing ordinary robots (Khosravi, 2013).
In cable-driven parallel robots changes in the position of final executive has a direct relationship with the length of cables. As a cable can only impose a stretching force, a cable-driven stimulus must be used in addition to freedom degrees. In this regard cable-driven robots are divided in two types: perfect and imperfect bound (Alikhani *et al.,* 2011).
Using cables in the structure of robots led to the emergence of new challenges for researchers and scientists. As cables can only produce stretching forces, the majority of controlling algorithms proposed for parallel and serial robots may not be applied directly in controlling cable-driven parallel robots (Khosravi and Taghi, 2013). Although in all the controlling algorithms stimuli can work in both positive and negative directions, they must work in just one direction in cable-driven parallel robots. Therefore,

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increasing stimulation in these robots is considered an essential need in order to enable the system to compensate the uni-directional stimulation deficiency (Khosravi, 2013). Moreover, the controlling algorithm may be designed in way to satisfy the stretching condition of cables in all the motion maneuvers. Although numerous researches have been done in the field of controlling common robots, few studies have concentrated on controlling cable-driven robots which have adopted controlling algorithms designed for parallel and serial robots. These methods include approaches which are based on Liapanov theory (Carricato, 2013), calculated torque (Su *et al.*, 2011) and sliding surfaces (Korayem, 2010).
Cable robots have a short but growing history. One of the first systems benefitted from cables in designing was Robo Crane. This cable robot was developed at NIST. This robot is similar to six degrees of freedom mechanism of Stewart which is placed reversely with this difference that 6 cable drives with electric motors are used instead of hydraulic actuators (Khosravi, 2013).

Considering the cable mass, Kozak has provided a static model of the cable and has shown that deformation or crookedness caused by cable mass has a considerable effect on the kinematics and hardness of the system (Khosravi, 2013).

With the assumption of low speed of the final executive which is close to static mode, Zi has suggested a mathematical model and has achieved the static deflection of the cable through this model (Khosravi, 2013).

Korayem has also provided a model by 3D modeling of cable and considering the deformation and flexibility of cable and has also resolved direct and reverse kinematics for a special system (Korayem *et al.*, 2010).

Khosravai and Taghi analyzed the stability and control of resistant PID in cable-driven parallel robots supposing that cables face stretching force. Considering the structured and unstructured indefiniteness in the dynamics of robots, a resistant controlling algorithm was proposed in terms of PID control. Moreover the stability analysis was performed based on the Liapanov theory (Taghirad and Khosravi, 2011).

Ghasemi focused on the limited control of 3D cable-driven robots through using the linear predictive control and linearization of input-output.

Although the structures of cable-driven and parallel robots are the same in this research, the only main difference lies in the fact that cable can just stretch the platform. This characteristic makes controlling cable-driven robots a more challenging task comparing parallel robots. We defined a controller for cable-driven robots in terms of force restriction (Ghasemi, 2011).

The current article aim is designing a sliding mode controller and providing its theoretical frameworks. Also the current article is going to theoretically compare the results achieved from sliding mode controller and resistant PID controller.

At first the current article is going to survey the dynamic equations of the system and achieve the cable equations for the robot; then it is going to reach the dynamics of the cable-driven parallel robots under the condition of negligible cable mass.

After that in this article it has been tried to design a sliding mode controller and to simulate the robot by choosing the appropriate controlling model; and then the results achieved from designing a controller for this robot are surveyed.

Kinematic and Dynamic Analysis of Robots

The Differential Equation of a Cable-Driven Parallel Robot

The mechanism of a cable-driven parallel KNTU robot consists of a 3-degree freedom, 2-degree translation in the direction of x or y and one degree rotation about the z axis. It also benefits from a redundancy degree regarding stimulation (Khosravi, 2013).

Figure 1: The cable-driven parallel KNTU robot

The Dynamic Equation of A Cable-Driven Robot

Considering the very insignificant mass of selected cables comparing the final mass of a robot, the dynamic of a cable-driven planar KNTU robot is (Khosravi and Taghi, 2013):

$$M(X)\ddot{X} + G(X) = -J^T\tau \qquad (1)$$

In this equation, M and G are the mass matrix and gravity vector of robot, respectively. Also J is robot's Jacobsian matrix which can be developed as following (Khosravi, 2013):

$$M = \begin{bmatrix} m & 0 & 0 \\ 0 & m & 0 \\ 0 & 0 & I_z \end{bmatrix}, \quad G = \begin{bmatrix} 0 \\ -mg \\ 0 \end{bmatrix} \qquad (2)$$

$$J = \frac{1}{143.4}\begin{bmatrix} 89.5 & -112 & 1736 \\ -89.5 & -112 & -1736 \\ 89.5 & 112 & -1736 \\ -89.5 & 112 & -1736 \end{bmatrix} \qquad (3)$$

Here, M=2.5kgr and are the final executive mass and the final executive moment of inertia about the P point in frame. Also g=9.8m/s2 is the acceleration vector and is cables' force. Consider the generalized coordinates of x vector as in which demonstrates the rotation angle around the z axis that is vertically placed on the screen coordinates (Khosravi, 2013).

The Stimuli Mechanical Equation

The mechanical equation of stimuli can be written as:

$$I_m\ddot{q} + D\dot{q} - r\tau = u \qquad (4)$$

Here, q is the vector of shift motor angles and is the diametrical matrix of stimuli's moment of inertia. D is the diametrical matrix consisting of the friction factor of stimuli's viscose. These matrices are positive and bounded from up and down. Moreover, r, t and u are radius, cables' stretching vector and engines' torque vector, respectively (Khosravi and Taghi, 2013).

The dynamic equation factors of the stimuli for the cable-driven planar KNTU robot follow:

$$I_m = 2.43\ Kg.cm^2 \qquad (5)$$

r=3.5cm and N=50. The friction factors of the stimuli's viscose D have not been considered.

Now assume that engines' shift angle vector (q) equals 0 when the final executive is located at the center of frame. An angular change in q causes aalong the cables. So we can write (Khosravi, 2013):

$$\Delta L = rq = L - L_0 \quad \Longrightarrow \quad q = r^{-1}(L - L_0) \tag{6}$$

is cables' length vector in x=0. Given and a derivation of the above-mentioned relation we will have:

$$\dot{q} = r^{-1}\dot{L} = r^{-1}J\dot{X}, \quad \ddot{q} = r^{-1}J\ddot{X} + r^{-1}\dot{J}\dot{X} \tag{7}$$

As the elements of Jacobsian matrix are numerical, its derivation will be a zero matrix. So:

$$\ddot{q} = r^{-1}J\ddot{X} \tag{8}$$

Inserting the above equation in the dynamic equation of stimuli results in:

$$I_m\left(r^{-1}J\ddot{X}\right) - r\tau = u \quad \Rightarrow \quad \tau = r^{-1}\left(I_m r^{-1}J\ddot{X} - u\right) \tag{9}$$

And inserting this relationship in the dynamic equation of cable-driven robots generates:

$$M(X)\ddot{X} + G(X) = -J^T\left[r^{-1}\left(I_m r^{-1}J\ddot{X} - u\right)\right] \quad \Rightarrow \quad \left(rM(X) + J^T I_m r^{-1}J\right)\ddot{X} + rG(X) = J^T u \tag{10}$$

So

$$M_{eq}(X)\ddot{X} + G_{eq}\left(X, \dot{X}\right) = J^T u \ , \quad M_{eq}(X) = \left(rM(X) + J^T I_m r^{-1}J\right) \ , \quad G_{eq}(X) = rG(X) \tag{11}$$

The general dynamic equation of system may be written as:

$$\ddot{X}_i(t) = f_i\left(X_i, \dot{X}_i\right) + g_{ij}(X_i)u_j(t) \ , \quad f_i\left(X_i, \dot{X}_i\right) = \frac{-G_{eq_{ij}}(X_i, \dot{X}_i)}{M_{eq_{ij}}(X_i)} \ , \quad g_{ij}(X) = \frac{1}{M_{eq_{ij}}(X_i)}J^T \tag{12}$$

$u_j(t) = [u_1 \quad u_2 \quad u_3 \quad u_4]^T$ is the control vector and $X_i(t) = [x \quad y \quad \phi]^T$ is the state vector of system. Also $f_i\left(X_i, \dot{X}_i\right)$ and $g_{ij}(X_i)$ are the dynamic of target system.

Given the number of robot's freedom degrees (n=3) and a redundancy degree in stimuli (j=1, …4, 4 stimuli) the relations resulted from controller (3 controllers, i=1,2,3) and stimuli's input follow:

$$u_k = (J^T)^{\dagger}u_{1_i} + rQ \tag{13}$$

$(J^T)^{\dagger}$is the virtual reverse matrix of J^T and Q is the void space of J^T matrix:

$$J^T Q = 0 \quad \Rightarrow \quad Q = -\begin{bmatrix} 0.5 \\ 0.5 \\ 0.5 \\ 0.5 \end{bmatrix} \tag{14}$$

This system may be rewritten as:

$$\ddot{X}_i = f_i + g_{ij}.\left((J^T)^{\dagger}u_{1_i} + rQ\right) = f_i + g_{ij}.rQ + g_{ij}(J^T)^{\dagger}u_{1_i} \tag{15}$$

$$\ddot{X}_i = a_i + b_{ii}u_{1_i} \tag{16}$$

$$a_i = f_i + g_{ij}.rQ, \quad b_{ii} = g_{ij}(J^T)^{\dagger} \tag{17}$$

In the above equation $a_i = \hat{a}_i + \Delta a_i$ and $b_{ii} = \hat{b}_{ii} + \Delta b_{ii}$ in which Δa_i and Δb_{ii} represent indefiniteness in the system parameters. In the target system, the dynamic vector a_i is not completely known but can be approximated as $\hat{a}_i$. It is assumed that the approximation error of a_i is limited to the known function of $A_i = A_i(X_i, \dot{X}_i)$. So we will have:

$$|\hat{a} - a| \leq A \tag{18}$$

Although the controlling production matrix of b may be unknown, non-linear and variable in terms of time, it has the following definite range:

$$b = (I + \Delta)\hat{b}, \quad \Delta_{ij} \leq D_{ij} \tag{19}$$

The nominal mass of the final executive in this robot is m=2.5kgr. Its load weight changes based on $|\Delta m| \leq 1\ Kgr$ in various experiments .

$a_i$andb_{ii} functions are written as:

$$a_i = f_i + g_{ij}.rQ = \begin{bmatrix} 0 \\ \frac{9.8}{m + 0.484} \\ 0 \end{bmatrix} \tag{20}$$

$$b_{ii} = g_{ij}\,(J^T)^{\dagger} = \begin{bmatrix} \frac{0.6241}{\beta}\alpha & -\frac{0.6241}{\beta}\alpha & \frac{0.6241}{\beta}\alpha & -\frac{0.6241}{\beta}\alpha \\ -\frac{0.781}{\beta}\delta & -\frac{0.781}{\beta}\delta & \frac{0.781}{\beta}\delta & \frac{0.781}{\beta}\delta \\ \frac{12.106}{\beta}\sigma & -\frac{12.106}{\beta}\sigma & -\frac{12.106}{\beta}\sigma & \frac{12.106}{\beta}\sigma \end{bmatrix} . \begin{bmatrix} 0.4006 & -0.3201 & 0.0207 \\ -0.4006 & -0.3201 & -0.0207 \\ 0.4006 & 0.3201 & -0.0207 \\ -0.4006 & 0.3201 & 0.0207 \end{bmatrix} =$$

$$\begin{bmatrix} \frac{0.2857m+0.1383}{m^2+0.793114m+0.149607} & 0 & 0 \\ 0 & \frac{0.2857m+0.0883}{m^2+0.793114m+0.149607} & 0 \\ 0 & 0 & \frac{m^2+0.793143m+0.149633}{m^2+0.793114m+0.149607} \end{bmatrix} \quad (21)$$

$$\alpha = 1612.0636m + 780.285$$
$$\delta = 1612.0636m + 498.266$$
$$\sigma = 12.25m^2 + 9.716m + 1.833$$
$$\beta = 5642.223m^2 + 4474.927m + 844.112$$

Approximated dynamics:

$$\hat{a}_i = \begin{bmatrix} 0 \\ 3.284 \\ 0 \end{bmatrix}, \qquad \hat{b}_{ii} = \begin{bmatrix} 0.10171 & 0 & 0 \\ 0 & 0.09574 & 0 \\ 0 & 0 & 1.000012 \end{bmatrix} \quad (22)$$

The Sliding Mode Control of a Cable-driven Parallel Robot

Designing a Sliding Mode Controller

To design a sliding mode controller we first define the system error vector as:
$e_i = X_{d_i} - X_i$ in which $X_{d\,i} = [x_d \quad y_d \quad \phi_d]^T$ is the desired amount of the system's state.

To define a sliding mode controller we need to determine an appropriate sliding surface. The sliding surface of a common sliding mode controller for a system is generally defined as:

$$S_i = \left(\frac{d}{dt} + \lambda_i I_{3\times3}\right)^{n-1} . e_i \quad (23)$$

The system is quadratic (n=2) and the linear slide surface follows:

$$S_i = \dot{e}_i + \lambda_i I_{3\times3}. e_i \quad (24)$$

To stable statuses on the slide surface, the first part of the controlling signal is equated to zero when uncertainties of model's parameters are eliminated from the sliding surface.

$$\dot{S}_i = \ddot{e}_i + \lambda_i I_{3\times3}. \dot{e}_i = 0 \quad (25)$$

To derivate the error and insert it in the above relation we have:

$$\dot{S}_i = \left(\ddot{X}_{d_i} - \ddot{X}_i\right) + \lambda_i I_{3\times3}. \dot{e}_i = 0 \quad (26)$$

So

$$u_{1_{eq}} = \frac{1}{\hat{b}}\left(\ddot{X}_d - \hat{a} + \lambda_i I_{3\times3}. \dot{e}\right) = \hat{b}^{-1}\tilde{u}_1 \quad (27)$$

To satisfy the desired condition, the second part of controlling signal is defined as:

$$u_{1_r} = K_i I_{3\times3}. sign(S_i) \quad (28)$$

So in general the controlling signal of the target system follows:

$$u_1 = \frac{1}{\hat{b}} u_{1_r} + u_{1_{eq}} \quad (29)$$

To prove the controlled system's stability through the controlling signal represented in the equation we define the Liapanov function as:

$$V = \frac{1}{2} S_i^T . S_i \tag{30}$$

Stability conditions the Liapanov function and its derivation to be positive definite (P.D) and negative semi-definite (N.S.D).
It is clear that the chosen function satisfies the first condition. Now to study the second condition we derivate Liapanov function and insert it in the associated relations:

$$\dot{V} = S_i^T . \dot{S}_i = S_i^T . \left(\ddot{X}_{d_i} - (a_i + b_{ii} u_1) + \lambda \dot{e}\right) \tag{31}$$

To reach the level, the following condition must be satisfied:

$$\frac{1}{2} \frac{d}{dt} S_i^T . S_i \leq -\eta_i I_{3\times3} . |S_i| \tag{32}$$

By insertinga_i, b_{ii} and u_1 in the derivation of Liapanov function we have:

$$S.\left(\ddot{X}_d - a - b\left(\frac{1}{\hat{b}}\left[\ddot{X}_d - \hat{a} + \lambda.\dot{e} + K.sign(S)\right]\right) + \lambda\dot{e}\right) \leq -\eta|S| \;\; \Rightarrow$$

$$S.\left(\ddot{X}_d - a - b\hat{b}^{-1}\ddot{X}_d + b\hat{b}^{-1}\hat{a} - b\hat{b}^{-1}\lambda.\dot{e} - b\hat{b}^{-1}Ksign(S) + \lambda\dot{e}\right) \leq -\eta|S| \;\; \Rightarrow$$

$$S.\left(\ddot{X}_d\left(I - b\hat{b}^{-1}\right) + b\hat{b}^{-1}(\hat{a} - a) + \lambda.\dot{e}\left(I - b\hat{b}^{-1}\right) - b\hat{b}^{-1}Ksign(S)\right) \leq -\eta|S| \;\; \Rightarrow \tag{33}$$

So to establish $|\hat{a} - a| \leq A$ we replace $\hat{a}$by $a + (\hat{a} - a)$. So:

$$S.\left(\ddot{X}_d\left(I - b\hat{b}^{-1}\right) + b\hat{b}^{-1}(a + [\hat{a} - a] - a) + \lambda.\dot{e}\left(I - b\hat{b}^{-1}\right) - b\hat{b}^{-1}Ksign(S)\right) \leq -\eta|S| \Rightarrow$$

$$S.\left(\ddot{X}_d\left(I - b\hat{b}^{-1}\right) + \left(b\hat{b}^{-1} - I\right)a + b\hat{b}^{-1}(\hat{a} - a) + \lambda.\dot{e}\left(I - b\hat{b}^{-1}\right) - b\hat{b}^{-1}Ksign(S)\right) \leq -\eta|S| \tag{34}$$

Simplification and derivation generates:

$$S.\left(\left(I - b\hat{b}^{-1}\right)\left(\ddot{X}_d - a + \lambda\dot{e}\right) + b\hat{b}^{-1}(\hat{a} - a) - b\hat{b}^{-1}Ksign(S)\right) \leq -\eta|S| \;\; \Rightarrow$$

$$S.\left(I - b\hat{b}^{-1}\right)\tilde{u}_1 + S.b\hat{b}^{-1}(\hat{a} - a) - b\hat{b}^{-1}K|S| \leq -\eta|S| \;\; \Rightarrow$$

$$K|S| \geq S.\hat{b}b^{-1}\left(I - b\hat{b}^{-1}\right)\tilde{u}_1 + S.\hat{b}b^{-1}.b\hat{b}^{-1}(\hat{a} - a) + \hat{b}b^{-1}\eta|S| \tag{35}$$

To establish the above relation we must choose the K controlling portion as:

$$K \geq \frac{A(I+D) - D|\tilde{u}_1| + \eta}{I+D} \tag{36}$$

$\eta$is a positive coefficient which determines the switching range. Therefore, selecting the appropriate error dynamic and satisfying the required conditions, desired control input is resulted.
If the change range of dynamics *f* and *b* grows up to 10%, K changes based on the following relation:

$$K \geq \frac{1.1\times A(I + 1.1\times D) - 1.1\times D|\tilde{u}_1| + \eta}{I + 1.1\times D} \tag{37}$$

Practical Simulation Results

Given the above explanations, we simulate the cable-driven KNTU robot through simulating the proposed method in the Simulink part of MATLAB Software to validate it.
To evaluate the practical characteristics of cable-driven robots, we simulated three desired but different paths in simulation mechanisms and studied systems' detection capability. Moreover note that the stretching force of cables should be positive in all the motion exercises and maneuvers.
As you see in Figure 2 we simulated the closed loop controlling system of the stretching cable-driven robot in the MATLAB Software.

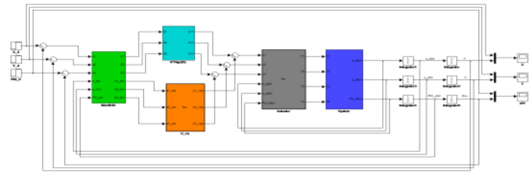

Figure 2: Simulation of the controlling closed loop system of cable-driven planar robot in MATLAB Software

RESULTS AND DISCUSSION

Results

In the first two experiments we assumed that the final executive was located in and studied its situation and mechanism's reaction through simulating the stair function as a reference input along x and .

Note that the stair input is one of the worst inputs inserted in a cable because it needs a sudden change in force. The stair input can stimulate the majority of cable dynamics. Therefore, evaluating the stair response of a cable-driven KNTU robot leads to an understanding of the response quality and practicality of a robot and its controlling system. We used a circular direction as the desired path for the next experiment which aimed to study the efficiency of cable-driven KNTU robots with a challenging and different reference path. The purpose of this experiment is to guide the final executive along a circle (radius=20cm) in the x and y plans and simultaneously maintains the angle change equal to zero.

In the first attempt of the final executive, we placed the robot in a zero position and studied behaviors of the mechanism by imposing the input as a desired position. By doing this experiment we aimed to evaluate detective ability of the system through simulating a stair with a range of 20cm along the x axis. Moreover, changes in the final executive's positions and angles had to be zero along y and z axes.

The results of inserting the mentioned input may be observed in Figure 3. As you can see, the detection error was so insignificant and the final executive followed the determined direction with an appropriate speed. The stretching forces of cables must always be positive. For instance the results of stretching forces in two cables that are almost positive are shown in Figure 4.

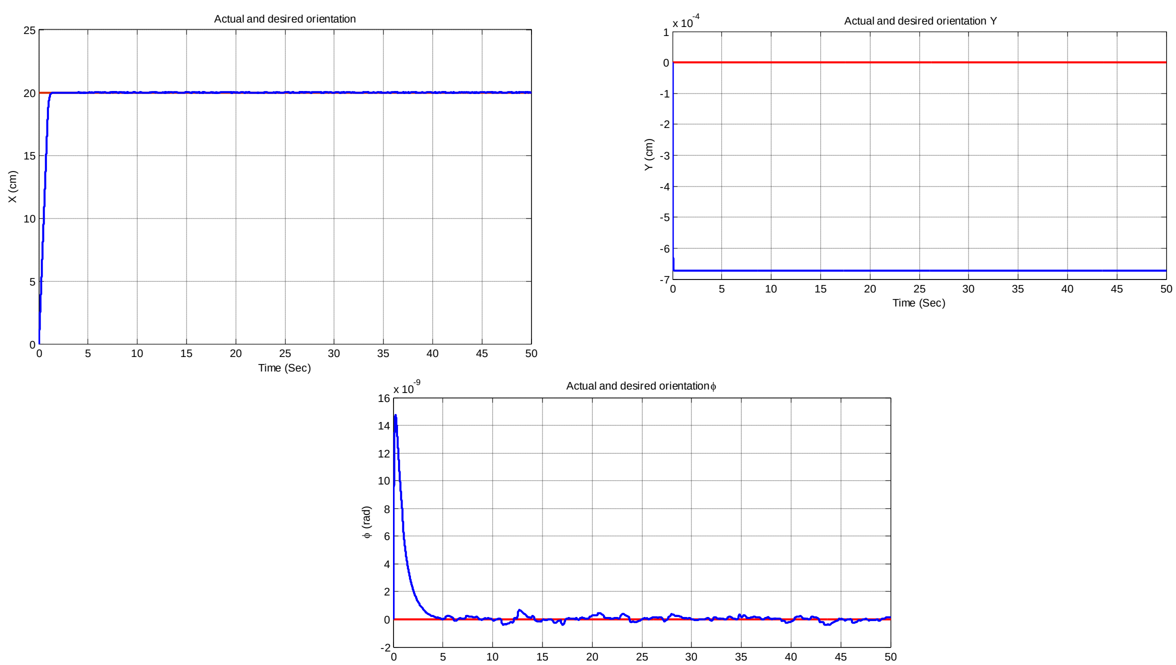

Figure 3: Results of the simulation by having $x_d = [20, 0, 0]^T$ as its input

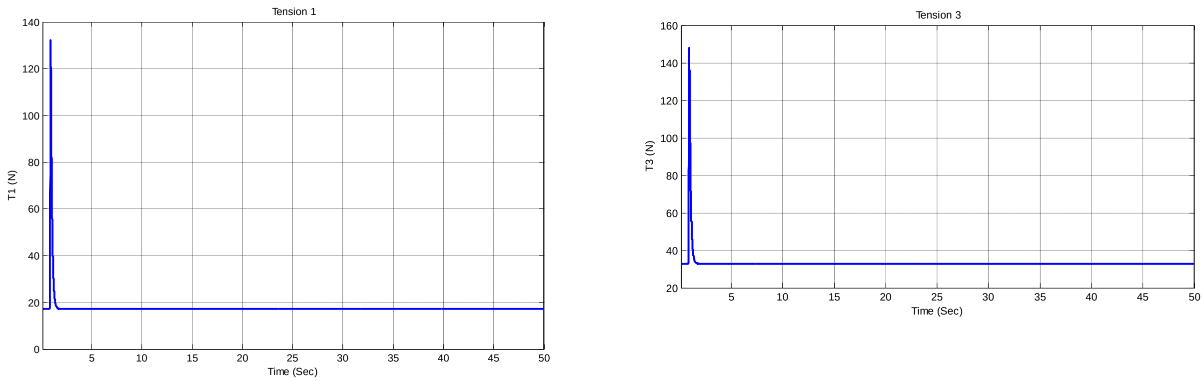

Figure 4: Cables' forces during the motion exercises having $x_d = [20, 0, 0]^T$ as the input

In the second experiment, assume that the desired place is a pure rotation and the final executive should move from the zero position and reach the place $x_d = \left[0, 0, \frac{\pi}{9}\ rad\right]^T$. As you may observe in figure 5, changes in the final executive follow a desired amount along x and y axes and practically poses the zero conditions.

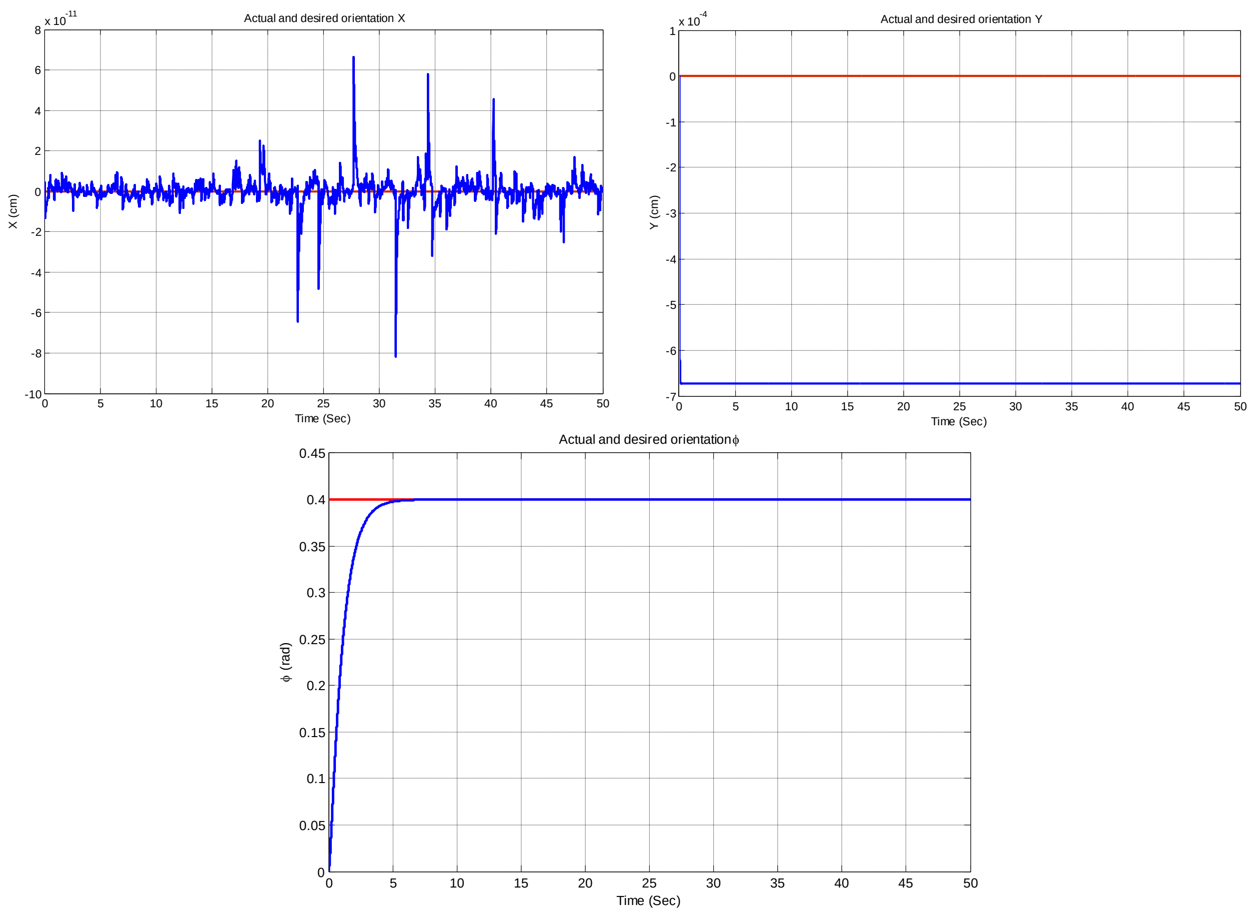

Figure 5: The results of simulation having $x_d = \left[0, 0, \frac{\pi}{9}\right]^T$ as its reference input

Figure 6 demonstrates the stretching forces of cables during motion maneuvers. As it may be observed the stretching forces of cables remain positive throughout the whole process.

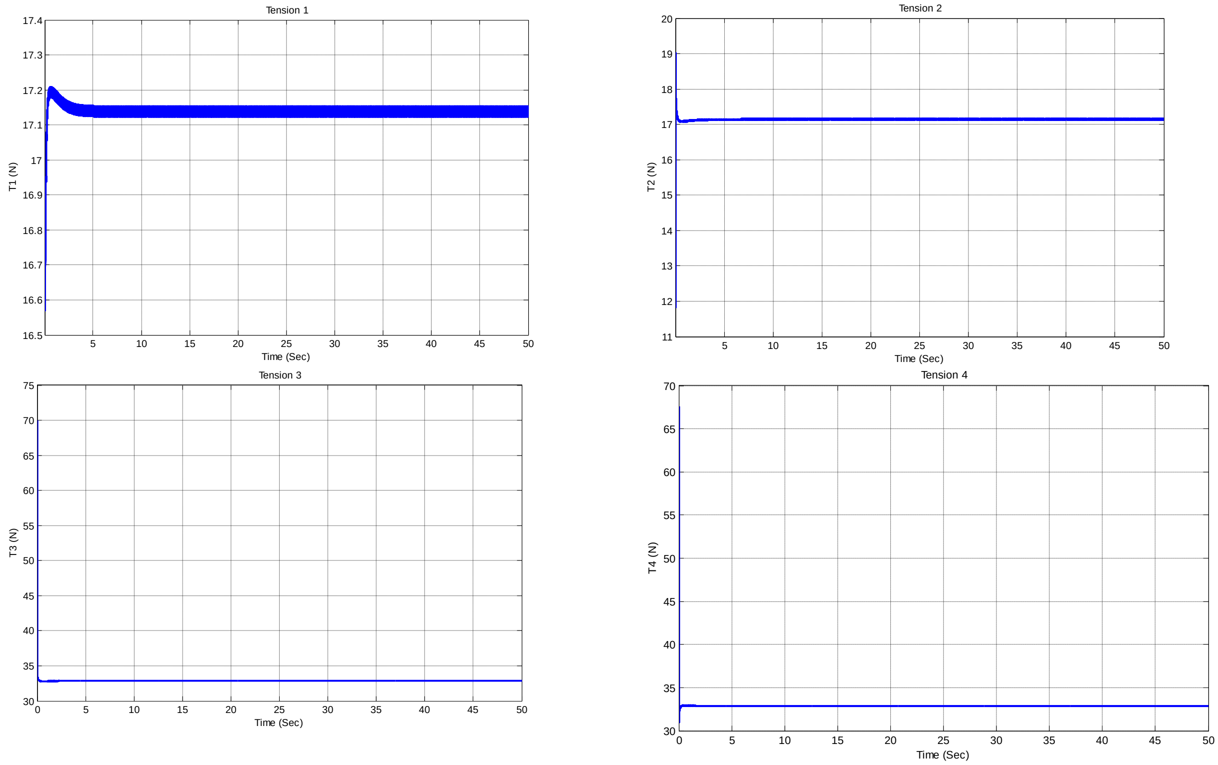

Figure 6: Cables' forces during the motion maneuvers having the input $x_d = [0, 0, \pi/9]^T$

In another experiment we used a circular profile as a desired direction to test the cable-driven KNTU robot and its efficiency in a different path. The purpose of this experiment was making the final executive to follow a circular path having the center of zero and the radius of 20cm in a plan in 10 seconds in a way that its angular changes remain zero throughout the whole path $\phi_d = 0$.
So the reference paths are selected as following:

$$x_d = 20\cos(0.2\pi t)$$
$$x_d = 20\sin(0.2\pi t)$$
$$\phi_d = 0$$

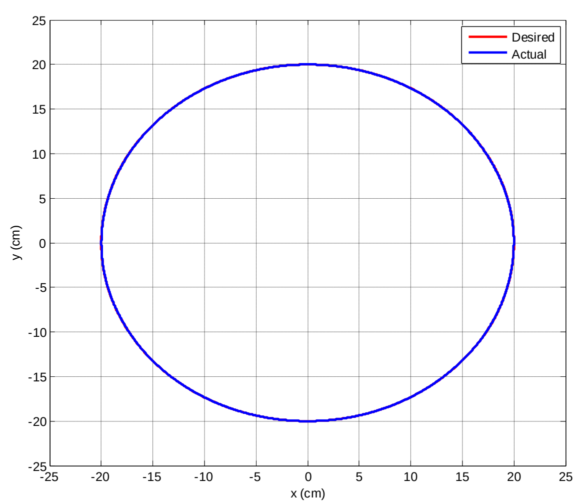

Figure 7: Simulation results with circular inputs

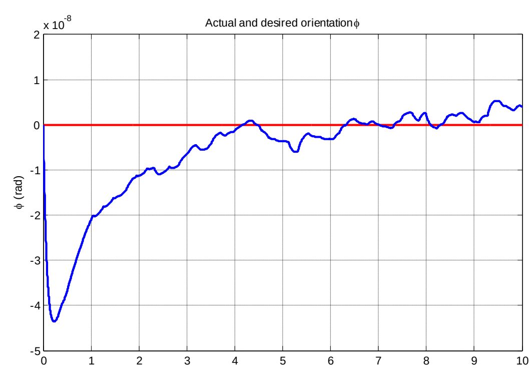

Figure 8: The ϕ angle during the circular motion maneuver

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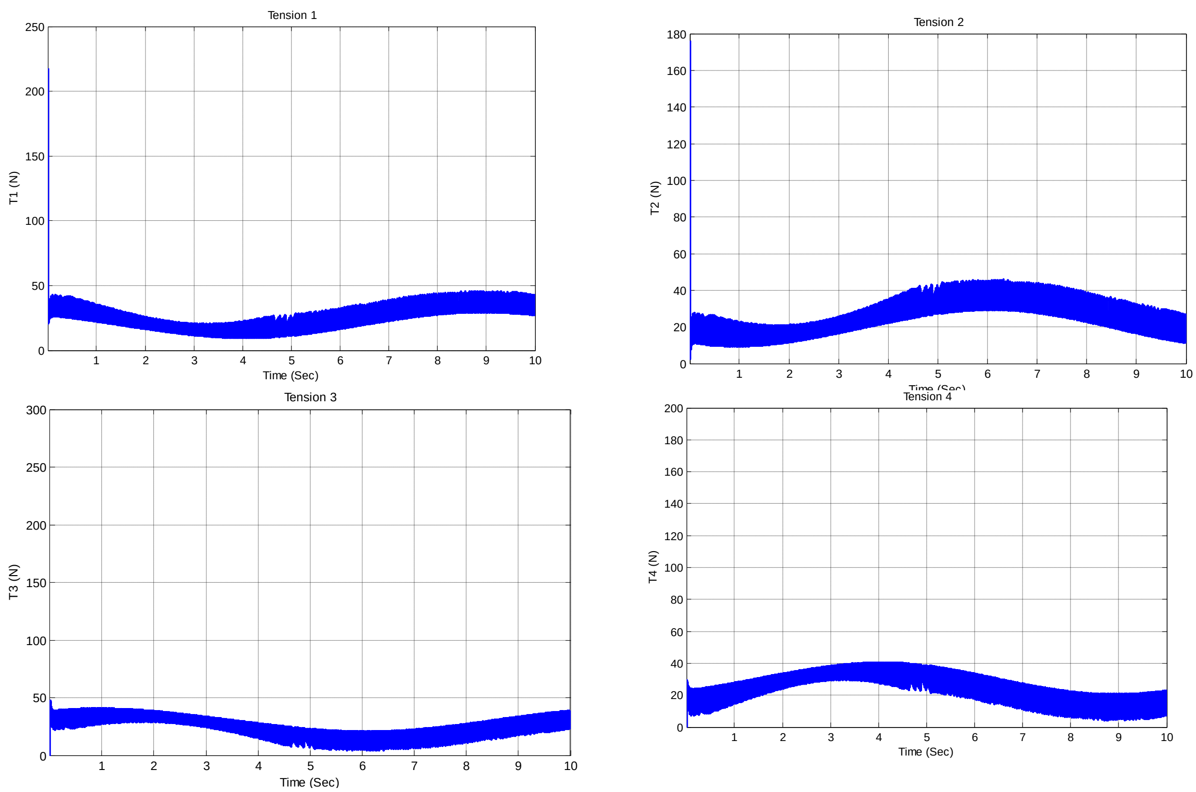

Figure 9: Cables' forces during the circular motion maneuver

Figure 7 demonstrates the reference circle and the real move of the final executive. As may be observed in figure 7, the robot has followed a reference path with the minimum possible error which is a desired result. Figure 8 shows the angular changes of the final executive during its circular movement and demonstrates that the system has little oscillations during the process of becoming zero and reaching the desired amount. The stretching forces of cables in this motion maneuver have been represented in Figure 8. Based on this figure, cables' forces are positive along the whole movement.

Achieved results indicate the superiority of sliding mode controller compared to the resistant PID controller. As it is observable, at the first attempt the detection error caused by the applied input was very insignificant and the final executive follows the determined direction with appropriate speed. Also during following the determined direction the final executive tolerates low fluctuation. Also as it is observable in the results the in changes of position and angle the final executive follows zero. Comparing the achieved results with PID controller it could be said that fluctuation in PID controller is more than fluctuation in sliding mode controller and sliding mode controller was faster in taking the mechanism to the optimal amount. At the next stage of simulation the changes of final executive along x and y axes are very insignificant and negligible and practically it reminds us of zero amount according to the defined conditions. Also the final executive has a good condition in terms of following the favorite direction and its motor-angle error is very insignificant and negligible. Based on the achieved results for PID controller, despite one initial severe fluctuation, changes of final executive along x axis were less than fluctuations during other times; whereas sliding mode controller had less initial fluctuation, but these fluctuations existed during the whole simulation process. In contrast it is possible to consider the changes of final executive in sliding mode controller much favorable than the PID controller. But the most important part of this stage is the motor-angle error of sliding mode controller which is insignificantly more than PID controller and it seems that in this respect PID has a better function.

By applying the parameters and running the simulations and considering a circular profile as the reference direction, it is observed that the movement of final executive has ideally covered the reference circle and very insignificant error is seen along the circular path of only some of the parts. As it has been said before, angle changes should also be zero during this maneuver. As the result of simulation with sliding mode controller shows, these changes ideally satisfy the zero condition. Comparing to PID controller, the detection errors are acceptable but compared to the sliding mode controller detection of circular profile is not favorable. Also angle changes on sliding mode controller have stability and better tend to zero; whereas in PID controller despite satisfying zero angle changes condition, these conditions have occurred in severer fluctuations.

Conclusion

Generally, controlling algorithms are defined and designed to have positive influences. The positive controlling effects differ in various parts of a mechanism. However, controlling algorithms are designed to improve the system. As it was mentioned the sliding mode controller has unique advantages and disadvantages. The results of our study demonstrated that the sliding mode controllers have caused positive stretching influences on the stability of the system in spite of the chattering phenomenon. Although some negligible detection errors in speed performance elements were observed, the controller succeeded to generate acceptable results. Many uncertainties of the system such as unsteadiness and friction were not considered.

Cable’s flexibility in such robots is another source of error which has not been considered in our study. Cable’s flexibility may cause position error in the final executive. In general, as it was discussed in chapter 4, the sliding mode controllers show excellent performance in many components specially the detection process resulted from the circular input. Also it has a better performance comparing the resistant PID controller in many conditions.

These results indicate that in case of appropriate choose of gain in a way that they can satisfy a series of conditions it is possible to have a better performance in terms of stability and other performance components. Based on the existence of positive forces in cables robot could preserve its structure and follow the defined directions.

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