

Dynamic Load Carrying Capacity of Spatial Cable Suspended Robot: Sliding Mode Control Approach

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Abstract: This paper proposes a control strategy for a cable-suspended robot based on sliding mode approach (SMC) which is faced to external disturbances and parametric uncertainties. This control algorithm is based on Lyapunov technique which is able to provide the stability of the end-effector during tracking a desired path with an acceptable precision. The main contribution of the paper is to calculate the Dynamic Load Carrying Capacity (DLCC) of a spatial cable robot while tracking a desired trajectory based on SMC algorithm. In finale, the efficiency of the proposed method is illustrated by performing some simulation studies on the ICaSbot (IUST Cable Suspended Robot) which supports 6 DOFs using six cables. Simulation and experimental results confirm the validity of the authors' claim corresponding to the accurate tracking capability of the proposed control, its robustness and its capability toward DLCC calculation.

Keywords: Cable Suspended Robot, Dynamic Load Carrying Capacity (DLCC), Sliding Mode Control

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1 INTRODUCTION

Cable transporter systems are widely used in industry such as high-rise elevators, cranes, conveyer belts, and tethered satellite systems, etc. A cable-suspended robot typically consists of a moving platform that is connected to a fixed base by several cables. A cable-suspended robot can precisely manoeuvre large loads and is resistant to environmental perturbations. The main advantages of cable suspended robots over conventional robots are: 1) larger workspace for the same overall dimension of the robot; 2) lightweight cables resulting in very safe and transportable system; and. The spatial sample is one particular type of cable robot with six cables. Alp and Agrawal [1] addressed the kinematic and dynamic models, workspace, trajectory planning, and feedback controllers for parallel cable manipulators, and demonstrated through simulation and experiments on a six-DOF cable suspended robot. However, cables have the unique property. They cannot provide compression force on an end-effector. This constraint leads to performance deterioration and even instability, if not properly accounted for in the design procedure. Several techniques have been suggested to guarantee positive tension in the cables while the end-effector is moving [1], [2]. In addition, using the null space of the Jacobian, workspace was studied that have positive cable tensions [3]. The statics workspace is defined as the set of positions wherein any operational force can be exerted on the end-effector with all positive cables tensions [4]. There have been a number of researchers who have applied varied controller and dynamic modelling for cable-actuated robots such as the feedback linearization control method. An algorithm toward calculation of Dynamic Load Carrying Capacity (DLCC) for rigid cable robot which is under controlling a closed loop controller was presented [5]. Also designing a sliding mode controller as a stabilizing controller for the given uncertain system has been used [6], finding the range of system states in terms of set points, substituting states in inequalities of the input so that constraints are satisfied.

In this paper, sliding mode approach is employed for stabilization and tracking a predefined trajectory. Also the DLCC of a cable robot is evaluated in a closed loop way using SMC method. Sliding mode is a nonlinear feedback control with variable structure with respect to the system states. The main advantage of sliding mode control is that the system is insensitive to extraneous disturbance and internal parameter variations while the trajectories are on the switching surface. There are two important factors that should be considered while calculating the DLCC of a robot at this method and they are the maximum torques that can be applied by motors and the maximum acceptable bounds of errors

that end-effector is permitted to move within [7]. The required constraints can be easily satisfied by the aid of proposed iterative algorithm in this paper which is based on SMC approach. Unlike general control laws, sliding mode control is more robust and is easy to be implemented. Sliding Mode Control algorithm as a robust control method can also be discussed for identification of maximum dynamic load carrying capacity, in the presence of disturbance and system uncertainties [8].

The paper is organized as follow: first dynamic equations of spatial cable robot are derived. Next a Sliding Mode Control as a powerful method of uncertain nonlinear systems in the condition of absence of disturbance and in the presence of disturbance is presented. Finally an algorithm is proposed to compute maximum allowable load by considering the limiting factors. In the last section some simulation results are derived and are compared with experimental tests in order to show the validation of the proposed theories.

2 DYNAMICAL MODELLING

For the spatial case, assume a triangular shaped end-effector like Fig. 1, which is suspended through 6 cables and has 6 degrees of freedom as x, y, ψ, Θ, ϕ . It is provable that the dynamical equation may be shown as [1]:

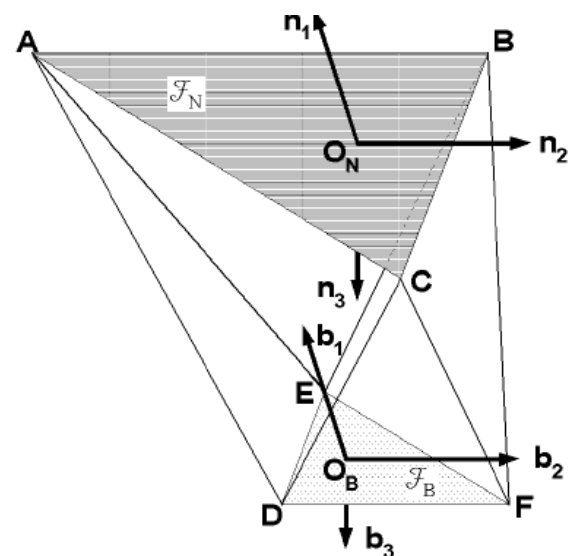


Fig. 1 Spatial model of cable robot

$$D(X)\ddot{X} + C(X, \dot{X})\dot{X} + g(X) = -s^T(q(X))T; \quad (1)$$

where:

$$D = \begin{bmatrix} mI_3 & 0 \\ 0 & P^TIP \end{bmatrix}; C = \begin{bmatrix} 0_3 \\ P^T \{ I\dot{P}\dot{\theta} + (P\dot{\theta}) \times I(P\theta) \} \end{bmatrix}; g = \begin{bmatrix} 0 \\ 0 \\ -mg \\ 0_3 \end{bmatrix}; \quad (2)$$

$$S = \begin{bmatrix} \frac{\partial q_i}{\partial x_j} \\ \dots \\ \frac{\partial q_i}{\partial x_j} \end{bmatrix}; P = \begin{bmatrix} 1 & 0 & -\sin\theta \\ 0 & \cos\mu & \sin\mu/\cos\Theta \\ 0 & -\sin\mu & \cos\mu/\cos\Theta \end{bmatrix}; \dot{\theta} = \begin{bmatrix} \dot{\Psi} \\ \dot{\Theta} \\ \dot{\phi} \end{bmatrix}$$

'T' is the vector of cables tension, 'X' is the vector of DOFs of the system, m is the mass of the end-effector, 'I' is the moment of inertia of the end-effector and 'q' is the length of the cables. Furthermore, the dynamics of the motor is as follow:

$$T = 1/r(\tau - J(d/dt(\partial\beta/\partial X)\dot{X} + \ddot{X}(\partial\beta/\partial X)) - C(\partial\beta/\partial X)\dot{X}) \quad (3)$$

where 'J' is the matrix of rotary inertia of the motors, 'c' is the viscous friction matrix of the motors, 'β̇' is the vector of angular velocity of the motors and 'τ' is the vector of motors torque. By coupling these two dynamics, we have:

$$T = 1/r(\tau - J(d/dt(\partial\beta/\partial X)\dot{X} + \ddot{X}(\partial\beta/\partial X)) - C(\partial\beta/\partial X)\dot{X}) \quad (4)$$

$$D(X)\ddot{X} + C(X, \dot{X})\dot{X} + g(X) = -S^T(q(X))T;$$

3 CONTROL SCHEME

The following equation is considered:

$$\dot{X}^{n-1} = f(X) + b(X)u \quad (5)$$

As well as the following sliding surface:

$$s = \left(\frac{d}{dt} + \lambda\right)^{n-1} \tilde{x} \quad (6)$$

where:

$$X = [\tilde{x}, \tilde{x}', \tilde{x}'', \dots, \tilde{x}^{(n-1)}] \quad (7)$$

$$\tilde{x} = x - x_d \quad (8)$$

As it is shown in Ref. [8], control law for tracking ($\tilde{x} \rightarrow 0$) has the following form:

$$U = u_{eq} - k.Sig(n(s)) \quad (9)$$

In which 'u_{eq}' is Equivalent Control Law (as defined with Phillipov law). It is noticeable that by applying this control law we actually apply $s\dot{s} < \varepsilon$ ($\varepsilon < 0$) condition.

In particular, the Lyapunov sliding condition forces system states to reach a hyperplane and keeps them sliding on this hyperplane. Essentially, a SMC design is composed of two phases: hyperplane design and controller design. However, in this paper a method proposed by Slotine is used [9]. In this method, the sliding surface is defined as:

$$s = \left(\frac{d}{dt} + \lambda\right)(x - x_d) = (\dot{x} - \dot{x}_d) + \lambda(x - x_d) \quad (10)$$

To determine the control law, the derivative of the sliding surface must be determined:

$$\dot{s} = (\ddot{x} - \ddot{x}_d) + \lambda(\dot{x} - \dot{x}_d) \quad (11)$$

Since sliding condition is defined by:

$$\dot{s} \leq -k.Sig(s) \quad (12)$$

So, in order to satisfy the sliding condition, Eq. (11) must be written as:

$$(\ddot{x} - \ddot{x}_d) + \lambda(\dot{x} - \dot{x}_d) = -k.Sig(s) \quad (13)$$

By substituting \ddot{X} from Eq. (1), Eq. (13) becomes:

$$D(X)\left\{\ddot{X}_d - \lambda(\dot{X} - \dot{X}_d) - k.Sig(s)\right\} + C(X, \dot{X})\dot{X} + g(X) = -S^T(q(X))T \quad (14)$$

Combining Eq. (3), (14) they can be expressed based on motor torque:

$$\tau = S_J^{-T} \left\{ rD[ksign(s)] + rD\lambda(\dot{X} - \dot{X}_d) - rD\ddot{X}_d - rC\dot{X} - rg \right\} + J\ddot{\beta} + c\dot{\beta} \quad (15)$$

4 SIMULATION OF CONTROL PROCEDURE

To investigate the proposed controller, some simulation studies are presented for spatial robot. In these studies, a circular trajectory is assumed that end-effector with controller follow the path perfectly. The simulation results are shown in Figures. The parameters used in simulation are given in Tables 1 and 2.

Table 1 Reference input for spatial simulation

$t \leq 4,$ $x = 0.05 \cos(4\pi t^2/64),$ $y = 0.05 \sin(4\pi t^2/64),$ $t > 4$ $x = 0.05 \cos(4\pi ((-t + 8)^2)/64)$ $y = -0.05 \sin(4\pi ((-t + 8)^2)/64)$ $z = 0.45 ; \psi = 0$ $\Theta = 0 ; \varphi = 0$
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Table 2 Characteristics of spatial system

Name	Symbol	Value	Unit
Momentum of inertia of the end-effector	I	$I_{xx} = I_{yy} = 1847779.15 * 1$ $I_{zz} = 2 * I_{xx}$	$kg.m^2$
Control Coefficient	λ	$diag [20]$	
Control gain	K	$diag [200]$	
Radius of the motor	r	$diag [0.015]$	m
Damping Coefficient	c	$diag [0.01]$	$N.m/raa$
Momentum of inertia of the pulley	J	$diag [3309.21 * 10^{(-9)}]$	$kg.m^2$
Mass of the end-effector	m	1	kg

Motor input-output path, torque, cable tension and error profile will be as bellow:

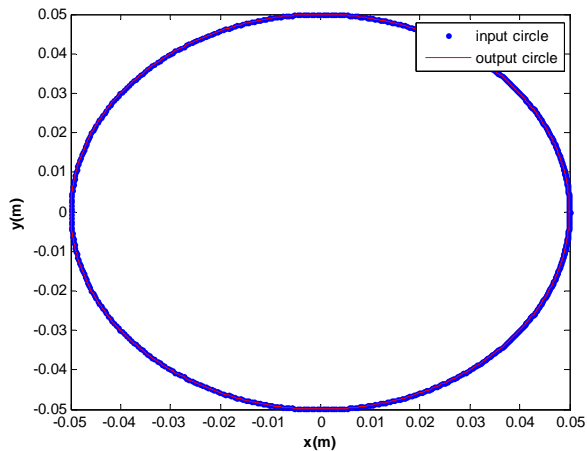


Fig. 2 Input-output path of spatial simulation in absence of disturbance

It is observable that all of the cable tensions are positives as was expected. Practical robotic systems have inherent system perturbations such as parametric uncertainties and external disturbances such as static friction, noise in control signals, etc.

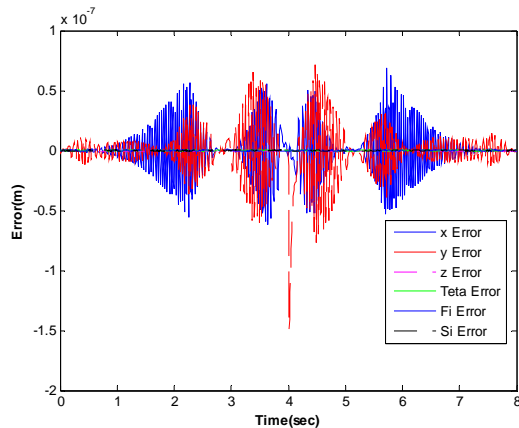
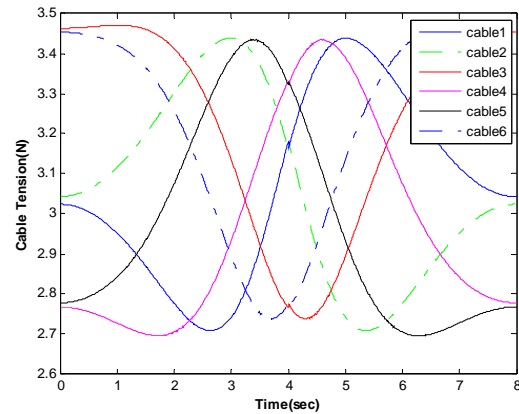
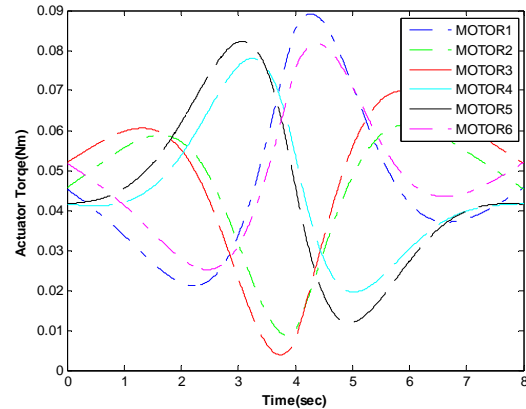


Fig. 3 Torques, tensions, and error profiles of spatial simulation in absence of disturbance

In this paper, the behaviour of the cable robot in the presence of external disturbances is considered. Let us denote the disturbances as $d = 0.5 \sin(5t)$. The real dynamic equation of the cable robot with the disturbance term is represented as follows:

$$\tau = S^{-1} \left\{ rD [ksign(s)] + rD\lambda (\dot{X} - \dot{X}_d) - rD\ddot{X}_d - rC\dot{X} - rg + s^T J \ddot{\beta} + s^T C \dot{\beta} \right\} + d \tag{16}$$

Dynamic response of the system in presence of disturbance is shown in Figs. 4 and 5.

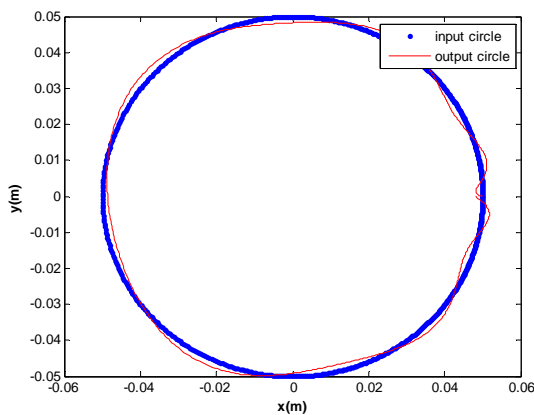


Fig. 4 Input-output path of spatial simulation in presence of disturbances

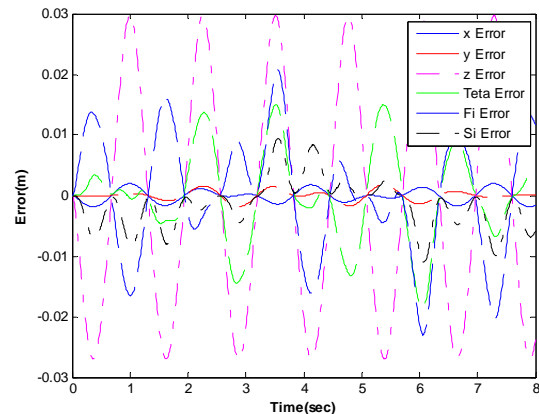
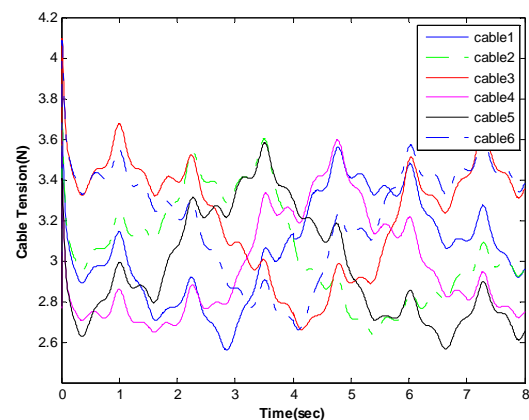
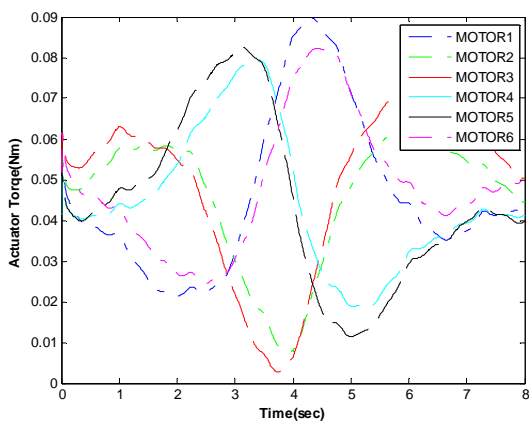


Fig. 5 Torques, tensions, and error profiles of spatial simulation in presence of disturbances

It can be seen that the destructive external disturbance is successfully filtered by the aid of proposed SMC controller since the fluctuations are neutralized by automatically switching of actuators' torque which eventually provides a smooth tracking with an acceptable error.

5 DETERMINING MAXIMUM LOAD_CARRYING CAPACITY

The dynamic load-carrying capacity (DLCC) of a robot is defined as the load that the cables can carry on a defined trajectory. The dynamics of cable robot can be used to extend its payload capability while taking into account torque and tension as realistic constraints. By considering the actuator torque and accuracy constraints and adopting a logical computing method, the maximum load-carrying capacity of a cable robot for a predefined trajectory can be computed. The actuator torque constraint is formulated on the basis of typical torque-speed characteristics of DC motors.

$$\tau_u = k_1 - k_2 \dot{q}; \tau_l = -k_1 - k_2 \dot{q} \tag{17}$$

where τ_u and τ_l are the upper bound and the lower bound of actuator constraint, respectively. The coefficients k_i are defined as

$$k_1 = T_s; k_2 = T_s / w_{nl} \tag{18}$$

where T_s is the stall torque and w_{nl} is the maximum no-load speed of the motor. The algorithm used for finding DLCC in closed-loop case is shown in Fig. 6.

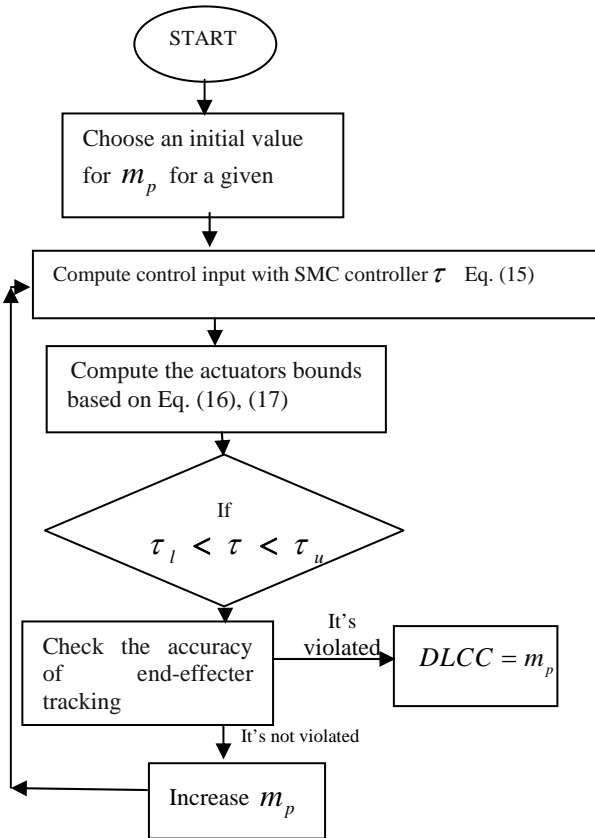


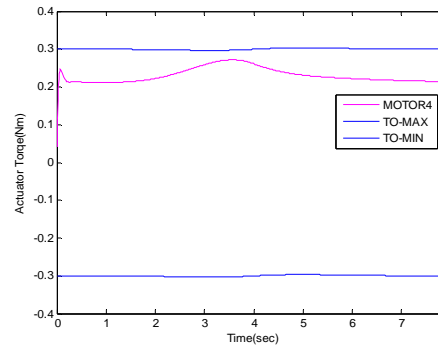
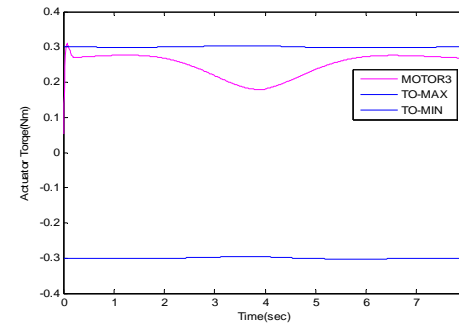
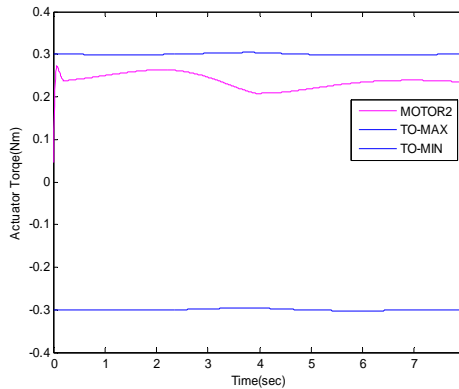
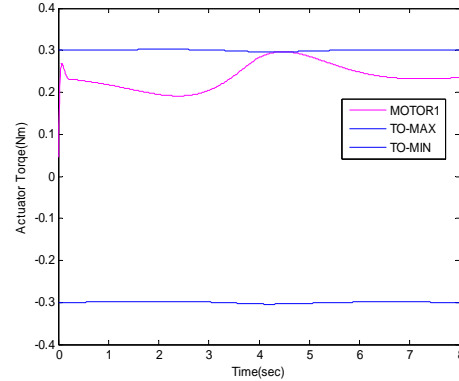
Fig. 6 Flowchart of computing dynamic load carrying capacity

The actuator torque at each point is computed, and using the computational procedure, the upper and lower bounds on torque available for dynamic load and the accuracy of end effector tracking is determined. Using this method we can find DDLC in each time so it will be identified for whole trajectory.

6 SIMULATION OF THE DLCC ALGORITHM

Saturation motors' torque are presented in Fig.7, and as it can be seen the first and fifth motors are saturated at the middle of the simulation.

As it is shown in Fig. 8 that error constraint is saturated for the system. By applying the proposed algorithm for closed loop plant the maximum allowable load computed as $m_p = 4.7kg$.



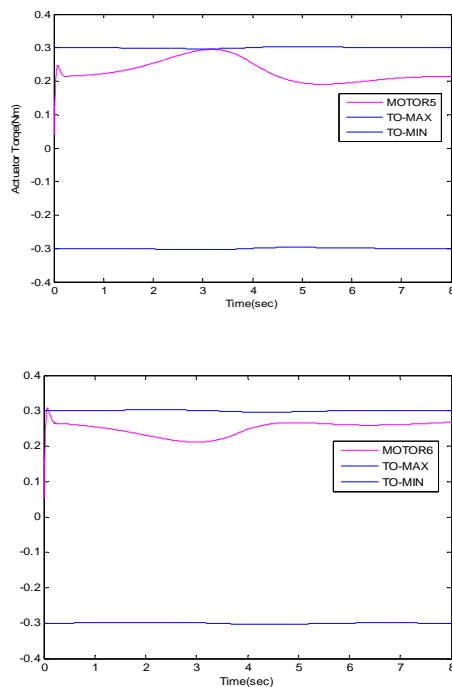


Fig. 7 Saturation profile of motor torques of spatial simulation

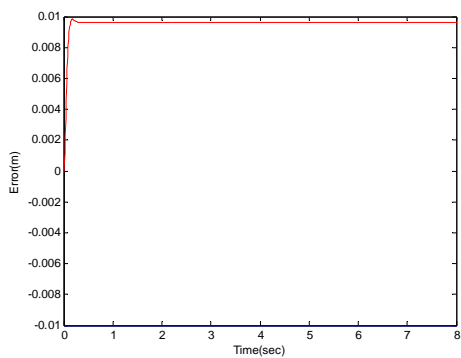


Fig. 8 Error profiles of spatial simulation

6 EXPERIMENTAL TESTS

In this step, these simulation results should be verified by experiment. To provide an example of the possible uses of spatial cable suspended robot which is designed and manufactured in IUST supporting six DOFs (Fig. 9), a simple curve experiment is performed.



Fig. 9 Scheme of the designed IUST cable robot

The geometrical properties of the cable suspended robot in IUST are listed in Table 3.

Table 3 features of the designed IUST cable robot

Body	
Height	120cm
Side length of base triangle	100-200 cm
Weight	350 kg
End effector	
Side length of base triangle	17 cm
Thickness	8 cm
weight	1,100 gr

The controller achieves the desired steady-state values with a small error, which may be due to system uncertainties such as friction in the pulley. Tracking of the end-effector in comparison to simulation result is shown in Fig. 10.

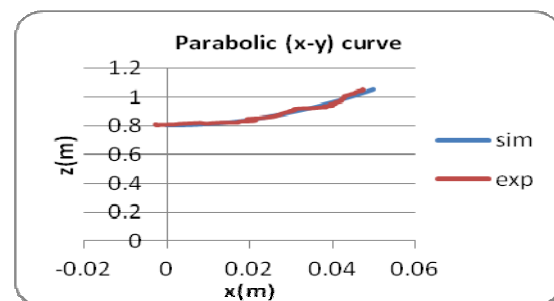


Fig. 10 Tracking of the end-effector in comparison to simulation results

Related angular velocity of the motors and its comparison to simulation results are also shown in Fig. 11.

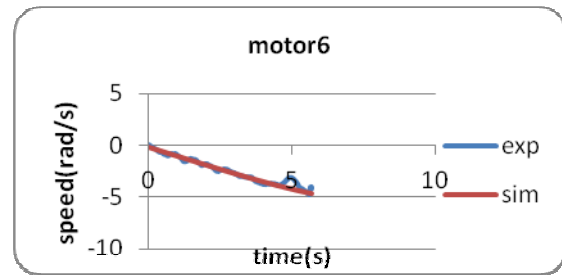
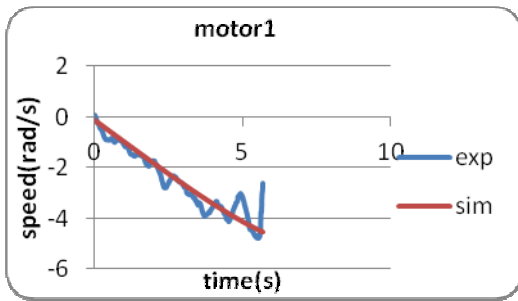
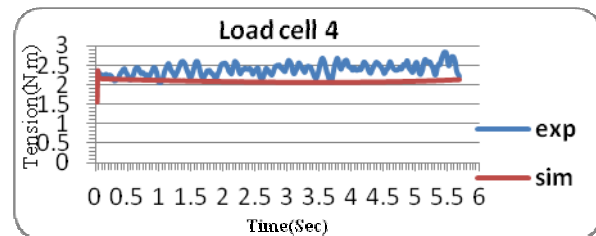
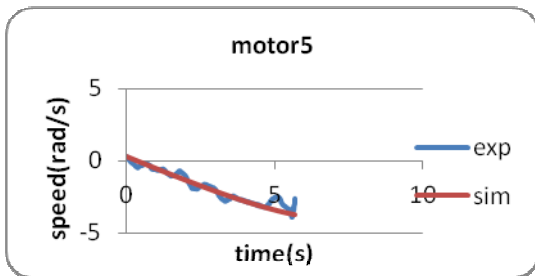
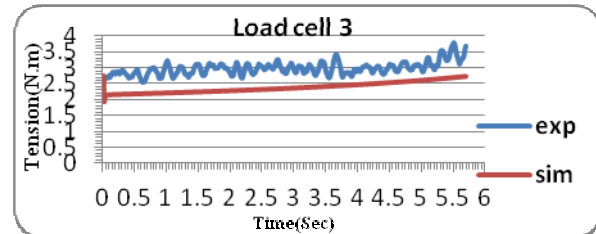
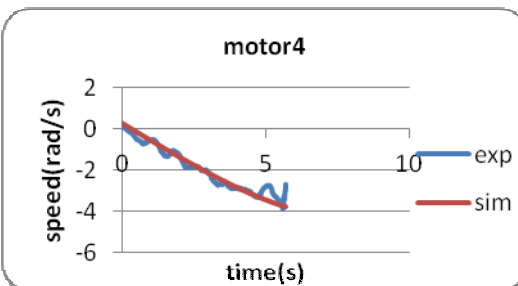
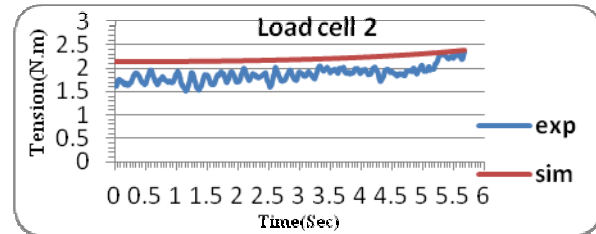
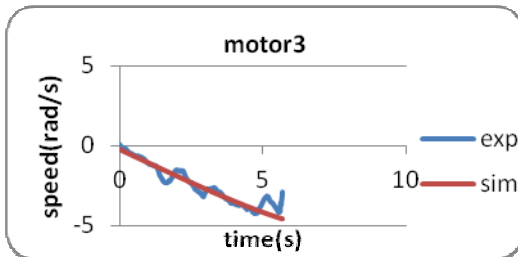
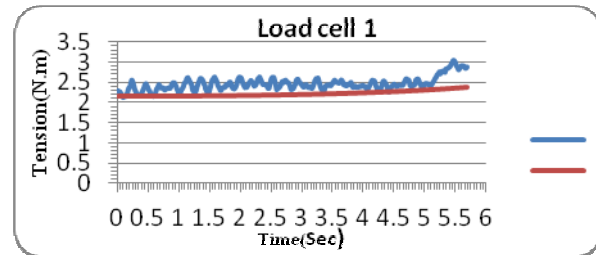
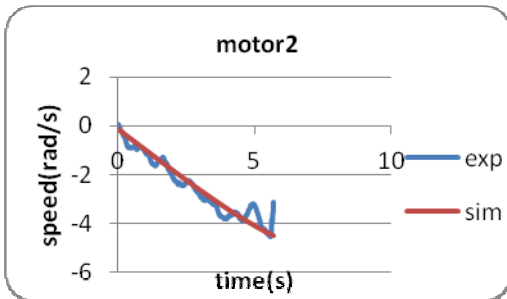


Fig. 11 Angular velocity of the motors and its comparison to simulation results

As it is shown in Fig. 11, the system response of the experiment shows a good match with simulation results. Cable tensions are shown in Fig. 12.



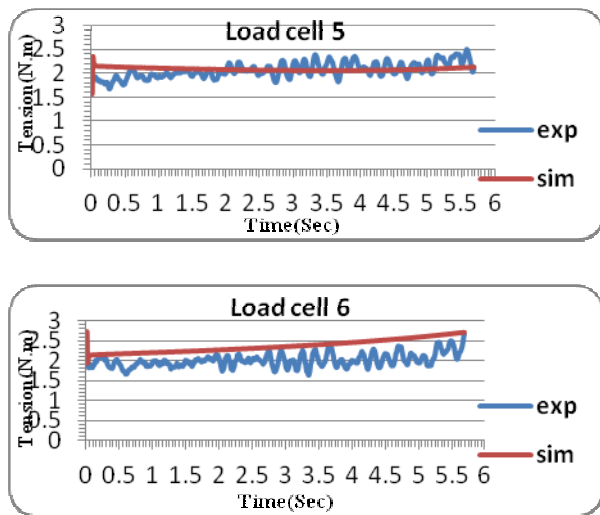


Fig. 12 Cable tensions in comparison to simulation results

According to these results it can be seen that experimental results are considerably compatible with simulation results and thus a trajectory tracking can be easily done by the aid of proposed close loop controller based on SMC approach. The efficiency of the proposed method is illustrated by simulations and laboratory experiments on a six degree-of freedom cable suspended robot. Therefore, in this paper Sliding Mode Controller (SMC) as a robust control algorithm is used for controlling the stability of the system while tracking a desired trajectory. The advantage of the proposed algorithm is calculation of the DLCC of the cable robot using close-loop computational technique based on SMC algorithm whereas in recent works, open-loop methods were used to calculate this parameter.

7 CONCLUSION

This paper addressed the issue of controlling the six degrees-of-freedom spatial cable robot of IUST. A sliding mode control was implemented on the mentioned under constrained cable robot as a stabilizing controller which is faced to external disturbances and parametric uncertainties. This paper presented an iterative approach for calculation of the Dynamic Load Carrying Capacity of cable suspended robots in a closed loop way and based on SMC approach. It was seen that the destructive effect of disturbances can be considerably neutralized by the aid of proposed controller. The maximum payload of the robot, considering parametric uncertainties for the closed-loop system was also calculated which was equal to 4.7 (kg). Simulation results have proved that not only SMC is applicable for accurate tracking of the

cable systems, but also provides a good closed loop calculation of DLCC. Moreover, experimental results demonstrated the validity of the proposed controller. The results showed a good match between the theory and the experiment.

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