Sliding Mode Control in Mobile Platform Joint Space for Multi-body Cable Driven Robot

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Abstract: The aim of this paper is to develop a suitable control of Multi-Body Cable-Driven Robot with satisfactory tensionnability condition. The desired trajectory is given in joint mobile platform space and thereby transformed on joint actuator space using the developed inverse kinematic. Under the control scheme, the actuator joint coordinates obtained by the sensor are used as feedback for the control system. Adding to the error in joint actuator space, the cable tensions which are computed based on the mobile platform dynamic and the optimization problem are used as inputs of the controller.

The sliding mode control method based on linear reaching law is used to control the effector of the robot. Asymptotic stability of the closed loop system is analyzed through Lyapunov theorem. Finally, a motion tracking based on the proposed control strategy is carried out on the Multi Body Cable-Driven Robot. The obtained results show the effectiveness and the feasiblity of the proposed control method.

1 INTRODUCTION

Cable-Driven Parallel Robots (CDPRs) represents a class of parallel robots which are becoming increasingly used in several applications, such as industry, rehabilitation, surgery, rescue, architecture, agriculture and sport. CDPRs consist of a cables as robot links connected to an end-effector (mobile-platform) from one side, and to the winches as the cable drivers fixed to the base. A suitable cable length motion allows to move the end-effector in desired position and orientation. Many researchers have been interested to CDPRs, by their remarquable advantages. These robots can be made lighter, stiffer, safer, and more economical than traditional serial ones since their flexible structure consists of lightweight and high load-bearing cables, which make these manipulators convenient in different uses. Depending on the design of the CDPR changes in terms of the number of cables and their configurations and the end-effector form. The majority of the studied CDPRs have a single rigid body end-effector with n Degrees Of Freedom (DOF), connected to m cables, and few of them had interested to multi-body end-effector, known as Multi-Body Cable Driven Robot (MBCDR), where it requires the more accuracy in design and control. In the design stage of CDPRs, a suitable cable numbers m and their configuration should be choosen (S.K.Agrawal and Y.Mao, 2012), (C.Gosselin and M.Grenier, 2011), to be able to control the desired n DOF of the used end-effector, as well as providing the necessary constraints for the given application. Indeed, as a major issue in CDPR, the cables can only exert tension and cannot push the end-effector. Therefore all used cables should be always in tension in the desired workspace in order to maintain the rigidity of the systeme, i.e ensure a best force distribution in all cables, known as tensionability condition (wrench closure, or force closure) (S. Rezazadeh, 2011). The tensile force should be always met simultaneously in all cables, for motion planning and control. Control of this kind of robots has attracted the attention of many researchers, mainly because of its great impact on the efficiency of robotic systems. Several control methods have been proposed for parallel manipulators. However, only a few of the proposed topologies can be implemented for cable driven parallel manipulators, which require a hight robustness and accuracy, due to the dy-

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namic coupled nonlinear parameters, unmodelled effects and external disturbances. Most of the proposed control schemes are based on dynamic model of the robot, which differs according to the measured parameters, those of the actuator space, and those of the mobile platform space (S.Rezazadeh and S.Behzadipour, 2008), (R.Babaghasabha and H.D.Taghirad, 2015), (T.Madani, 2016), (T.Madani, 2017), (W.Lv and Z.Ji, 2017). In the literature, the major developed control strategies of CDPR are limited to those with single rigid body end-effector. Indeed, the classical control techniques, such as PID, have been designed (M.A.Khosravi and H.D.Taghirad, 2014), they are computationally simple but they remain limited for the nonlinear system properties. Indeed the lack of the dynamic effects in these controllers may limit the tracking performance. To improve the controller performances, nonlinear controller can be used (R.Babaghasabha and H.D.Taghirad, 2015). Although these control schemes can perform well for industrial applications, but not for others such as medical applications due to more uncertainties and disturbances. Sliding mode control (SMC), as a variable structure nonlinear control method, has inherent insensitivity and robustness against uncertainties and disturbances (V.U.J.Guldner, 1999), (Y.Kali, 2015). A good design of this controller allows him to be relatively suitable for the control of human robot interaction systems. This area is well-investigated for rigid bodies, but very little studied for multibodies. Since in the present application the object driven by the cables (i.e. the human limb) is a multibody. Therefore, the objective of this paper is to study a MBCDR, taking into account all the constraints discussed by the conventionnel CDPR in addition to its multi body mobile platform constraints, wich lead to a new control strategy for this type of robots. The proposed controller structure guarantees fully tension forces on the cables, and it is able to fulfill the stringent positioning requirements for these type of manipulators. The rest of the paper is organized as follows. In section 2 the model of MBCDR is developed in term of the kinematic and the dynamic. Section 3 the proposed control strategy for the MBCDR has been described based on sliding mode method. To check the effectiveness of the proposed approach, the simulation tests has been conducted and the results are shown in section 4. To sum up, section 5 discusses the conclusions and problems for further work.

2 MULTI-BODY CABLE-DRIVEN ROBOT MODELING

2.1 Robot Description

The general form of multi-body system with M links constrained by cables is depicted by figure 1. The multi-body system is considered as a serial configuration with revolute joints. However, the only assumption considered on the multi-body system is that all of the joints are binary, i.e. they are connected between two links only. For the multibody cable-driven mechanisms, we consider that the multibody has a serial kinematics and the constraints are holonomic, each cable is attached from one end to a link and pulled from the other end by a stationary winch. However, the concept can be easily extended to more general joints.

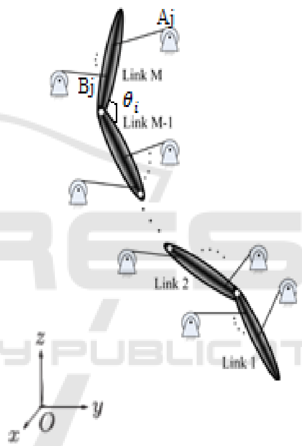

Figure 1: Multi-Body Driven by Cable.

As for CDPR, the main of MBCDR consists on fixed base where pulleys are attached and mobile platform designed by M articulated links. The cable robot is a mechanical system that transforms the movements of its actuators into movement of his mobile platform. In order to analyze the movement of this mechanism, the following notation is adopted:

- The rotation angles of the motors defined in $\mathbb{R}^m$ are denoted by $q = [q_1, \dots q_m]$, m denoting the number of actuators.
- The cable lengths defined in $\mathbb{R}^m$ by $\rho = [\rho_1, \dots \rho_m]$.
- The platform joint space coordinates defined in $\mathbb{R}^n$, are denoted $\theta = [\theta_1, \dots \theta_n]$, where n the DOF of the platform.
- The platform task space coordinates x defined accordingly to used demensional space.

2.2 Kinematic Modeling

The Inverse Kinematic (IK) problem for a cable robot, consist in determining the cable lengths ρ, or the actuators joint coordinates q, necessary for a given pose x of the mobile platform.
For the MBCDR, the mobile platform pose x can be expressed in term of its joint coordinates θ_i. Therefore, the IK MBCDR problem refers to find the relation f between ρ_j or q_j and $\theta_i, i \in [1,\dots n]$:

$$q_j = f(\theta_i) \tag{1}$$

Generally the mobile platform pose x are obtained by adjusting the cable length designated by $\rho_j, j \in [1,\dots m]$. The cable length represents the distance between its attachment point A_j at the fixed structure and the attachment point B_j on the mobile platform defined relatively to the associate reference frame. In this order the cable length is defined by:

$$\rho_j = \|x + QB_j - A_j\| \tag{2}$$

where Q is the rotation matrix of the mobile platform frame.
It is assumed that there is a linear relationship between the cable length ρ_j and the actuator joint coordinates q_j expressed in meters and radians, respectively, by:

$$\rho_j = \rho_{0j} + r_j q_j \tag{3}$$

where ρ_{0j} the initial length cable expressed according the structure geometry, and r_j is expressed by:

$$r_i = \kappa_j \sqrt{e_j^2 + \frac{p_j^2}{2\pi}} \tag{4}$$

with κ_j the transmission ratio of the j^{th} winder with the j^{th} motor, e_j and p_j the radius and the pitch of the j^{th} winder respectively. Note that κ_j and p_j are constants.
These equations are defined according to the particular structure of the robot, and still available in the case of an inextensible cable and whose winding system ensures that e_i remains constant over time (The cable does not roll on itself).
However, the mobile platform pose x, is expressed in its joint space coordinates following the associate homogeneous transformation matrix, which leads to define the $H(\theta_i)$ function.

$$x = H(\theta_i) \tag{5}$$

Finally the IK is expressed by:

$$q_j = \frac{1}{r_j}(\|H(\theta_i) + QB_j - A_j\| - \rho_{0j}) \tag{6}$$

or

$$q = R^{-1}(\rho - \rho_0) \tag{7}$$

where R is a diagonal matrix containing the r_i coefficients such that $R = diag\{r_1, r_2, \dots, r_m\}$.

The cable speeds are calculated from the derivative of the cable length with time, as following:

$$\dot{q} = R^{-1}\dot{\rho} \tag{8}$$

The cable accelerations are obtained by taking the time derivative of equation (8):

$$\ddot{q} = R^{-1}\ddot{\rho} \tag{9}$$

2.3 Dynamic Modeling

2.3.1 Dynamic Actuator Model

The first step for motion control design is to obtain a dynamic model of the actuators. Due to the fact that it is much faster compared to the mechanical part, neglecting the dynamics of the electrical part, and also a first order linear model can be used. The dynamic model of the actuators associates the vector of motor torques τ_m at joint acceleration $\ddot{q}$. As regards only the angular accelerations of the motors, we consider here only the equations of l. It is assumed that motors, reels and pulleys are cylinders of homogeneous material.

Each actuator has its elements positioned along a single axis or two rotational axes. Thus, it is assumed that the inertia matrices of the various components, brought to the center of the bound mark to the motor, are diagonal and positive definite. Therefore, the dynamic actuator is defined by equation 10 as following:

$$\tau_m = I_m\ddot{q} + f(\dot{q}) + RT \tag{10}$$

where $I_m = diag\{I_{m1}, I_{m2}, \dots, I_{mm}\}$ is the diagonal matrix containing the moments of inertia of the m winders around the axis of rotation of its motor, $f \in \mathbb{R}^m$ is the vector of torques due to friction, T is the vector of cable tensions, and $RT \in \mathbb{R}^m$ is a vector representing the applied torques by the cables on the actuator.
In order to express the friction term, the static friction model is adopted such as (A.Chemori, 2014):

$$f(\dot{q}) = F_s sign(\dot{q}) + F_v\dot{q} \tag{11}$$

with F_s and F_v two diagonal matrices whose traces are respectively equal to $F_s = tr\{fs1, f_{s2}, \dots, f_{sm}\}$ and $F_v = tr\{f_{v1}, f_{v2}, \dots, f_{vm}\}$ where f_{sj} and f_{vj} respectively denote the coefficients of dry friction (or Coulomb) and viscous j^{th} actuator.

2.3.2 Dynamic Mobile-platform

Applying Newton's formalism to the platform (W.M.Spong and M.Vidyasagar, 2006), the dynamic equation governing the dynamics of the platform is written as follows:

$$M(\theta)\ddot{\theta} + N(\dot{\theta}, \theta) = U \quad (12)$$

With $M(\theta)$ and $N(\dot{\theta}, \theta)$ respectively represent the inertia matrix, the centrifugal force matrix and coriolis, and the matrix of gravitational forces. U is the vector of the generalized forces corresponding to the generalized coordinates θ.
In order to determine the relationship between the generated torque U and the cable tensions T, the principle of virtual work is used, where δW is the virtual displacement. Indeed, the cable tensions T will result in the cable being pulled out by $\delta\rho_d$. Then :

$$\delta W = T\delta\rho_d = U\delta\theta \quad (13)$$

since

$$\delta\rho_d = \frac{\partial\rho_d}{\partial\theta}\delta\theta \quad (14)$$

the change of pulled out cable $\delta\rho_d$ can be related to the change of cable that remains in the system $\delta\rho$ by:

$$\rho_d + \rho = constant$$

which gives:

$$\frac{\partial\rho_d}{\partial\theta} + \frac{\partial\rho}{\partial\theta} = 0 \quad (15)$$

by substitution

$$U = -(\frac{\partial\rho}{\partial\theta})^T T = J_c(\theta)^T T = WT \quad (16)$$

where J_c is the jacobian matrix given by:

$$J_c = -\frac{\partial(\rho_1, \ldots, \rho_m)}{\partial(\theta_1, \ldots, \theta_n)} \quad (17)$$

Finally, the dynamic of MBCDR is expressed by the coupled following equations:

$$\begin{cases} \tau_m = I_m\ddot{q} + f(\dot{q}) + RT \\ M(\theta)\ddot{\theta} + N(\dot{\theta}, \theta) = WT \end{cases} \quad (18)$$

3 PROPOSED CONTROL STRATEGY

The main objective in general motion robot control is to track a desired trajectory (H.Faqihi and M.N.Kabbaj, 2016), defined in feasible workspace with high accuracy even in presence of uncertainties and external disturbances.

In the proposed control strategy of MBCDR, the measurement of the actuator articulation joints is given, and thereby used to close the main loop of the control system. The objective is to design a robust controller $\tau_m(t)$ to guarantee the convergence of the tracking error to zero $(q(t) - q_d(t)) \to 0$ in finite time, by ensuring the tensionability of cables during motion.
The proposed control strategy is given by the flowchart Fig.2. The target position and velocity of the end-effector is set up by using the developed inverse kinematic. The error between the measured value and the target value is regarded as an input of the control system. The actuator torque is computed by the sliding mode control and tension distribution method.

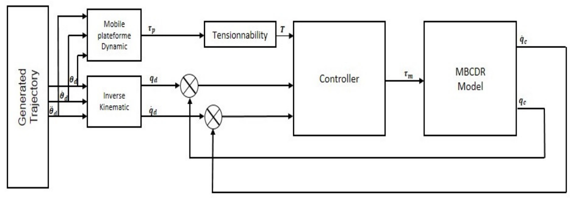

Figure 2: Proposed flowchart control strategy.

3.1 Tensionability Condition

In order to ensure the tensionnability condition of a cable-driven multibody system, different approach can be used following the system configuration. The proposed system is considered as three-link multibodies supported by four cables. Therefore, when controlling such redundantly actuated CDPR, the number of tension distributions is infinite. At any point along a trajectory, there exists an infinity of possible sets of cable tensions.
From equation (16)

$$U = J_c^T T$$

the number of cables is larger than the DOF of the system. Then the cable tension is underdetermined. Since the cables can only pull but not push, it is impossible for the tensions in the cables to be negative. In the actual system, due to the existence of friction along the cables, the minimum tension in a cable can be set above a positive value to keep all of the cables taut. Also, because the motors connected to the cables can only produce a limited amount of torque, there may be a maximum limit on cable tensions as well. Therefore, T can satisfy:

$$T \in (T_{min}, T_{max}) \quad (19)$$

Using equations. (16) and (19) as constraints, an optimization problem may be formulated to find a proper set of cable tensions to generate selected torques.
A quadratic objective function can be used for the optimization problem, which minimizes the norm of cable tension vector. The advantage of using quadratic

programming over linear programming is that the solution to T will change more continuously when the Jacobian matrix in the equality constraint of equation (16) changes, which will help to avoid abrupt changes in cable tensions when the leg moves from one configuration to another.
Mathematically, the determination of the cable tensions of MBCD can be formulated as follows (C.Gosselin and M.Grenier, 2011):

$$\begin{cases} min & T^T T \\ s.t & J_c T = U \\ and & T_{min} \leq T \leq T_{max} \end{cases} \tag{20}$$

The above can be solved using a quadratic programming solver.

3.2 Design of the Control Law

A fast response, insensitivity to parameter variation and disturbance, and simple physical realization of sliding mode method allow him to be suitable candidate to control the MBCDR in this paper.
Assuming that the kinematics and the desired task space trajectory are exactly known and away from singular configuration.
Let define the tracking error and its derivative respectively by:

$$\begin{aligned} e(t) &= q(t) - q_d(t) \\ \dot{e}(t) &= \dot{q}(t) - \dot{q}_d(t) \\ \ddot{e}(t) &= \ddot{q}(t) - \ddot{q}_d(t) \end{aligned} \tag{21}$$

where $q_d(t) \in \mathbb{R}^n$ the desired trajectory.

Therefore, using equation (18) yields

$$\ddot{e}(t) = I_m{}^{-1}[\tau(t) - f(\dot{q}(t)) - RT(t)] - \ddot{q}_d(t) \tag{22}$$

In sliding mode control, the variable control systems are designed to drive and then constrain the system stable to lie within a neighbourhood of the switching function. The robust sliding mode control design approach consists of two components. The first involves the design of a switching function so that the sliding motion satisfies design specifications. The second is concerned with the selection of a control law which will make the switching function attractive to the system state.
In order to maintain the end-effector to track desired trajectory in the presence of unknown and disturbances, the linear sliding surface is defined as:

$$s(t) = [s_1(t), \ldots, s_m(t)]^T = \dot{e}(t) + \lambda e(t) \tag{23}$$

where $\lambda = diag\{\lambda_1, \ldots, \lambda_n\}$ is a positive definite constant matrix to be selected.

The first derivative of the considered sliding surface, equation (23), is given in the following from:

$$\dot{s}(t) = \ddot{e}(t) + \lambda \dot{e}(t) \tag{24}$$

Therefore the continuous equivalent control law that would achieve $\dot{s}(t) = 0$ may be expressed as

$$\tau_{eq}(t) = I_m[\ddot{q}_d(t) + \lambda \dot{e}(t)] + RT(t) + f(\dot{q}(t)) \tag{25}$$

In order to improve the control performance of sliding control, the reaching law must suitably designed. A good reaching law can not only weaken chattering in the system, but also speed up the system sliding time from any initial state to sliding surface, and improve the robustness of the system. In this paper, the reaching law is adopted as follows:

$$\tau_{sw}(t) = -Ksign(s(t)) - \beta s(t) \tag{26}$$

where $K > 0$, $\beta > 0$ and $sign(.)$ represents the symbolic function

$$sign(s) = \begin{cases} 1 & s > 0 \\ 0 & s = 0 \\ -1 & s < 0 \end{cases} \tag{27}$$

Finally:

$$\begin{aligned} \tau(t) = I_m[\ddot{q}_d(t) + \lambda \dot{e}(t) + Ksign(s(t)) + \beta s(t)] \\ + RT(t) + f(\dot{q}(t)) \end{aligned} \tag{28}$$

3.3 Stability of Controlled System

Using the Lyapunov function, the stability analysis of the proposed robust control law is accomplished. Defining the lyapunov function as following:

$$v_m(t) = \frac{1}{2} s^T(t) s(t) \tag{29}$$

Then

$$\dot{v}_m(t) = s^T(t)\dot{s}(t) \tag{30}$$

$$\dot{v}_m(t) = -Ks^T(t) sign(s(t)) - \beta s^T(t) s(t) \tag{31}$$

From equation (31), we may know that when $s(t) > 0$, $sign(s(t)) > 0$; when $s(t) < 0$, $sign(s(t)) < 0$; so $\dot{v}_m(t) < 0$ is always correct, and the system can reach the sliding mode face in finite time.
Finally, the obtained torque actuator based on the sliding mode controller is given by:

$$\tau = \tau_{eq} + \tau_{sw} \tag{32}$$

$$\tau = I_m[\ddot{q}_d + \lambda \dot{e} + Ksign(s) + \beta s] RT + f(\dot{q}) \tag{33}$$

4 SIMULATION RESULTS

To check the effectiveness of the proposed control scheme in real application, an MBCDR based on three links as mobile platform is used. The study case referes to a cable driven robot for locomotor rehabilitation of lower limb (A.Badi and Archambault, 2018).

Firstly, the trajectory is generated in task space, which represent real rehabilitative motion exercice of the lower limb end-effector's, figure 3. The generated trajectory is after converted in joint space of the mobile platform defined by θ_i where the physiological constraints are considered, as discussed in (H.Faqihi, 2017).

Therefore the desired position and velocity joint actuator $(q_j, \dot{q}_j)$ are computed by using the IK equations developed in section 2. These joint actuator parameters are used to be input-of the discussed controller, figure 2. On the other hand, the cable tensions are computed from desired trajectory based on the dynamics of the mobile platform and the defined constrained optimization problem, following the fixed constraints $T_{min} = -70N$ and $T_{max} = 70N$. The obtained results of cable tensions for the four cables are given in figure 4. It's shown that the tensions still limited in the fixed boundaries.

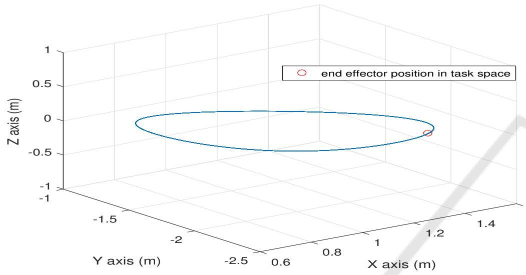

Figure 3: Genrated trajectory in task space.

The obtained cable tensions are used as input of controller based on sliding mode method to compute the suitable actuator torque, given in figure 5. The obtained signal have the cyclic pace according to the aplied cyclic trajectory.

The used parameters of controller are fixed to reach tracking trajectory with desired performances in term of accuracy and response time. The obtained results for tracking trajectory are given in figure 6 where the tracking position for all the four actuators are shown.

We note that the computed angle actuators converge to the desired ones after a certain time around $0.075s$. Then, the used controller ensures a good tracking trajectory evaluated by the computed errors as shown in figure 7.

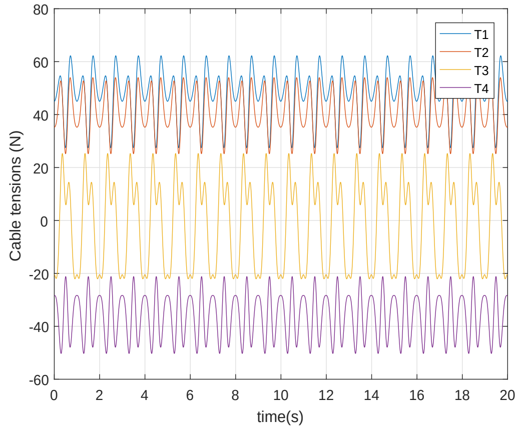

Figure 4: Computed cable tensions.

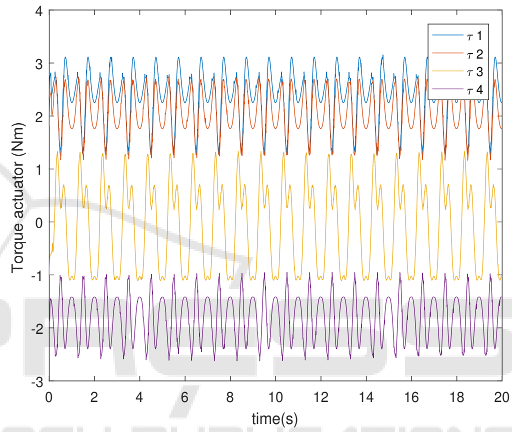

Figure 5: Obtained Torque.

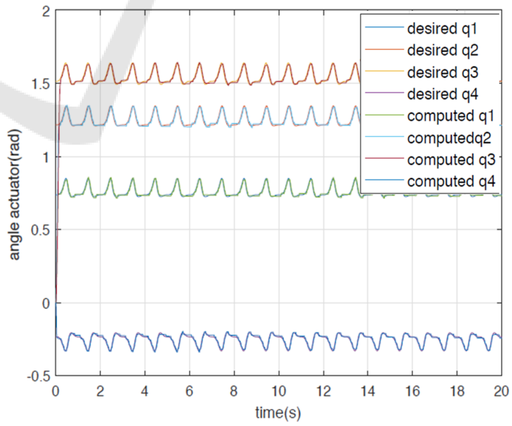

Figure 6: Tracking Trajectory.

5 CONCLUSION

In this paper, a new sliding mode control strategy of the Multi-Body Cable-Driven Robot is studied based on joint actuator space, and tensionnability condition.

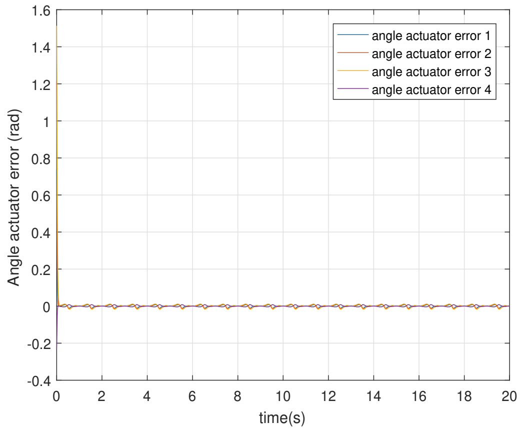

Figure 7: Joint errors.

The robot model is developed taking into account the cable and the mobile platform flexibilities to describe the kinematics and the dynamics of the coupled system. The proposed control strategy rests on actuator joint coordinates feedback compared to desired trajectory given in mobile platform joint space and transformed to the actuator joint space. The obtained error is used to design the sliding control law. As principal issue of cable robot is to ensure the cable tensionnability during motion. In this order, constrained optimization algorithm is developed based on mobile platform dynamics. The cable tensions are computed, and thereby used as another input of controller. The stability of the proposed controller is discussed based on Lyapunov function.

To validate the feasibility and the effectiveness of the Multi-Body Cable Driven Robot control, a reference trajectory is generated to move all the mobile platform degrees of freedoms, and thereby, applied to the proposed conltrol strategy. Using suitable gains controller, the simulation results have presented a good motion tracking.

The present study can be improved by introducing into the controller, a cable tension feedbacks via the use of the appropriate sensors or by solving the Forward Kinematic of the Multi-Body Cable Driven Robot. if the main is to incorporate the dynamic of system

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