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COMPARATIVE ANALYSIS OF DIFFERENT MODELING APPROACHES ON CABLE-SUSPENDED PARALLEL ROBOTS

Fabiola da Silva Rosa
Estevan Hideki Murai
Henrique Simas

UFSC - Federal University of Santa Catarina
Campus Reitor João David Ferreira Lima, s/n
Trindade, Florianópolis - SC, 88040-900 - Brazil
engfabiolarosa@gmail.com; eng.estevan.murai@gmail.com; hsimas@gmail.com

Abstract. Cable-driven parallel manipulators are a robot class where cables connect the fixed platform and the moving platform. These cables increase or decrease their length to change the robot position. The cable-driven parallel robots have some advantages compared to rigid parallel robots. Cable robots have reduced mass and inertia, their payload to robot weight ratio is larger, they can achieve higher dynamic performances, they have a larger workspace, the manufacturing and maintenance costs are reduced, they are easier to assembly and disassembly, and they have superior modularity and reconfigurability. Despite these advantages, some factors complicate cable robot modeling and control. Since the cable is flexible, and it must always be under a tension force, the control algorithm has to consider the cable tension in every robot posture. Besides, the control algorithm needs to predict and avoid collisions. These collisions can occur among cables, between cables and the environment, between cables and other robot rigid structures, and between the platform and the environment. Also, the position precision and trajectory tracking are limited. Cable-suspended parallel robots are a cable robot subclass. In this case, there is no cable under the moving platform, and the gravity is considered a constraint, similar to a cable under the platform. Comparing suspended and non-suspended cable robots, suspended robots have fewer cables and, consequently, fewer collisions possibilities. Nevertheless, since there is no cable under the platform, it is more complex to maintain the cables tension in every robot posture. Besides that, precise tracking trajectory control is more complicated to achieve. Moreover, suspended robots may become unstable, easy to vibrate, and even out of control under external disturbances. The robot precision is related to its modeling. Thus, the cable model is one of the most critical considerations in cable robot modeling. In general, a complex model is a precise model. However, if the model is too complicated, it is required a substantial computational time to solve it. In the literature, four different cable modeling was found: inextensible and massless cable, inextensible cable with non-negligible mass, elastic and massless cable and elastic cable with non-negligible mass. The main goal of this work is to present and compare these four different cable modelings in order to help designers on choosing the most suitable modeling regarding each cable robot case.

Keywords: cable-suspended parallel robots, comparative analysis, modeling

1. INTRODUCTION

Cable-driven parallel manipulators (CDPM), also called tendon-based Stewart platforms Verhoeven (2004) or cable robots for short, are manipulators inspired by conventional parallel robots, like the well known Stewart-Gough Platform illustrated in Figure 1. In cable robots, cables replace the rigid legs, and the moving platform changes its position when the lengths of the cables are increased or decreased. Cable robots have been extensively studied in the last decades because of their advantages and many fields of application. The extensive use of cable robots is related to their advantages versus serial robots and conventional rigid parallel robots:

- they have **reduced mass and inertia** since cables are lighter than rigid links (Pott, 2018);
- their **payload to robot weight ratio is larger** (Hiller *et al.*, 2005);
- they can achieve **high dynamic performances** because of their lightness (Bruckmann *et al.*, 2013; Kawamura *et al.*, 1995);
- CDPMs have a **larger workspace** compared to rigid parallel robots since they can work on a wide range of cable length (Pott, 2018);

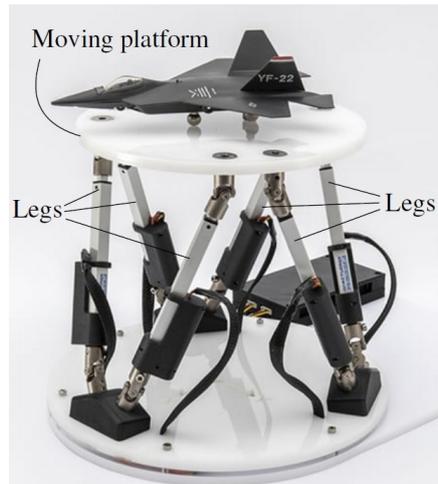


Figure 1. Stewart platform. Adapted from Acrome (2019).

- the **costs on manufacturing and maintenance are reduced** mainly because of the reduced number of joints (Zhang *et al.*, 2018);
- **easy to assembly and disassembly** because of the reduced number of joints;
- consequently they have **superior modularity and reconfigurability** (Von Zitzewitz *et al.*, 2013);
- being easy to assembly and disassembly, they are also **easier to transport**.

Despite being extensively studied in the last decades, these robots still have some challenges, mainly regarding their control design. Possible collisions must be avoided: among cables, between the cables and the platform, between cable and the environment, and between the platform and the environment.

Another problem is that cables are non-rigid, and they can only pull and not push. Therefore, cables must under tension force in every robot posture. The cable's flexibility also limits the robot precision. The factors listed above make the control design of cables robots challenging.

As explained before, because the cables are flexible, they can only be pulled and not pushed. Therefore, in cable robots, fully constrained end-effectors require $n + 1$ cables to control n degrees of freedom (Vu *et al.*, 2018).

However, there is one class of cable robots that uses gravity as a constraint to keep the tension of the cables called cable-suspended parallel robots (CSPR), as shown in Figure 2. In this case, the gravity acts as a cable pulling the moving platform downwards.

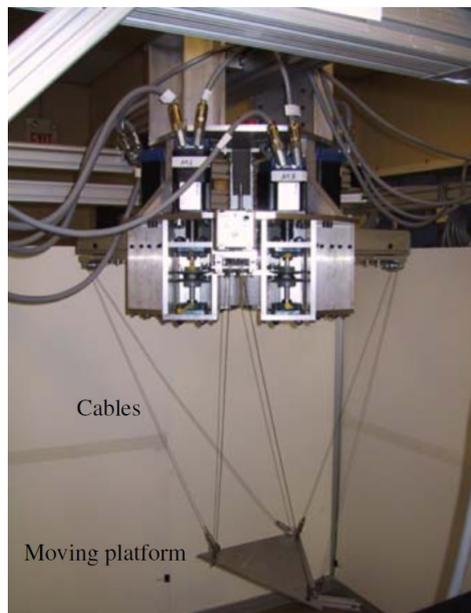


Figure 2. A cable-suspended parallel robot built at the University of Delaware. Adapted from Zhang *et al.* (2006).

CSPRs present, among other interesting characteristics, large workspaces and high reconfigurability, which make them attractive for a large variety of applications, especially for pick and place operations over wide spaces (Berti *et al.*, 2015).

However, suspended robots present several challenging problems, mainly regarding their control and accuracy. In order to solve some problems, many works proposed methods for modeling cable-suspended parallel robots.

A robot can be modeled to analyze its forces, energy, and their effect over motion. The modeling involves three interrelated subjects: kinematics, statics, and dynamics (Tsai, 1999). For cable robots, the connection between kinematics and statics has had greater relevance than in conventional robots, due to the mandatory cable tension in all robot postures (Pott, 2018).

CSPRs control is even more complicated because they may become unstable, easy to vibrate, and even out of control under external disturbances, especially when the end-effector is unloaded. These weaknesses are due to the low stiffness of CSPRs along the vertical direction. Therefore, additional caution should be taken when designing CSPRs to improve their accuracy and reduce their vibration (Yuan, 2015).

The cable model is one of the most important issues when modeling the cable robot kinematics, statics, or dynamics behavior. The cable-suspended parallel robot modeling are classified into four types: inextensible and massless cable, inextensible cable with non-negligible mass, elastic and massless cable, and elastic cable with non-negligible mass.

Despite many works found in the literature research, none of them proposes a general model for all cable-suspended parallel robots. For that reason, the main goal of this work is to present a comparative analysis of different modeling approaches on these robots in order to aid the designer on choosing the most suitable approach for his/her robot.

2. CABLE-SUSPENDED PARALLEL ROBOTS

One subclass of cable robot is the **cable-suspended parallel robot** (CSPR). In order to understand the CSPR, let \vec{u}_i be the i th cable direction, then a platform pose is called suspended, if for all cable i , the Equation 1 holds true.

$$\vec{u}_i \cdot \vec{g} < 0, \quad i = 1, \dots, m \quad (1)$$

where \vec{g} is the direction of gravity. If the robot is predominantly operated in suspended configurations, it is common also to call the cable robot *suspended* or in *crane configuration*, indicating that the additional robot constraint is imposed by gravity.

For CSPRs, since all the cables are above the end-effector, the payload can be shared by each cable. Thus, they usually have a large load capacity. Moreover, compared with non-suspended CDPMs, there are fewer collisions possibilities because there are fewer cables. These two characteristics make suspended CDPMs more suitable for pick-and-place applications and applications with large workspace Berti *et al.* (2015); Yuan (2015).

However, suspended CDPMs may become unstable, easy to vibrate, and even out of control under external disturbances, especially when the end-effector is unloaded. These weaknesses are due to the low stiffness of CSPRs along the vertical direction. Therefore, additional caution should be taken when designing CSPRs to improve their accuracy and reduce their vibration Yuan (2015).

3. MODELING APPROACHES

A robot can be modelled to analyze its forces, energy and their effect on motion. The modeling involves three interrelated subjects that can be studied together or separately: **kinematics**, **statics** and **dynamics** (Tsai, 1999).

In **kinematics**, the aspects studied are: position, velocity, acceleration and higher-order position derivatives (Tsai, 1999). This robot modeling part does not regard forces and torques that cause motion, and it just analyzes how the motion of different parts of a robot is coupled (Pott, 2018).

According to Tsai (1999), **statics** deals with the relations of forces that produce equilibrium among the members of a robot. Inertia forces are disregarded in static force analysis. The forces of equilibrium depend on the manipulator instantaneously posture, and they are not time-dependent.

Dynamics analyzes the forces and torques required to cause the motion of a system of bodies. In dynamics, the links inertia is one of the main concerns (Tsai, 1999). Also, according to Tsai (1999), the dynamics of a robot manipulator is a very complicated subject.

A cable robot can be modeled regarding its kinematics, statics, and dynamics. In general, for this type of robot, the connection between kinematics and statics has to be considered carefully compared to conventional robots (Pott, 2018). A proper kinematic modeling can only be established if the cables are under a feasible tension. If the tension of the cables is too low, the kinematic relations change, and the model can not describe the robot behavior (Pott, 2018).

A cable robot modeling can be used in two manners: in **real-time applications**, such as the robot control, and **non real-time applications**, such as workspace analysis, force capability, analysis of cables tension, stiffness analysis, and design optimization.

An important consideration when modeling a cable robot is the cable model. Four cable models were found in

literature, and they are explained in the following sections: inextensible and massless cable, inextensible cable with non-negligible mass, elastic and massless cable, and elastic cable with non-negligible mass.

3.1 INEXTENSIBLE AND MASSLESS CABLE MODELING

When modeling a cable-suspended parallel robot, most works consider cables inextensible and massless. In this case, the forward and inverse kinematics, as well as the statics, are modeled in the same manner as rigid parallel robots. The cable is considered a straight line that changes its length, such as a prismatic joint. In dynamics, the difference between rigid parallel robots and cable robots is that in cable robots, the legs are considered massless.

The first work dealing with CSPR modeling was proposed by Havlik (1999). The author defines theoretical equations in kinematics, statics, and dynamics for a 3 DOF CSPR considering gravity as a constraint.

Many other papers have dealt with cable-suspended robots considering cables rigid and massless (Gosselin, 2013; Berti *et al.*, 2013; Carricato and Abbasnejad, 2013; Woernle, 2013; Berti *et al.*, 2015; Muraro, 2015; Gosselin and Foucault, 2015; El-Ghazaly *et al.*, 2015; Husty *et al.*, 2018; Bordalba *et al.*, 2018; Mottola *et al.*, 2018; Vu *et al.*, 2018; Zake *et al.*, 2019; Surdilovic and Radojicic, 2019; Tang *et al.*, 2019). However, for large scale robots with very long cables, the cables are relatively heavy Pott (2018). Therefore, for large CSPRs, this model is too simple, compromising the accuracy of the robots.

3.2 INEXTENSIBLE CABLE WITH NON-NEGLIGIBLE MASS MODELING

The cable as a massless straight body is a valid assumption for small and medium-size robots. However, for large-dimension cable-driven robots or heavy payloads, such an assumption may be invalid (Gouttefarde *et al.*, 2012).

Since the cable mass and its elasticity are co-related, most works regarding the cable with a non-negligible mass also consider the elasticity in the cable model. Thus, only one paper was found in the bibliographic review with inextensible cable with non-negligible mass (Gouttefarde *et al.*, 2012).

In the modeling proposed by Gouttefarde *et al.* (2012), the cable has a parabolic profile illustrated in Figure 3. For a hefty inextensible cable static behavior, the cable profile is given by the Equation 2.

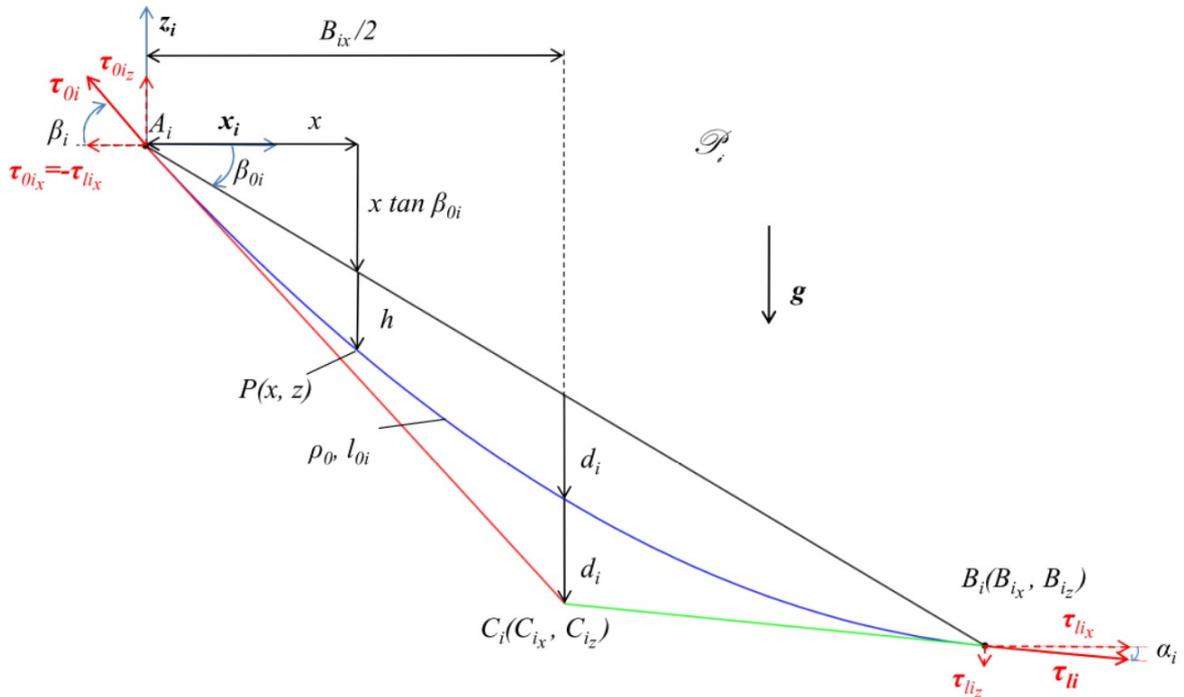


Figure 3. Parabolic cable profile proposed by Gouttefarde *et al.* (2012).

$$z = \frac{-\rho g L_i}{2\tau_{l_{ix}} B_{ix}} x(B_{ix} - x) + x \tan \beta_{0i} \quad (2)$$

where x and z are the coordinates of a point P on the cable and L_i is the chord length $A_i B_i$. As illustrated in Figure 3, β_{0i} is the angle between the horizontal line and the chord ($\beta_{0i} = \tan^{-1}(B_{iz}/B_{ix})$). Also, ρ is the cable linear density,

g is the gravity acceleration and τ_{li_x} is the component in x of the force τ_{li} applied by the platform to the cable at its end point B_i .

With this cable modeling, the authors proposed a new simplified static analysis of parallel robots driven by inextensible cables of non-negligible mass.

The authors evaluated the errors on the cable tension resulting from the simplifications considering an inextensible cable with a parabolic profile compared with the cable model as elastic catenary. Figure 4 shows that the error on the cable tension considering the cable mass is substantially smaller, even disregarding the cable elasticity. The elastic catenary model is explained in subsection 3.4

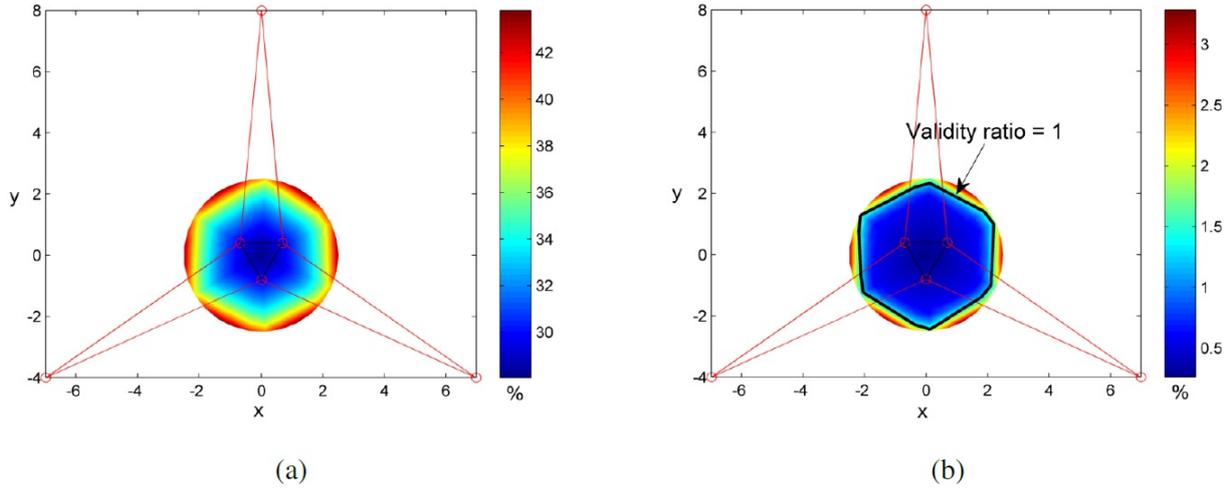


Figure 4. Maximal relative error (%) on maximal cable tension over the plane $z = 0$ and for a null orientation of a $50kg$ platform. (a) Inextensible and massless model versus elastic catenary model and (b) Simplified hefty parabolic cable model versus elastic catenary model. Adapted from Gouttefarde *et al.* (2012).

3.3 ELASTIC AND MASSLESS CABLE MODELING

It was explained before that cable mass and elasticity are co-related, and for that reason, most works model the cable considering both aspects or neither. Thus, as the inextensible cable with a non-negligible mass model, only one paper was found in the preliminary bibliographic review modeling the cable as elastic and massless Zhang *et al.* (2006).

Considering the 6 DOF CSPR illustrated in Figure 2, one cable extremity is connected to the motor, and the other extremity is connected to the end-effector. The cable tension for the i th cable at the motor is u_i and at the end-effector is f_i .

At a end-effector given position the cable nominal length i is L_i . With the assumptions of constant density ρ , area of cross section A and Young's modulus E of a rope, the equations of motion for the i th according to Zhang *et al.* (2006) are:

$$\frac{\partial^2 w_i(z_i, t)}{\partial z_i^2} = \frac{1}{c_i^2} \frac{\partial^2 w_i(z_i, t)}{\partial t^2}, \quad \forall z_i \in (0, L_i), \quad i = 1, \dots, 6 \quad (3)$$

where $w_i(z_i, t)$ is the deflection of a rope along its length and $c_i^2 = E_i/\rho_i$. The boundary conditions on the motion of a cable are:

$$E_i A_i \frac{\partial w_i(z_i, t)}{\partial z_i} \Big|_{z_i=0} = u_i(t), \quad i = 1, \dots, 6 \quad (4)$$

$$E_i A_i \frac{\partial w_i(z_i, t)}{\partial z_i} \Big|_{z_i=L_i} = f_i(t), \quad i = 1, \dots, 6 \quad (5)$$

Considering the six cables identical, with the same cross-sectional area, Young's modulus and density, the authors calculated a linearized system dynamics and simulated an end-effector desired trajectory, both illustrated in Figure 5.

According to the authors, the difference between the desired trajectory and the simulated trajectory is partially due to the friction, which is not considered in the model. However, the mass was also disregarded, and maybe it can influence the results.

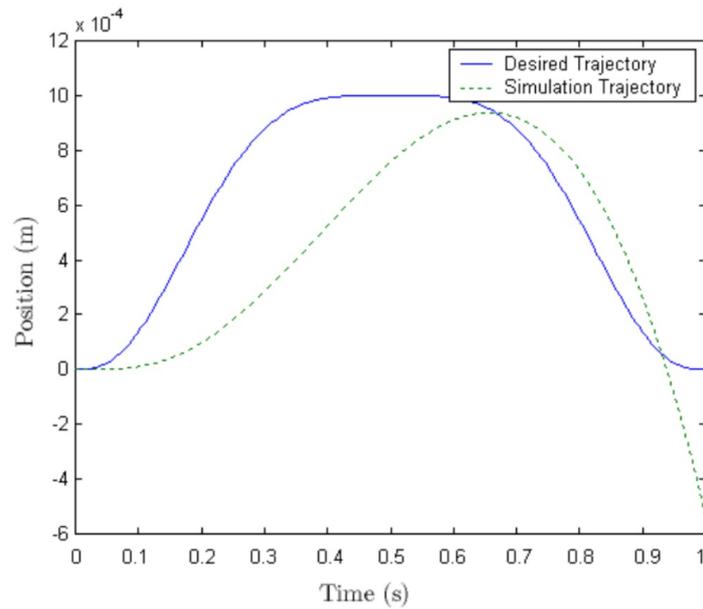


Figure 5. Desired trajectory and end-effector simulated trajectory. Adapted from Zhang *et al.* (2006).

3.4 ELASTIC CABLE WITH NON-NEGLIGIBLE MASS MODELING

Due to the mass of the cables, the cables are subject to sagging and get a curved form, which can significantly differ from the standard model straight line. This must be taken into account when modeling large-scale cable robots with very long cables, when the cables are relatively heavy, when cables are kept under low tension, or when high accuracy of the robot shall be achieved (Pott, 2018).

The cable stiffness is related to the cable mass influence on the cable sag. When the cable is not very rigid, the cable mass increases its influence on the cable sag. By knowing that, when adding complexity to the cable model, most works consider both cable mass and elasticity.

In the preliminary literature review, 8 papers were found modeling the cable as elastic with non-negligible mass. In 6 works, the cable profile is modeled as elastic catenary (Kozak *et al.*, 2006; Korayem *et al.*, 2007; Zi *et al.*, 2008; Riehl *et al.*, 2009; Arsenault, 2013; Newman *et al.*, 2018) as illustrated in Figure 6. The works that do not model the cable as a elastic catenary are: Ottaviano *et al.* (2019); Merlet and Alexandre-dit Sandretto (2015).

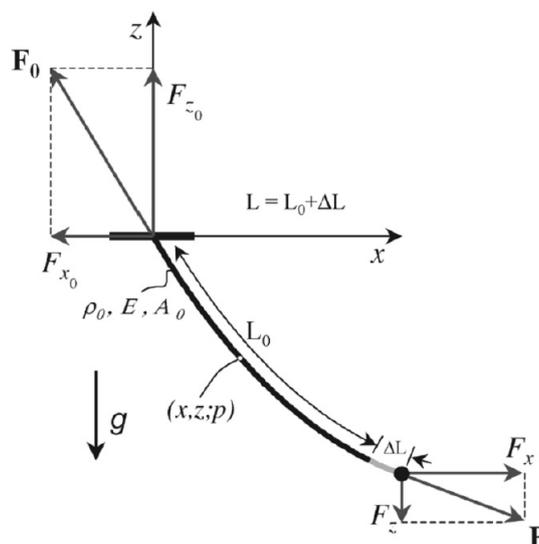


Figure 6. Diagram of a sagging cable as a elastic catenary. Adapted from Kozak *et al.* (2006).

According to Kozak *et al.* (2006), the solution for the displacement of a non-symmetric sagging elastic cable has been known since at least the 1930s. In the planar space, the coordinates x and z of a point p on the cable segment is given respectively by:

$$x(s) = \frac{F_x s}{EA_0} + \frac{|F_x|}{\rho_0 g} \left[\sinh^{-1} \left(\frac{F_z + \rho_0 g (s - L_0)}{F_x} \right) - \sinh^{-1} \left(\frac{F_z - \rho_0 g L_0}{F_x} \right) \right] \quad (6)$$

$$z(s) = \frac{F_z}{EA_0} s + \frac{\rho_0 g}{EA_0} \left(\frac{s^2}{2} - L_0 s \right) + \frac{1}{\rho_0 g} \left[\sqrt{F_x^2 + (F_z + \rho_0 g (s - L_0))^2} - \sqrt{F_x^2 + (F_z - \rho_0 g L_0)^2} \right] \quad (7)$$

where F_x and F_z are the force \mathbf{F} components applied to the unfixed cable end and L_0 is the unstrained cable length, both known variables. ρ_0 is the unstrained linear density, E is the elastic modulus, A_0 is the unstrained cross-sectional area, ΔL is the cable strain, g is the gravity acceleration, and s is the cable segment unstrained length.

Then, according to Kozak *et al.* (2006), the static profile of any homogeneous elastic cable under the influence of gravity and acted on by force applied to the end of the cable, can be solved using these equations above. Then, using Equations 6 and 7, the authors compared the theoretical and experimental results of the cable profile shown in Figure 7. In this Figure, the experiment point is zoomed, showing the difference between theoretical and experimental results carefully.

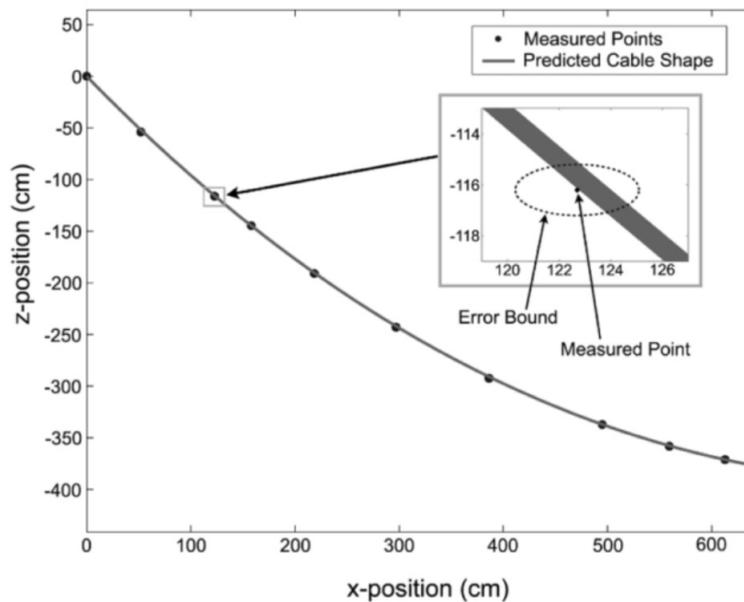


Figure 7. Measured and predicted cable shape. Adapted from Kozak *et al.* (2006).

The experiment was performed indoors to avoid wind and other disturbances. The cable profile was measured directly using a simple plumb-line measurement technique at multiple points along its length. The cable predicted profile was computed based on the applied force (Kozak *et al.*, 2006). The authors considered the cable measured and the predicted profiles very similar, even zooming the graphic in Figure 7.

Other works that consider the cable with an elastic catenary profile used the modeling proposed by Kozak *et al.* (2006) to calculate different CSPRs workspaces.

4. COMPARATIVE ANALYSIS

The complexity of a cable model can be changed according to the robot's required accuracy. Comparing Equation 2 for inextensible cable with non-negligible mass, Equations 4 and 5 for elastic and massless cable and Equations 6 and 7 for elastic cable with non-negligible mass is clear the increase on the cable modeling complexity.

The elastic catenary profile provides the best-known model for a cable. However, considering the experimental results, this model is very time-consuming. For that reason, it was not found in literature any work using the elastic catenary in real-time applications, such as robot control.

It is presented in Table 1 a comparative analysis between the four cable models presented in section 3. This table brings the most common pros and cons related to each cable model.

Precision errors, found mostly in less complex models, increase according to the robot size since the precision error is directly related to the cable size.

Even though algorithms with complex models requires considerably more computational time to solve, the designer must always be caution with precision errors in large robots. The model choice will be a balance between computational time and precision on trajectory tracking and the moving platform position.

Table 1. Comparative analysis between four different cable modeling found in literature.

Model	Pros	Cons
Inextensible and massless cable	Model simplicity	Precision errors, mostly in large robots
	Control response is faster when compared to complex models	Cable mass and elasticity are neglected
Inextensible cable with non-negligible mass	Fewer precision errors when compared to the model "inextensible and massless cable"	Cable sag has precision errors when the elasticity is not considered, mostly in large robots
Elastic and massless cable	Fewer precision errors when compared to the model "inextensible and massless cable"	Cable sag has precision errors when the mass is not considered, mostly in large robots
Elastic cable with non-negligible mass	Complex model, it considers cable mass and elasticity	Modeling results on complex systems with many equations
	Fewer precision errors when compared to less complex models	

5. FINAL CONSIDERATIONS

This paper presented a comparative analysis of different modeling approaches on cable-suspended parallel robots. A literature review was performed and four different cable models were presented.

The comparative analysis aims to aid designers when designing a new cable-suspended parallel robot. It was shown that the model choice will be a balance between computational time and precision on trajectory tracking and the moving platform position. Furthermore, the bigger the robot size, the more complex the choice of an appropriate modeling.

Despite many works found in the literature research, none of them proposes a general model for cable-suspended parallel robots. For that reason, it is suggested as a future work the development of a general model for cable-suspended parallel robots considering cables elastic with non-negligible mass in order to aid designers on designing new cable robots and controlling these new robots.

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