A Cartesian Cable-Suspended Robot for Aiding Mobility

Gianni Castelli and Erika Ottaviano

Abstract In this paper we propose the analysis and simulation of a cable system developed to be used in large-scale handling for applications in urban, civil and naval environments. For the proposed system, which belongs to the Cartesian Cable-Suspended Robots (CCSR), the main issue is that it can provide translational motion of the end-effector being suspended, thus it may be considered well suited for a number of applications including the proposed one. In this paper we focus our attention on a spatial version of the cable system designed to improve the mobility of end-users in urban environment. Kinetostatics and dynamic simulation are proposed and discussed.

Key words: Cable-Suspended Robot, Modelling, Simulation.

1 Introduction

Cable driven robots have been developed and tested for several years, but their practical implementation in industrial and naval environments and in civil work sites is still an open issue. Many fully-constrained manipulators were proposed for a number of possible applications, but feasible tasks are often limited due to the increasing number of cables, [1]. Probably, the most interesting solution for the above-mentioned areas of application regards cable-suspended robots, i.e. in a crane-like configuration, but there are still several open issues related to the design and control of these cable robots that limit their practical use. Under-constrained robots rely on gravity force, indeed in a crane-like configuration the moving platform is suspended and operated by cables that are connected to the base. Some reported research on cable-

---

Gianni Castelli and Erika Ottaviano
Dept. of Civil and Mechanical Engineering, University of Cassino and Southern Lazio, via G. Di Biasio 43, 03043, Cassino (FR), Italy. e-mail: ottaviano@unicas.it

suspended robots are: the 3D cable robot ROBOCRANE [2]; the Sky-Cam [3], a Cargo Transfer System [4]. Other aspects on design and control can be found in [5]. Applications of cable suspended robots were proposed in [6] for rescue operations, and [7] for industrial applications. In this paper a cable-based system named as CaSIMo (Cable System for Improving Mobility) is proposed to improve the mobility of end-users in urban environment. The design and implementation of safe and reliable devices that are able to help end-users to provide a better quality of life is becoming of great inter-est in the scientific community. Lot of efforts have been devoted to the development of the concept of Home & Building Automation, but little has been done for the city concept. In fact, there are still several architectural barriers such as stairs, rivers, roads, canals, not only in old European cities but even in modern towns that limit the mobility of people with motor impairment. Thus, in this context we have considered the development of technical solutions able to overcome such architectural barriers, when classical solutions such as bridges cannot be adopted. The manipulator can provide translational motion being suspended [8], thus it can be proposed for a number of applications such as industrial pick and place operations. But, if large-scale applications are involved, a correct modelling of the system is necessary to obtain accurate positioning of the end-effector, as shown in [9], [10]. In addition, cable characteristics should be taken into account since the robot has to lift and transport people in a safe and robust way. The developed models and simulations take into account issues such as cable mass, elasticity and the effect of uncertainties in cable connections, according to previous works proposed by the authors in [9], [10].

2 A Cartesian Cable Suspended Robot (CCSR)

The robot understudy belongs to the class of Cartesian Cable- Suspended Robot (CCSR) [8]. Cable-robots that belong to this class are the C4 [11], the crane in [12] and DeltaBot in [13]. The proposed Cartesian Cable Suspended Robot has eight cables arranged in-parallel by pairs, each pair having the same length. The proposed CCSR has 3 translational DOFs by keeping a constant orientation. Therefore, the position workspace will be considered in this context. In particular, the geometry and force closure allow the robot to maintain a constant orientation. Four pairs of parallel cables are attached to the end-effector and collected by eight spools mounted on the upper base after passing through guide holes on the spools' frames. According to the scheme of Fig. 1, for each pair of cables, a close-chain can be identified, as for example A_{11} A_{21} B_{11} B_{21}. Since segments A_{11} A_{21}=B_{11} B_{21} = h, and cables $l_{11} = l_{21}$, hence each pair of segments of this close-chain will be parallel too, if the cables are all in tension. Therefore, if it is true for the four pairs of cables, rotations about X and Y are not allowed. Furthermore, if the top of the frame

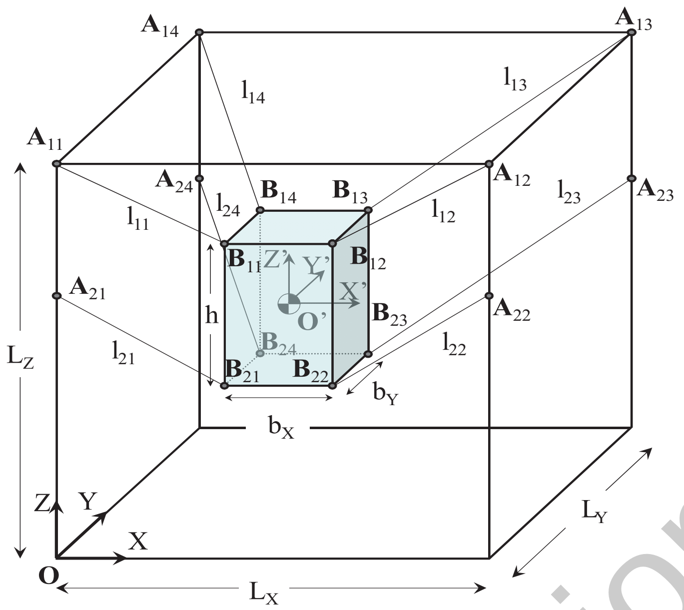


Fig. 1 Scheme for a kinetostatic analysis of a Cartesian Cable-Suspended Robot [15].

A_{11} A_{12} A_{13} A_{14} and top of end-effector B_{11} B_{12} B_{13} B_{14} are similar, that is $b_x/b_y = L_x L_y$ in Fig. 1, the end-effector cannot perform rotation about Z axis. A proof for the translational-motion is reported in [8,14] for the CCSR structure.

The general Inverse Kinematics equation can be written as

$$l_{ij} = \|\mathbf{X} + \mathbf{R}\mathbf{b}_{ij} - \mathbf{a}_{ij}\| \tag{1}$$

in which l_{ij} is the length of each cable, $\mathbf{X}$ is the position vector of the reference point O' on the end-effector, $\mathbf{R}$ is the rotation (identity matrix), $\mathbf{B}_{ij}$ (for i,j=1,...,n) is the position vector of the bij point attached to the moving platform expressed in the moving reference frame, and $\mathbf{a}_{ij}$ is the position of the exit point of each cable on the fixed frame. For force equilibrium it holds

$$\sum_{i=1}^{4}\sum_{j=1}^{2}\mathbf{F}_{ij} = -\sum_{i=1}^{4}\sum_{j=1}^{2}F_{ij}\widehat{\mathbf{I}}_{ij} = \mathbf{P}; \sum_{i=1}^{4}\sum_{j=1}^{2}\mathbf{t}_k = -\sum_{i=1}^{4}\sum_{j=1}^{2}F_{ij}\widehat{\mathbf{I}}_{ij} \times \mathbf{R}\mathbf{b}_{ij} = \mathbf{M} \tag{2}$$

$\mathbf{F}_{ij}$ in Eq. 2 is the cable tension that is applied to cable. Moreover, $\mathbf{P}$ and $\mathbf{M}$ are the resultant vector force and torque (wrench $\mathbf{W}$) that are exerted on or by the environment. Substituting the above-mentioned terms into 2 yields to

$$\mathbf{J}^{\mathrm{t}}\mathbf{F} = \mathbf{W} \tag{3}$$

in which **F** represents the vector of cable forces, **J** is the Jacobian matrix. It has been assumed that there are no external wrenches other than gravity. Equation 3 can be used to evaluate the vector **F** for a given trajectory. By using the Moore-Penrose Matrix Inverse we obtain a solution that is the minimum Euclidean norm corresponding to the lowest energetic value for the set of scalar cable forces. In most of reported works, it is assumed that the connection point to the mobile platform coincides with the centre of the pin. In particular in the following this assumption is considered correct for the mobile attachment points, but for the base attachments suitable pulleys are modelled, according to [10],[16]. Cables are represented as lumped mass systems. Elasticity is included by considering that a mass less cable behaves as linear spring and its elasticity coefficient can be evaluated as function of the cable section area A, the Young Modulus E, and the cable length l. The complete model is then obtained by discretizing the cable into a chain of several mass-spring elements. Therefore, each cable will be composed by N lumped masses m_i, and N+1 linear springs connecting the adjacent masses with elasticity coefficient k_i. In [9] it has been assumed that all the m_i masses are equal, as well as the k_i coefficients. The sum of the m_i masses equals the total cable mass, and k_i is equal to (N+1) k, in which k is the overall cable elasticity. It is important to point out that, given the position and trajectory of the end-effector, cable lengths and forces can vary considerably according to the developed model. Therefore, if accurate simulation is required those aspects must be considered.

3 CaSIMo: Cable System for Improving Mobility

CaSIMo is a robotic system that can be used to improve end-users mobility in urban environment allowing the person on a wheelchair (and eventually companions) to overcome rivers, roads and any other large obstacle in cities with safety and a remarkable simplicity of use. Figure 2 shows an urban installation of the CaSIMo to overpass a canal. The proposed system is based on an innovative design of the CCSR manipulator described in previous Section. It is composed by a cage to accommodate passengers and suitable actuation to drive steel cables. The cage is equipped with a push-button panel like lifts. The cage is also equipped with an automated system for opening and closing the doors. The particular arrangement of cables' connection allows to reduce the oscillations along the movement directions and prevents the fall of the cage even if an accidental cable breaking occurs. Current rules used for the design of lifts have been considered for the general definition of the system. The geometry of the CCSR provides two characteristics to the CaSIMo system: 1) safety: if a cable breaking occurs the redundant number of cables prevents accidental falls of the cage; 2) stability: the geometry helps to prevent oscillations in the direction of the movement.The CaSIMo

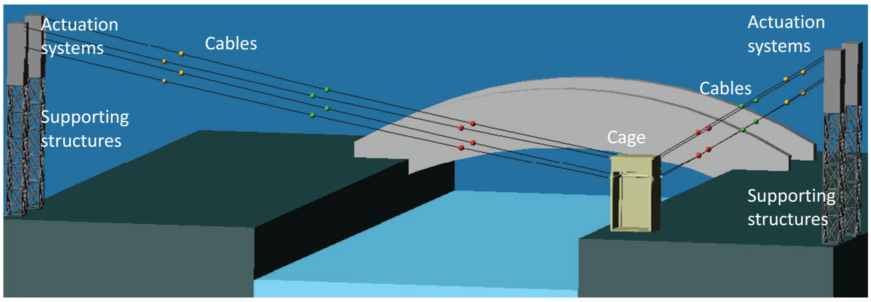


Fig. 2 An example of the CaSIMo in an urban installation to overpass a canal.

can be built by using commercial type components and therefore the total cost of the device is similar than other cable systems. Furthermore, thanks to the absence of evident large sized supporting structure, it greatly reduces the environmental and architectural impact. In Figure 2 main dimension for designing the CaSIMo system are: dimension of the canal to overpass 12.5 m; cage dimension 2.8 m × 1.5 m× 1.5 m, it can hold 3 or 4 people with total mass of 1000 kg. Steel cables have been chosen with a diameter of 10 mm, breaking load of 83 kN and linear density of 0.49 kg/m.

According to the chosen cables, pulleys with a diameter of 500 mm have been selected. Pulleys centers' of rotations are given in Table 1. We have developed a model for the cable release point (referred as the anchor position or anchor point) that varies as the position and orientation (pose) of the mobile platform is changed. Therefore, for the developed simulations the anchor positions have been calculated for each pose of the cage according to the pulleys' diameter. According to these design data a workspace analysis has been performed. Figure 3 shows cable tension distribution for cables 11 and 21 respectively (see the scheme in Figure 1) in a cross-section area taken in the plane of motion of the cage Center of Mass (CM).

The cross-section area is 9 m x 26.1 m = 230 m^2, the safe area of the CaSIMo that we can obtain maintaining a constant orientation of the cage is 195 m^2, which represents the 84 % of the working area.

A suitable safety factor is chosen being 15 kN the maximum allowed value for the cable tension. If we consider this force limit the cage can be lifted of about 3 meters, which is a value more than satisfactory for the application. In particular, cable tension determination takes into account this maximum force value.

Table 1 Position of the centers' of rotation for pulleys in the model of Fig. 2.

	A_{11}	A_{21}	A_{12}	A_{22}	A_{13}	A_{23}	A_{14}	A_{24}
X(m)	0	0	32	32	32	32	0	0
Y(m)	0	0	0	0	3.5	3.5	3.5	3.5
Z(m)	8	7.2	8	7.2	8	7.2	8	7.2

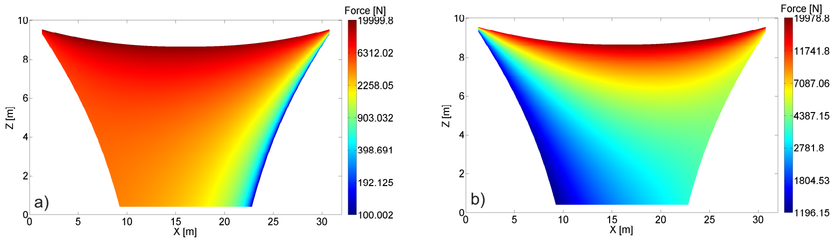


Fig. 3 Cable tension distribution in a workspace cross-section: a) F_{11}; b) F_{21}.

4 Simulation Results

A simulation of the cage transfer is reported in the sequence of Fig. 4. The proposed simulation takes 40 s: 5 s at the beginning and the end are used to reach the static equilibrium of the system. During the first phase the cage is lifted up by 3 m. During the 2nd phase the cage is moved along X direction by 15 m, finally, during the 3rd phase the cages is lifted down. For simulation purposes, only people are not displayed during the simulation given in Fig. 4, but their effect is considered as an additional mass in the cage.

Results are shown in Figs. 5 to 7 for the dynamic simulation run under ADAMS environment. In particular, the cables' tensions and required power, velocity and acceleration of the Center of Mass (CM) for the cage are shown. It is worth noting that, although the suspended nature of the cable system, the simulation shows negligible rotations of the cage (the 3rd angle only has a maximum rotation of 2 deg). Since the system has to transport people, accelerations effects of the cage can be almost neglected, although the simulation time can be considered short according to the task.

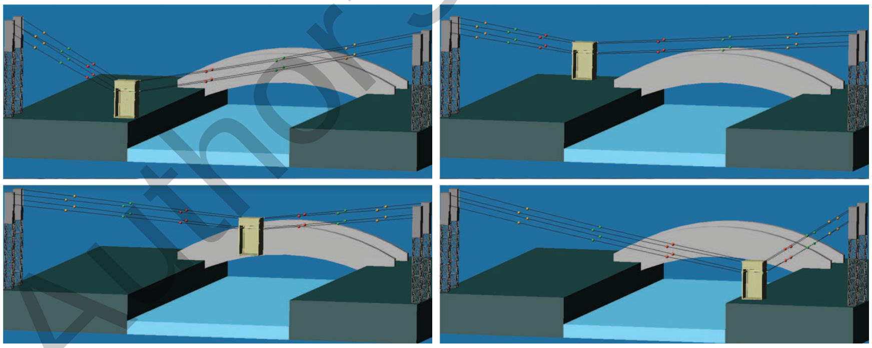
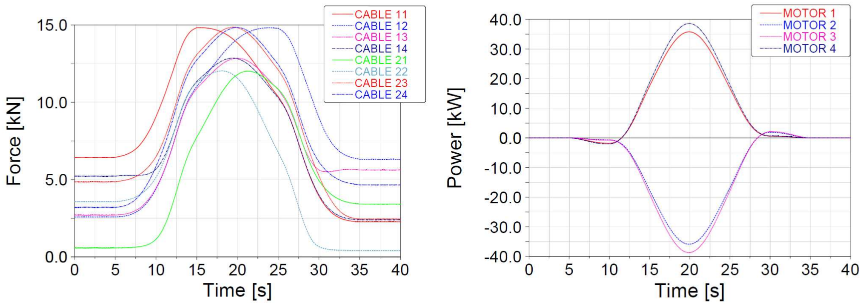
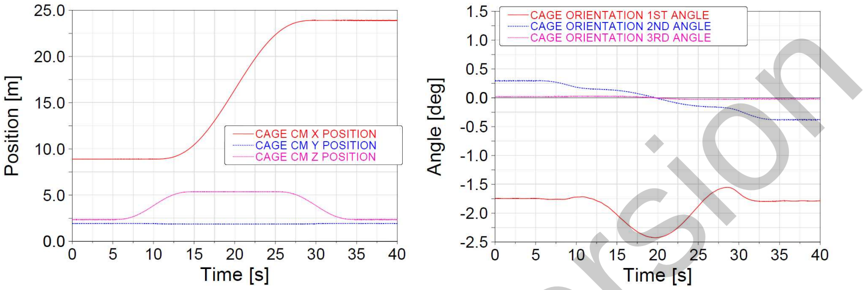


Fig. 4 A sequence of the cage transfer phases with CaSIMo.



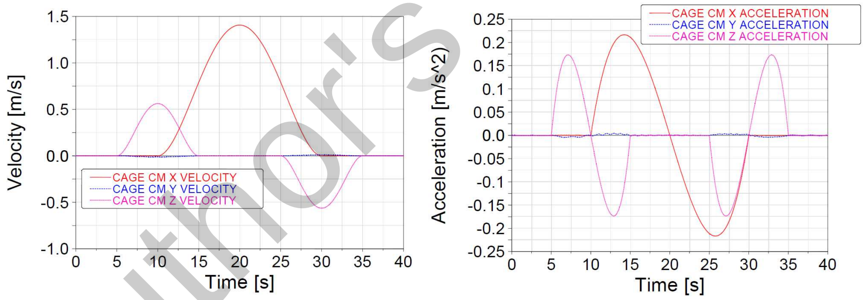
a) b)

Fig. 5 Simulation numerical results: a) Cables' tensions b) Required power.



a) b)

Fig. 6 Simulation numerical results: a) Cage CM position; b) Cage angular orientation.



a) b)

Fig. 7 Simulation numerical results: a) Cage velocity; b) Cage acceleration.

5 Conclusion

In this paper a large dimension cable system has been proposed to be used for mobility and handling applications with high level of safety and stability.

In addition, since the cable based manipulator is proposed here to transfer people, cable mass and elasticity, and transmission system are considered. The proposed cable robot belongs to the class of CCSR, its particular design allows translational motion only and then it is well suited for the application. Nevertheless, the proposed model makes this design well suited for large-scale handling applications, such as in naval and civil environments.

References

1. Kawamura S., Kino H., Won C., High-Speed Manipulation by Using Parallel Wire-Driven Robots, Robotica, vol.18, no.1, 2000, pp. 13-21.
2. Albus J., Bostelman R., Dagalakis N., The NIST Robocrane, Jnl of Robotic Systems, vol.10, no.5, 1992, pp.709-724.
3. August Design, www.august-design.com, 2013.
4. Tadokoro S., Verhoeven R., Hiller M., Takamori T., A Portable Parallel Manipulator for Search and Rescue at Large-Scale Urban Earthquakes and an Identification Algorithm for the Installation in Unstructured Environments, in Proc. IEEE/RSJ IROS Int. Conf. on Intelligent Robots and Systems, 1999, pp. 1222-1227.
5. Yamamoto M., Noritaka Y., Akira M., Trajectory Control of Incompletely Restrained Parallel-Wire-Suspended Mechanism Based on Inverse Dynamics, IEEE Trans. on Robotics, vol.20, no.5, 2004, pp. 840-850.
6. Merlet J.-P., Kinematics of the wire-driven parallel robot MARIONET using linear actua-tors , IEEE Int. Conf. on Rob. and Aut., Sophia Antipolis, 2008, pp. 3857-3862.
7. Izard J.-B., Gouttefarde M., Michelin M., Tempier O., Baradat C., Reconfigurable Robot for Cable-Driven Parallel Robotic and Industrial Scenario Proofing, 1rst Int. Conf. on Cable-Driven Parallel Robots, Ed. Springer, Stuttgart, 2012, pp. 135-148.
8. Castelli G, Ottaviano E, Gonzàlez A, Analysis and simulation of a new Cartesian cable-suspended robot, Proc. IMechE Vol. 224 Part C: J. Mechanical Engineering Science, 2010, pp. 1717-1726,DOI: 10.1243/09544062JMES1976
9. Ottaviano E., Castelli G., A Study on the Effects of Cable Mass and Elasticity in Cable-Based Parallel Manipulators, Proc. of the18th CISM-IFToMM Symp. On Robot Design, Dynamics and Control, Udine, Springer Ed., 2010, pp. 149-156.
10. Ottaviano E., Castelli G., Issues on the Modelling of Cable-Based Parallel Manipulators, Congresso dell'Associazione Italiana di Meccanica Teorica e Applicata (AIMETA), Bologna, 2011, paper MEM-13-0.
11. Bosscher P., Williams II R. L., Bryson L. S., Castro-Lacouture D., Cable-Suspended Robotic Contour Crafting System, Automation in Construction, vol.17, no.1, 2007, pp. 45-55.
12. Krut S., Ramdani N., Gouttefarde M., Company O., Pierrot F., A Parallel Cable-Driven Crane For SCARA-Motions, Proc. of the ASME 2008 IDETC/CIE 2008, New York, 2008, Paper DETC2008-49969.
13. Dekker R., Khajepour A., Behzadipour S., Design and Testing of an Ultra-High-Speed Cable Robot, Int. J. of Robotics and Automation, vol. 21, no. 1, 2006, pp. 25-34.
14. Voglewede P. A. Ebert-Uphoff I., Application of the Antipodal Grasp Theorem to Cable Driven robots, IEEE Trans. on Robotics, Vol. 21, No. 4, 2005, pp. 713-718.
15. Ottaviano E., Castelli G., Rea P., Macchina automatica cartesiana CCSR (Cartesian Cable-Suspended Robot) basata su sistema a cavi per la movimentazione di carichi, Italian Patent n. FR2009A000025, 02/11/2009.
16. Notash L., McColl D., Workspace Investigation of Wire-Actuated Parallel Manipulators with Uncertainties in Wire Connections, ASME 2010, Mech. and Rob. Conf., Montreal, 2010, Paper DETC2010-28228.