DESIGN AND MODELING OF CONTAINER CRANE SYSTEMS USING CABLE SUSPENSION MANIPULATOR PLATFORM

Abrahão Campos Moutinho Vieira, abrahaocampos@poli.ufrj.br
Gustavo Fernandes Bittencourt, gufbittencourt@poli.ufrj.br
Omar Lengerke, olengerke@ufrj.br
Max Suell Dutra, max@mecanica.coppe.ufrj.br
Mechatronic Systems & Robotics Research Group – COPPE/UFRJ
Postal Box 68.503 – CEP 21.945-970 – Rio de Janeiro, RJ, Brazil

Abstract. *Cable suspension manipulator is a special class of parallel manipulator using cables and support a payload platform by several spatially arranged cables. The present contribution treats a design and modeling a new concept of a container crane system that combine the ability of crane to support heavy payloads in a large workspace with the dexterity of robot manipulator. In particular, this system is considered that is being developed at Robotics Laboratory – UFRJ.*

Keywords*: Cable Suspension Manipulator, Crane Systems, Offshore Systems.*

1. INTRODUCTION

The port operations of cargo handling activities are performed daily in order to load and unload the mercantile ships responsible for transporting various types of products around the world. In these operations, risks of accidents are topics relevant to the context, since the movement of loads quickly and efficiently, reducing costs related to the time of operation is a goal to be achieved through constant technological development of equipment (cranes) and the expertise of its operators (Vis and Koster, 2003). The safety in the transport of cargo has its correct packaging, its safety, its identification and its handling, plus the stress of the equipment, which is governed by international standards (König, Zilch and Lappas, 1979).

The design and modeling of container crane systems consists of a system of cargo transport through a platform suspended by three cables (Figure 1) (Matheus, 2001). Each cable is fixed on trolley that translates on a trail. Thus, the system has three rails on which each rail has an electric car that can move through its length. Another feature is the possibilities of the cables have their length increased and decreased (Arai and Osumi, 1992). Thus, the load platform has the ability to translate and orient it in space. This idea is related to cable-suspended robots; the literature in this area is growing (Albus, Bostelman and Dagalakis, 1993; Roberts, Graham and Lippitt, 1998 and Su, Duan, Nan and Peng, 2001).

The above advantages have made cable-based robots very promising for certain applications such as high-speed robotics and material handling in large workspaces (Behzadipour and Khajepour, 2005). The main advantages in using cables in parallel manipulators can be listed as follows: (i) Large range of motion in comparison with linear actuators, (ii) smaller required space, (iii) negligible inertia, (iiii) higher movability in comparison with spherical joints, and (iiiii) lower cost.

First there was an issue involving the contextualization of the types of systems currently used in ports for the transport of cargo, especially containers. We verified the advantages and disadvantages of these systems, and that from these characteristics; it has motivated the study of the proposed work. The main advantage of the crane system is due to the loading platform has six degrees of freedom, i.e., the platform can translate and orient it in space, which is not possible with the cargo transport systems currently used. The project is the development of simulation modeling of the system and dynamic analysis. The dynamic model must take into account the active forces, to get the torque needed to perform a trajectory using Universal Mechanism software (UM).

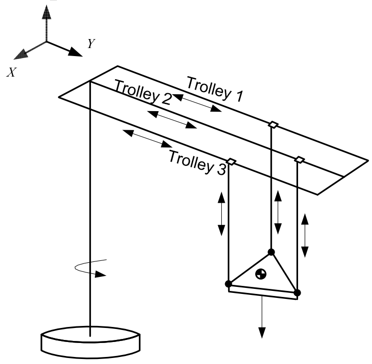

Figure 1. The general structure

2. SYSTEM DESIGN AND DESCRIPTION

Cranes are widely used to transport heavy loads and hazardous materials in shipyards, factories, nuclear installations, and high-building construction. They can be classified into two categories based on their configurations: gantry cranes and rotary cranes.

The cable suspension manipulator consists of an end-effector and three cables that suspend the end-effector, as shown in Figure 1. The cables are driven by motors that are mounted on the mobile support vehicles, and the cables are routed through pulleys on the tops of the stanchions (Karihaloo and Parbery, 1982, Daqaq and Masoud, 2006). By reeling the cables in and out the position of the end-effector can be controlled. Because a lot of cable can be stowed on a motor reel, the manipulator can have a large workspace, allowing it to operate over large disaster areas. The geometry of the cable robot will be discussed in greater detail later in this section. The cable suspension manipulator has been conceived at LabRob (Laboratory of Robotics, COPPE/UFRJ). It is composed by a mechatronic system, as shown in Fig. 2.

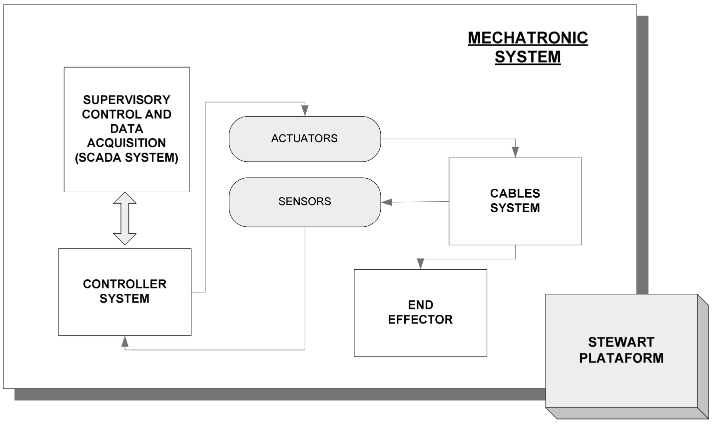

Figure 2. Mechatronic system for cable suspension manipulator

The actuation system of the proposed manipulator is composed by four DC motors, which can extend or retract cables. A choice has been made regarding to the manipulator's architecture. In Figure 3, the general design of cable robot plataform is shown the arrangement of the three-cable hand-directed sculpting system. The system is large: it stands almost 1 m high and is supported by one Stewart plataform and a equilateral triangle of side 0,9 m.

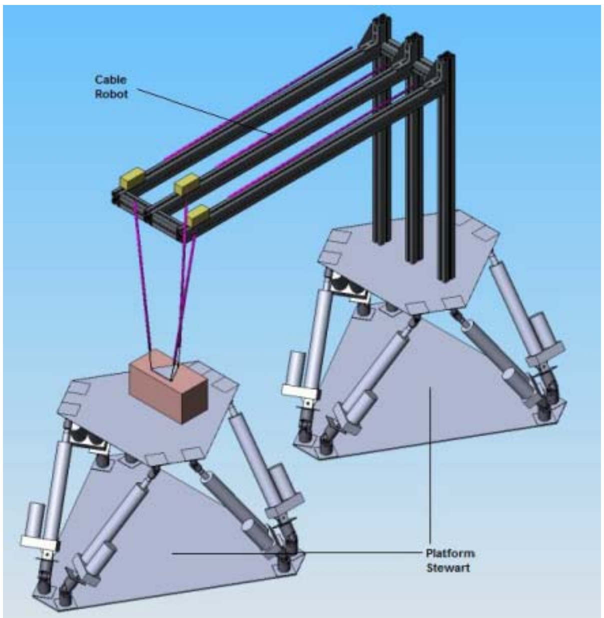

Figure 3. General design of cable robot platform

In Figure 4 shows a general design of cable suspension manipulator platform. The system consists of a structure of EN AW- 6060 aluminum with a total of 250 N. At the top of the structure, contains 3 independent linear guides that together support a load of 500 N through steel cables. These linear guides can translate over the structure and the steel cables have a vertical motion. The steel cables were simulated as if they were springs and rigid. The advantage of this system is to control the position of the load, since the linear guides are mutually independent and can control the length of steel cables.

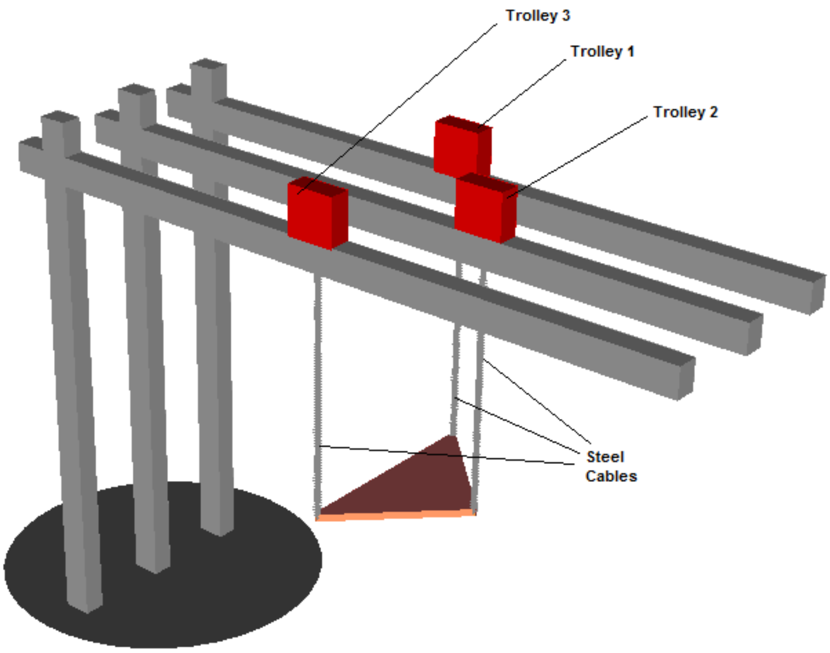

Figure 4. General design of cable robot platform using UM software®.

To ensure the integrity of the structure, several tests are realized. First, considered the load of 170N was also distributed at the end of each jib (Figure 5).

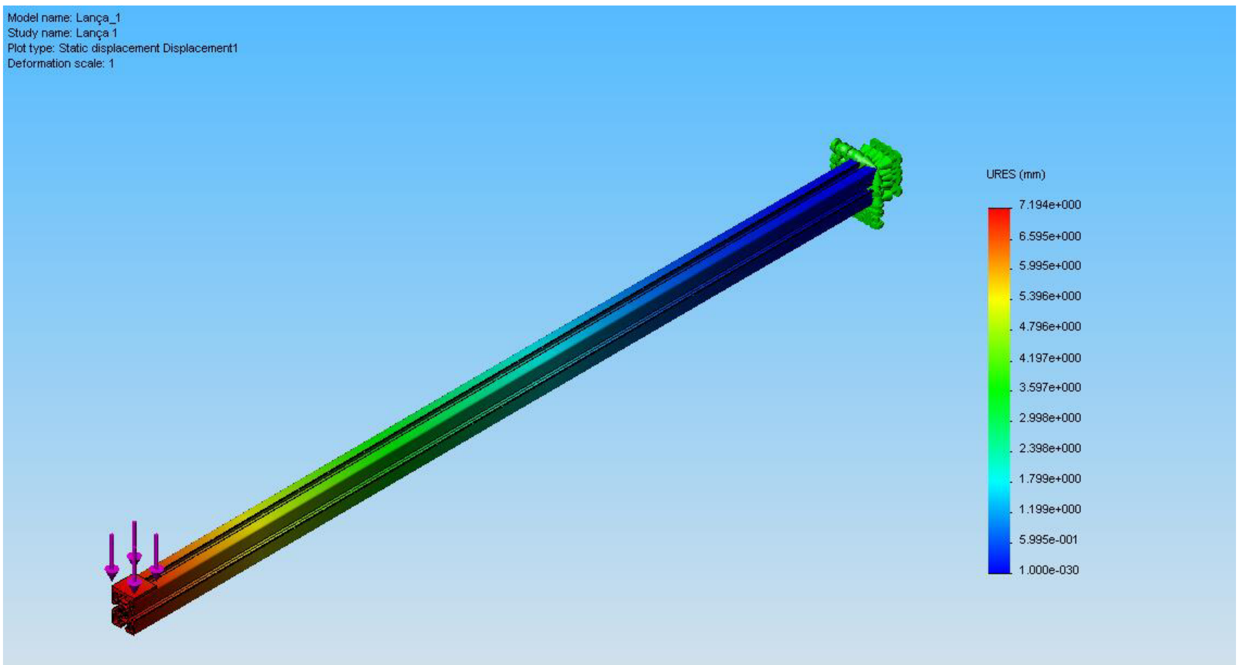

Figure 5. Displacement analysis for 170N

In another situation, analyses on an extreme scenario where the total load of 500N were concentrated in a single jib. The system would have to be rigid enough to ensure the functioning of the system (Figure 6) and the results obtained (Table 1) based on materials and features of the structure (Rexroth, 2009), can be observed that the values are below the limits.

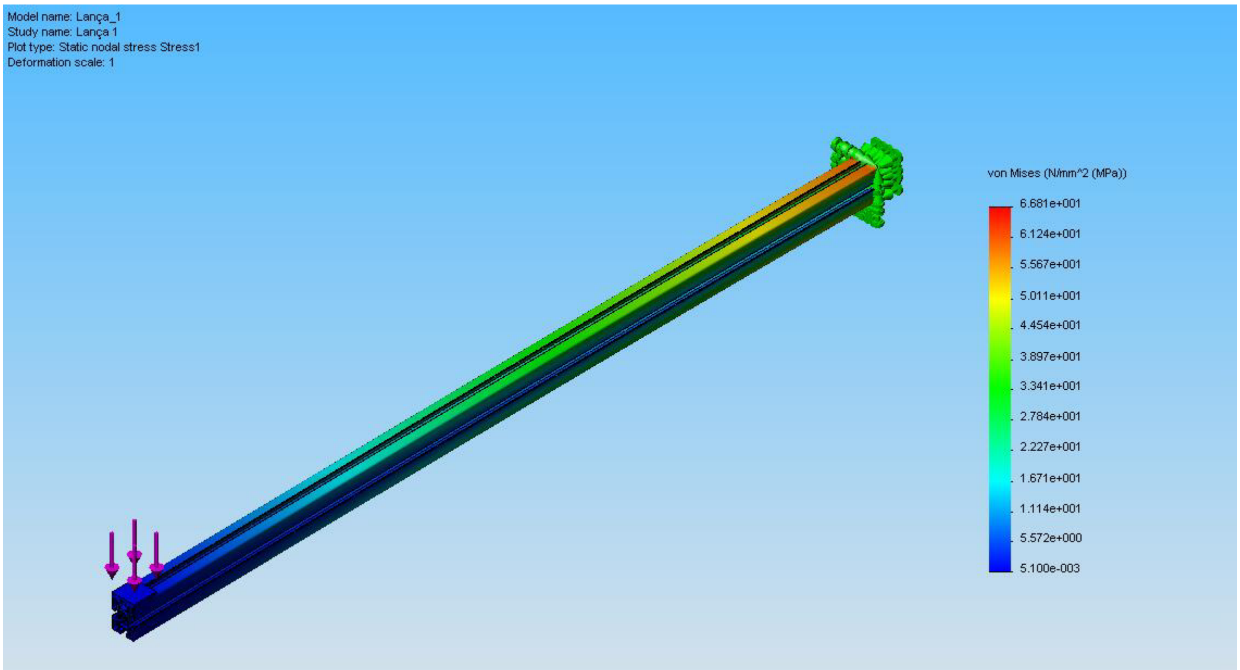

Figure 6. Tension analysis for 500N – Safety factor 2.9

Table 1. – Results of analysis

Force (N)	170	500
Max. Tension (Mpa)	22.71	66.81
Max. Displacement (mm)	7.194	21.116

4. KINEMATICS STUDY

The direct kinematics of the crane robot needs very complicated calculation. This is partly because the model of a wire includes free ball joints at both ends and partly because the mechanism has closed loops. The kinematics of the robot are calculated by solving the simultaneous equations given by the geometrical constraints of the three wire lengths and by force constraints of gravity.

For the trolley 1, the transformation matrices are:

$$ {}^{0}\boldsymbol{R}_{1}^{1} = \begin{pmatrix} c\phi & -s\phi & 0 & 0 \\ s\phi & c\phi & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}, {}^{1}\boldsymbol{T}_{2}^{1} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & a_0 \\ 0 & 0 & 0 & 1 \end{pmatrix}, {}^{2}\boldsymbol{T}_{3}^{1} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & a_1 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}, {}^{3}\boldsymbol{R}_{4}^{1} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & c\phi_1 & -s\phi_1 & 0 \\ 0 & s\phi_1 & c\phi_1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}, $$

$$ {}^{4}\boldsymbol{R}_{5}^{1} = \begin{pmatrix} c\eta_1 & 0 & s\eta_1 & 0 \\ 0 & 1 & 0 & 0 \\ -s\eta_1 & 0 & c\eta_1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}, {}^{5}\boldsymbol{T}_{6}^{1} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & -c_1 \\ 0 & 0 & 0 & 1 \end{pmatrix} $$

For the trolley 2, the transformation matrices are:

$$ {}^{1}\boldsymbol{T}_{2}^{2}=\begin{pmatrix}1&0&0&0\\0&1&0&0\\0&0&1&a_0\\0&0&0&1\end{pmatrix},\ {}^{2}\boldsymbol{T}_{3}^{2}=\begin{pmatrix}1&0&0&-L_2\\0&1&0&a_1\\0&0&1&0\\0&0&0&1\end{pmatrix},\ {}^{3}\boldsymbol{T}_{4}^{2}=\begin{pmatrix}1&0&0&0\\0&1&0&a_2\\0&0&1&0\\0&0&0&1\end{pmatrix},\ {}^{4}\boldsymbol{R}_{5}^{2}=\begin{pmatrix}1&0&0&0\\0&c\phi_2&-s\phi_2&0\\0&s\phi_2&c\phi_2&0\\0&0&0&1\end{pmatrix}, $$

$$ {}^{5}\boldsymbol{R}_{6}^{2}=\begin{pmatrix}c\eta_2&0&s\eta_2&0\\0&1&0&0\\-s\eta_2&0&c\eta_2&0\\0&0&0&1\end{pmatrix},\ {}^{6}\boldsymbol{T}_{7}^{2}=\begin{pmatrix}1&0&0&0\\0&1&0&0\\0&0&1&-c_2\\0&0&0&1\end{pmatrix} $$

For the trolley 3, the transformation matrices are:

$$ {}^{1}\boldsymbol{T}_{2}^{3}=\begin{pmatrix}1&0&0&0\\0&1&0&0\\0&0&1&a_0\\0&0&0&1\end{pmatrix},\ {}^{2}\boldsymbol{T}_{3}^{3}=\begin{pmatrix}1&0&0&L_2\\0&1&0&0\\0&0&1&0\\0&0&0&1\end{pmatrix},\ {}^{3}\boldsymbol{T}_{4}^{3}=\begin{pmatrix}1&0&0&0\\0&1&0&a_3\\0&0&1&0\\0&0&0&1\end{pmatrix},\ {}^{4}\boldsymbol{R}_{5}^{3}=\begin{pmatrix}1&0&0&0\\0&c\phi_3&-s\phi_3&0\\0&s\phi_3&c\phi_3&0\\0&0&0&1\end{pmatrix}, $$

$$ {}^{5}\boldsymbol{R}_{6}^{3}=\begin{pmatrix}c\eta_3&0&s\eta_3&0\\0&1&0&0\\-s\eta_3&0&c\eta_3&0\\0&0&0&1\end{pmatrix},\ {}^{6}\boldsymbol{T}_{7}^{3}=\begin{pmatrix}1&0&0&0\\0&1&0&0\\0&0&1&-c_3\\0&0&0&1\end{pmatrix} $$

Matrices of rotation around the axes *x, y* e *z*.

$$ \boldsymbol{R}_x=\begin{pmatrix}1&0&0&0\\0&c\varphi&-s\varphi&0\\0&s\varphi&c\varphi&0\\0&0&0&1\end{pmatrix},\ \boldsymbol{R}_y=\begin{pmatrix}c\psi&0&s\psi&0\\0&1&0&0\\-s\psi&0&c\psi&0\\0&0&0&1\end{pmatrix},\ \boldsymbol{R}_z=\begin{pmatrix}c\theta&-s\theta&0&0\\s\theta&c\theta&0&0\\0&0&1&0\\0&0&0&1\end{pmatrix} $$

Matrix of rotation around the axis (*z, y, x*), which correspond to the *Bryant* angles (*θ, ψ, φ*) respectively.

$$ \boldsymbol{R}_{zyx}=\begin{pmatrix}c\theta c\psi & c\theta s\psi s\varphi-c\varphi s\theta & c\theta c\varphi s\psi+s\theta s\varphi\\ c\psi s\theta & s\theta s\psi s\varphi+c\theta c\varphi & c\varphi s\theta s\psi-c\theta s\varphi\\ -s\psi & c\psi s\varphi & c\psi c\varphi\end{pmatrix} $$

The distance between the platform center and its vertices are represented by matrices or vectors:

$$ \boldsymbol{d}_1=\begin{pmatrix}1&0&0&0\\0&1&0&L_1\dfrac{\sqrt{3}}{3}\\0&0&1&0\\0&0&0&1\end{pmatrix},\ \boldsymbol{d}_2=\begin{pmatrix}1&0&0&-L_2\\0&1&0&-L_1\dfrac{\sqrt{3}}{6}\\0&0&1&0\\0&0&0&1\end{pmatrix},\ \boldsymbol{d}_3=\begin{pmatrix}1&0&0&L_2\\0&1&0&-L_1\dfrac{\sqrt{3}}{6}\\0&0&1&0\\0&0&0&1\end{pmatrix} $$

$$ \boldsymbol{d}_1=\begin{bmatrix}0 & L_1\dfrac{\sqrt{3}}{3} & 0\end{bmatrix},\ \boldsymbol{d}_2=\begin{bmatrix}-L_2 & -L_1\dfrac{\sqrt{3}}{6} & 0\end{bmatrix},\ \boldsymbol{d}_3=\begin{bmatrix}L_2 & -L_1\dfrac{\sqrt{3}}{6} & 0\end{bmatrix} $$

Position and orientation matrices of a random point in the workspace of cable manipulator.

$$\boldsymbol{M}_{PO} = \begin{pmatrix} [\boldsymbol{R}_{zyx}] & \boldsymbol{p} \\ \boldsymbol{0} & 1 \end{pmatrix}, \ \boldsymbol{p}_p = \begin{bmatrix} x_p & y_p & z_p \end{bmatrix}$$

5. DYNAMIC SIMULATION

The dynamics of industrial robots with open-chain linkages have been extensively studied for many years. The most commonly used methods for solving the problem of robot dynamics are the Lagrangian and Newton-Euler methods (Zang, Wan, Liu and Linn, 2002). The Lagrangian approach is well-structured and can be expressed in closed-form, but it is computationally inefficient. The Newton-Euler approach results in a very efficient set of recursive equations, but it is not suited for deriving advanced control laws. In addition, both methods suffer from serious weaknesses and difficulties when dealing with robots with closed-chains. To solve the problems, Kane applied his equation into the dynamics of robots in 1983 (Xu, Chung, Choi and Ma, 1999). In this paper, a further development is made on Universal Mechanism (UM) software® (Yazykov and Pogorelov, 2004). In Figure 7, can see observed the layout of application. In the interface is the control panel, which can controller the displacement of the linear guides (trolley) as the length of cables steel. In other side, is a animation window that shows the dynamic simulation of system and finally, are shows graphs and plots of the simulation system.

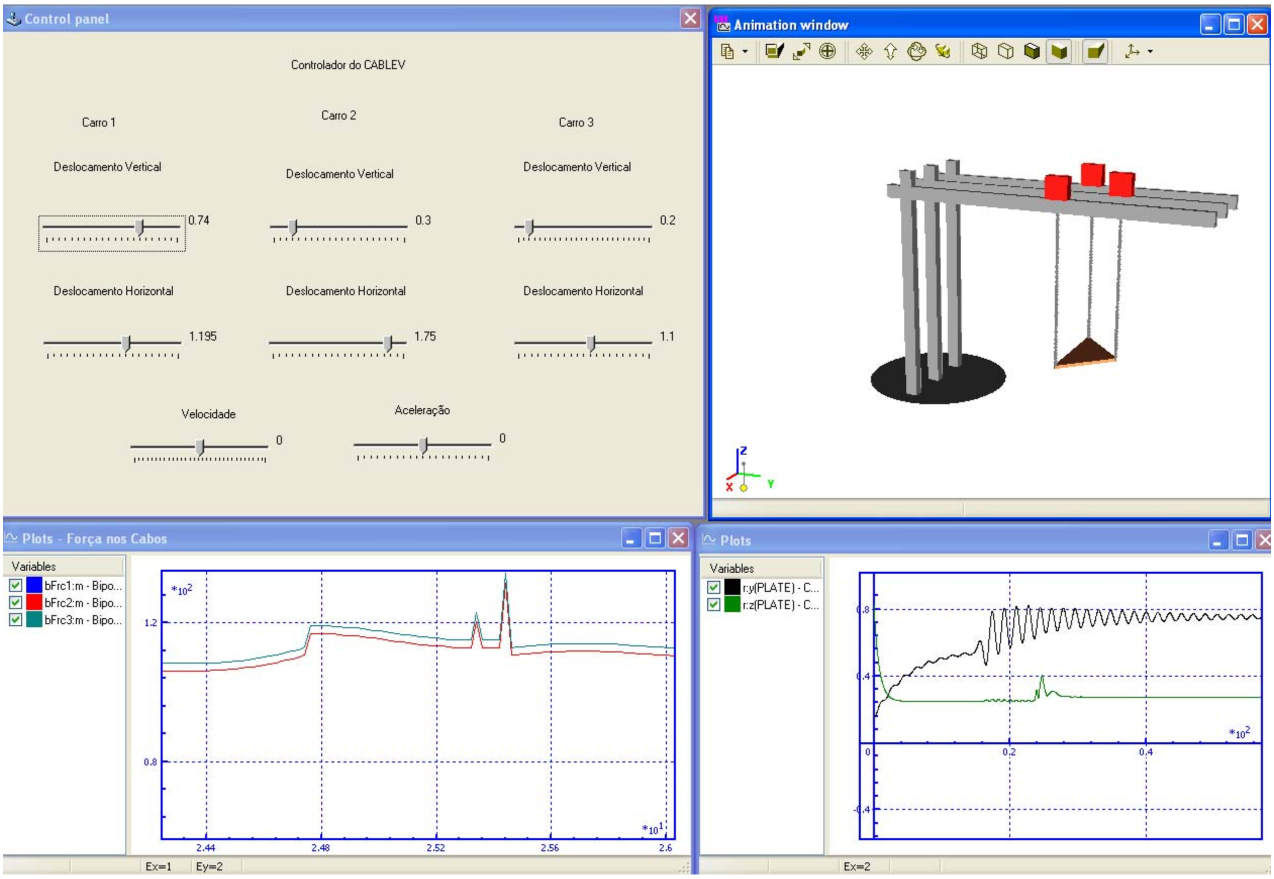

Figure 7. Layout application software

The trajectories analysis of the load (cargo) is realized for two situations. First, when the load is moved horizontally toward the end of the jib, then the length of the cables is increased, shifting the load vertically down. Finally, the cables are reduced in size, moving the load vertically upwards and subsequently guides the linear return to its original position as shown in Figure 8 and Figure 9.

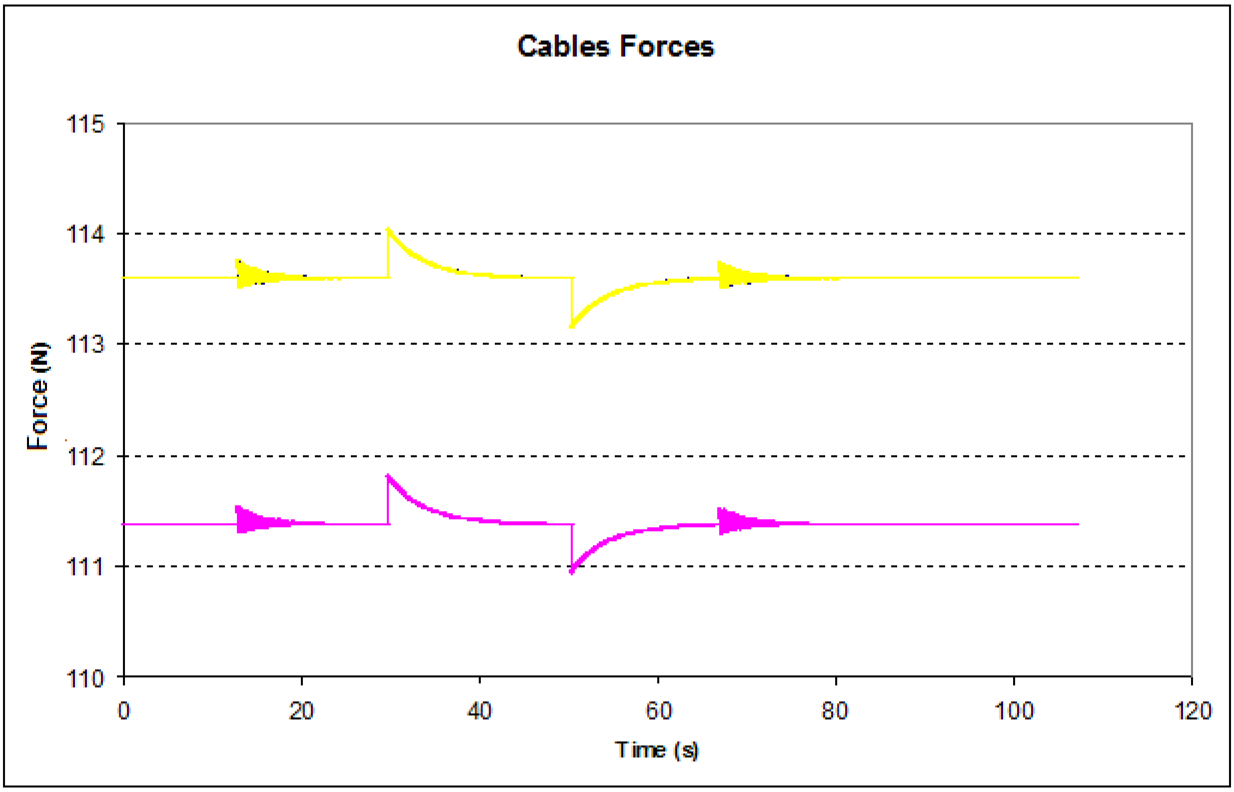

Figure 8. Cable forces - first situation

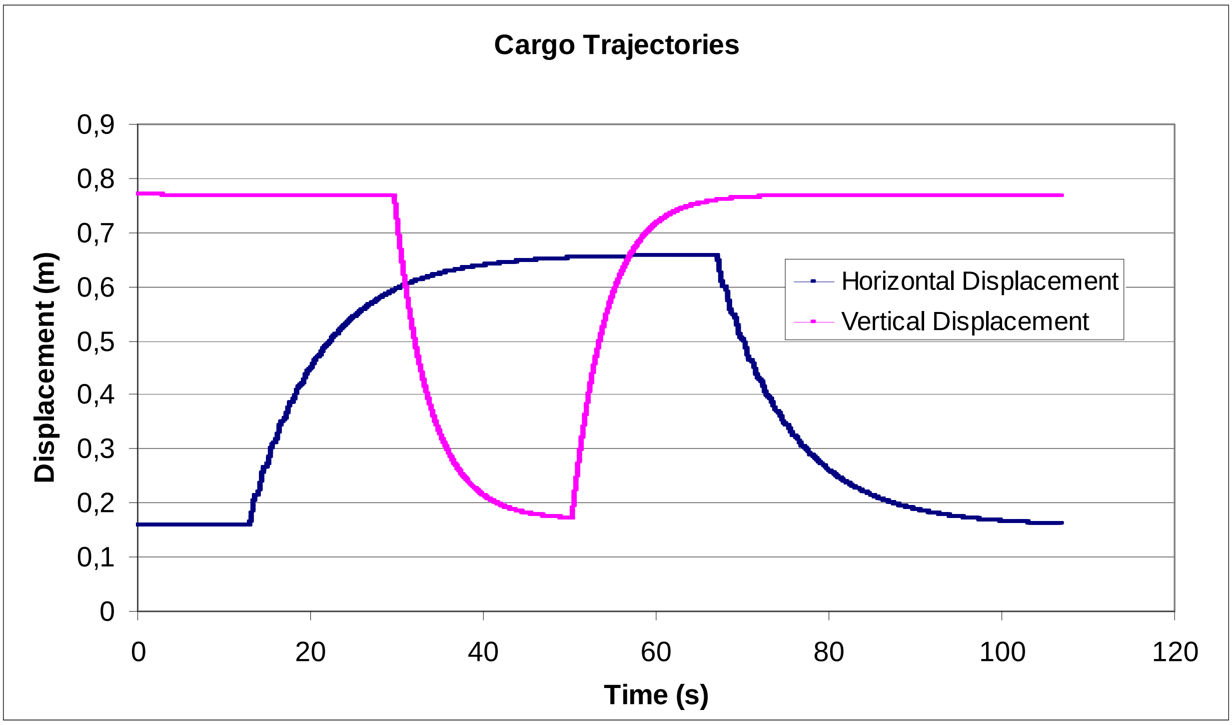

Figure 9. Cargo trajectories - first situation

In the second simulation, the vertical and horizontal movements occurred simultaneously and forces as shown in Figure 10 and Figure 11.

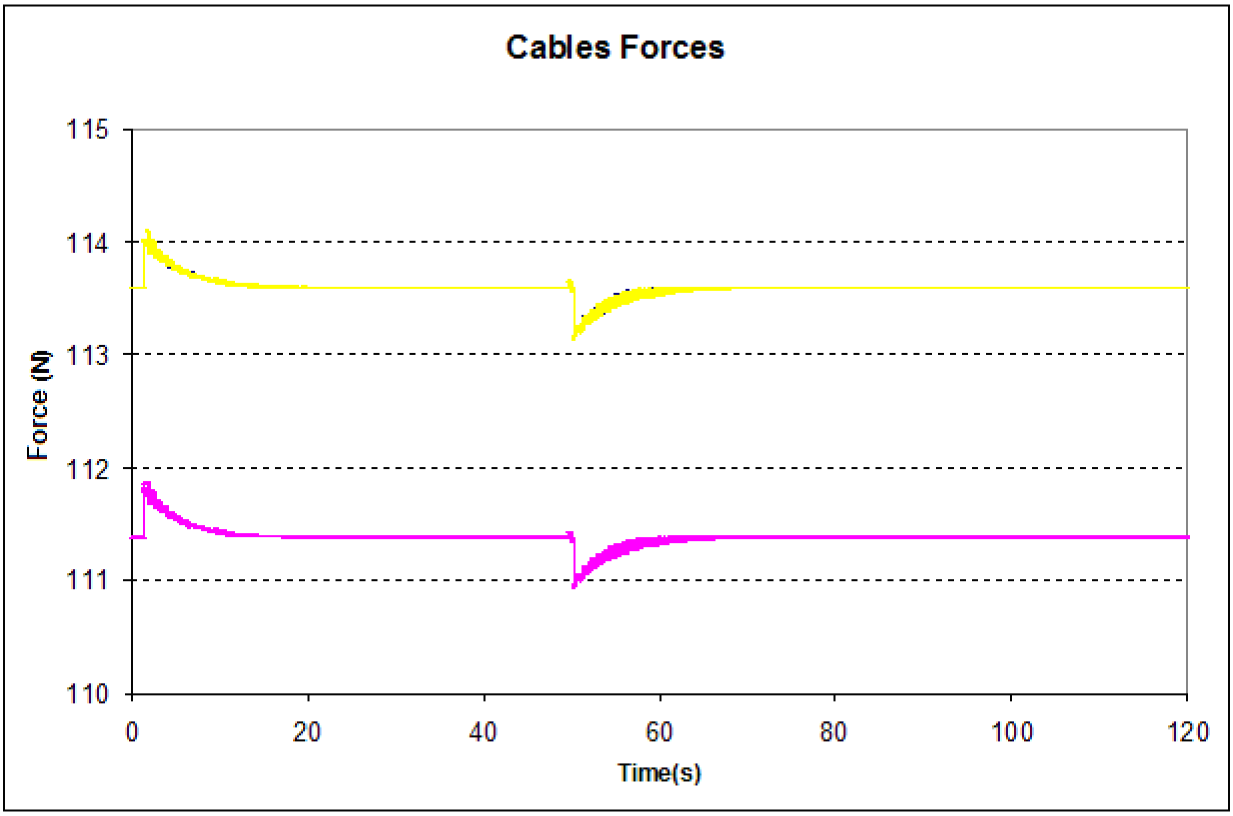

Figure 10. Cable forces - second situation

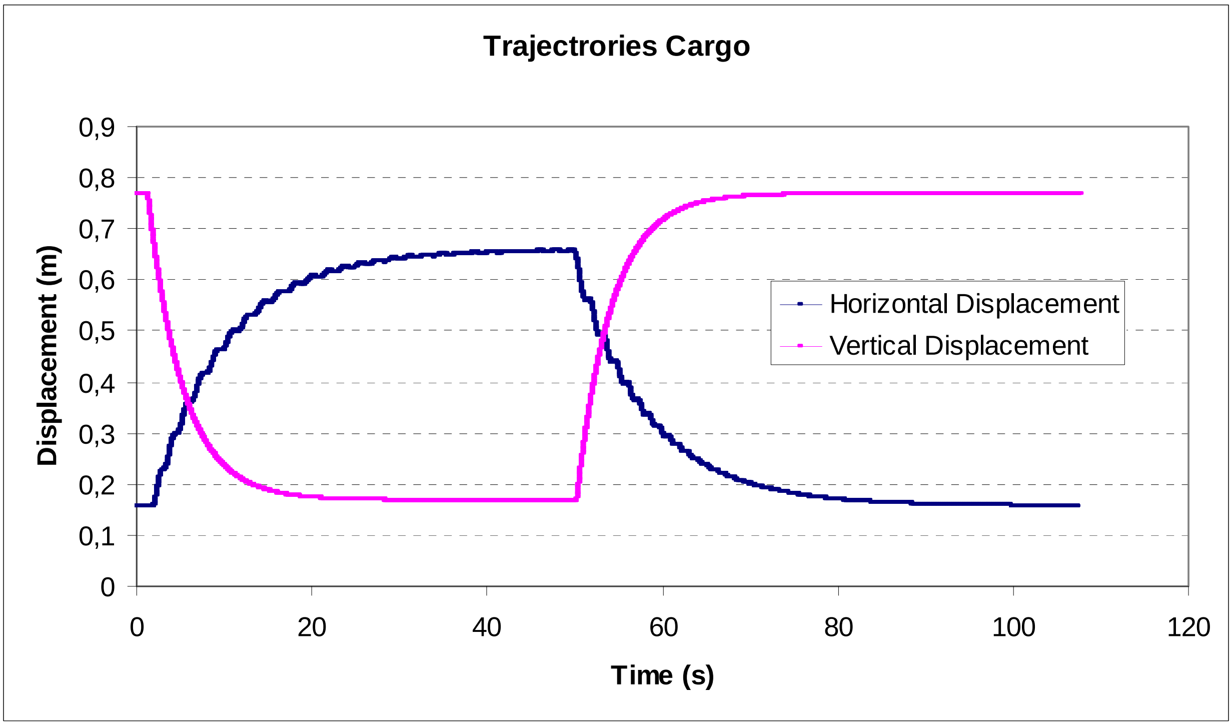

Figure 11. Cargo trajectories - second situation

Comparing the two results, observes that there was no significant difference in the module of the forces, however during the trajectory can be observed a larger oscillation in the second situation.

5. CONCLUSIONS

The concept of a new cable-based manipulator with six degrees of freedom was presented. In this manipulator, cable parallelograms are used to provide pure translational motion to the end-effector. The characteristics of cable robots are very different from those of serial manipulators, and involve problems which, although they may be similar to those encountered for serial structure, need a specific treatment. The complexity of their implantation, of their control and of their design that is a potential problem. Control is a key issue, especially for machines, for which most controllers are basically the same as those used for classical linear machines, and therefore not appropriate for a non-linear machine (Maier and Woernle, 1999, Ziyad, Nayfeh and Nayfeh, 2005).

CAD and simulation software must also be addressed, especially for the development of cable robots having less than 6 degree of freedom. Synthesizing machines with less than 6 degree of freedom is an exciting field of research, but we lack the simulation tools to perform a critical analysis of these new mechanisms, and to determine how useful they may be. Within the CAD system, a module for trajectory planning should be developed. But trajectory planning for closed-chains has not reached the same level as for serial chains; other related problems should be addressed, such as optimal part positioning or optimal use of eventually redundant degree of freedom.

The future works plans include: detailed mechanical design of the system components, alternative calibration routines and cable robot control methods.

6. REFERENCES

Albus, J.S. Bostelman, R., Dagalakis, N.G., 1993, “The NIST ROBOCRANE”, Journal of Robotic Systems, Vol. 10, No. 5, pp. 709-724.

Arai,T., Osumi, H., 1992, “Three wire suspension robot”, Industrial Robot, 19, pp 17-22.

Behzadipour, S. Khajepour, A., 2005, “A New Cable-Based Parallel Robot with Three Degrees of freedom”, Multibody System Dynamics, pp. 371-383

Daqaq, M., F., Masoud, Z., N., 2006, “Nonlinear Input-Shaping Controller for Quay-Side Container Cranes”, Nonlinear Dynamics, vol. 45, pp. 149-170.

Karihaloo, B., L., and Parbery, R., D., 1982, “Optimal Control of a Dynamical System Representing a Gantry Crane”, Journal of Optimization Theory and Applications, Vol.36, No. 3, (March), pp. 409-417.

König, G., Zilch, K., and Lappas, G., 1979, “Wind loading of shipyard gantry cranes – full-scale measurements”, Journal of Wind Engineering and Industrial Aerodynamics, Vol. 4 (August), Issues 3-4, Pages 429-435.

Maier, T., Woernle, C., 1999, “Flatness-Based Control of Underconstrained Cable Suspension Manipulators”, Advances in Multibody Systems and Mechatronics, pp.277-290

Matheus, M., 2001, “Mittelalterliche Hafenkräne”, Europäische Technik im Mittelalter, 4ed., Berlin, Uta Lindgren, pp. 345-348.

Rexroth Bosch Group, 2009, “Linear Motion and Assembly Technologies”, version 1.0, 67 p.

Roberts, R.G., Graham, T., Lippitt, T., 1998, “On the Inverse Kinematics, Statics, and Fault Tolerance of Cable-Suspended Robots”, Journal of Robotic Systems, Vol. 15, No. 10, pp. 581-597.

Su, Y.X., Duan, B.Y., Nan, R.D., Peng, B., 2001, “Development of a Large Parallel-Cable Manipulator for the Feed-Supporting System of a Next-Generation Large Radio Telescope”, Journal of Robotic Systems, Vol. 18, No. 11, pp. 633-643.

Vis, I., F., A. Koster, R., de, 2003, “Transshipment of containers at a container terminal: An overview”, European Journal of Operational Research, Vol. 147, Issue 1, 16 (May), Pp. 1-16.

Xu, X., Chung, W., Choi, Y., Ma, X., 1999, “A New Dynamic Formulation for Robot Manipulators Containing Closed Kinematic Chains”, Robotica, UK, Cambridge University Press, Vol. 17, pp. 261-267.

Yazykov, V.N., Pogorelov, D.Yu., Mikhalchenko, G.S., 2004, “Railway Vehicle Simulation Using Non-Elliptical Wheel-Rail Contact Model”. In: XXI International Congress of Theoretical and Applied Mechanics (ICTAM), Warsaw, Poland, August 15-21.

Zang, C., Wan, Y., Liu, J.,Linn, R., 2002, “Dynamic Crane Deployment in Container Storage Yards”, Transport Research, Part B 36, pp. 537-555.

Ziyad, M., N., Nayfeh, A., H., Nayfeh, N., A., 2005, “Sway Reduction on Quay-side Container Cranes Using Delayed Feedback Controller: Simulation and Experiments”, Journal of Vibration and Control, Vol. 11,No. 8, pp. 1103-1122.

7. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.