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KINEMATIC AND STATIC ANALYSIS OF THE CABLE DRIVEN SPATIAL MECHANISM FOR BEDRIDDEN PATIENTS.

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Abstract.*The lack of postural correction and handling of bedridden patients leads to a number of complications to themselves and to caregiver, including falls. The movement and accommodation of these patients for regular checkups or even to the practice of hygiene activities and eating also become difficulties. Scabs and cardiovascular complications are other problems that bedridden face due to restricted mobility. The solution proposed here is the use of a spatial cable-driven robot, which can be easily handled and moved around, thus providing greater autonomy and comfort to patients with needs and significant improvements in working conditions for health professionals. Robots actuated by cables have gained importance in recent decades and because they consist in parallel structures they are considered descendants of the Stewart Platform. In order to present the robot model, the mechanism's analytical inverse kinematics has already been developed, thus obtaining the length of each cable and the attachment of each point on the mobile platform, given a certain posture and orientation. From these data it is possible to analyze the static model using the Davies method in order to evaluate the torque on the motors and tension in the cables.*

Keywords:*kinematic and static analysis, cable driven robot, assistive technology.*

1. INTRODUCTION

The problem of moving bedridden patients is directly related to the force that must be done to lift them (Zanon, Marziale, 2000; Radovanovic; Alexander, 2002) and the places where they can be touched, especially for patients with burns, elderly (because they are very fragile) and for those who are very overweight. For this reason the movement of patients is considered of great difficulty in realizing, as also that most nursing professionals who perform this function are female (Zanon, Marziale, 2000).

One proposed solution to handling such patients is the use of a robot actuated by cables, which can be easily handled and moved, fulfilling needs of patients and facilitating the work of nurses. A robot applied to this end should be able to suspend, translate and turn the patient as well as change its position.

Robots actuated by cables are considered parallel and descendants Stewart platform (1965), offering advantages compared to classical parallel robots, since they are lighter, i.e., easy shifting and that can be built using a large number of cables, which increases the load supported and in the specific case, the safety of the patient being handled.

This paper presents the development of kinematic and static models for the proposed mechanism, being a space robot actuated by cables applied to the movement of bedridden patients. The kinematic model was developed using analytical inverse kinematics, while for static model was applied to the Davies method, which is based on screw theory.

2. CABLE DRIVEN ROBOTS

Descendants of parallel Stewart platform, dating 1965, the space robots actuated by cables are also parallel structures, however, flexible cables take the place of the rigid legs. Their construction are similar to those of a Stewart platform, in fact, as shown in Fig. 1, a space robot is actuated by cables formed by a mobile platform where the end effector is positioned, a base or fixed platform, whose purpose is to sustain the load providing the necessary rigidity to the robot, the cables which enable the realization of motion, and the motors or actuators that drive the movement of the cables and are connected to the fixed base.

Although this type of robot has characteristics similar to the classical parallel robots, there are some important differences regarding to the workspace, speed and acceleration of the end effector, among others (Bruckmann*et al.* 2008). The flexibility of the cables can cause major changes in length of the kinematic chain, enabling workspace´s geometric limitations of classic robots to be overcame. The workspace can also be changed by increasing the number of cables, a fact that also increases the load capacity and safety of what is transported. Thus, one can have more cables degrees of freedom of the end effector. The cables are modeled as rigid, i.e., there are forces acting traction only.

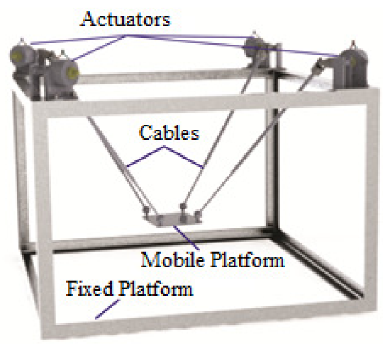

Figure 1: Parallel robotic structure actuated by wires.

Moreover, the cables can be wound by the drums in a very fast manner, while the mass robot motion is very small, which allows the robot to reach very high speeds and acceleration at the end effector.

2.1 CLASSIFICATION

The precursors of the classification of robots actuated by cables, Ming & Higuchi, between them, in 1994 in two classes: the Completely Restrained Parallel Manipulator, CPMR, and the Incompletely Restrained Parallel Manipulator, IRPM. Ten years later Verhoeven divided the class into two of the CPMR, adding the category of Redundantly Restrained Parallel Manipulator, RRPM . This classification is made according to difference between cable number and the number n of degrees of freedom of the robot.

The CPMR (Completely Restrained Parallel Manipulator), which has the platform position determined by the kinematic constraint defined by the tension of the cables, and the number of cables is given by $m = n + 1$. The IRPM (Incompletely Restrained Parallel Manipulator), where besides the kinematic constraint defined by the cable, a dynamic equation is necessary to position the platform and the number of wires is less than or equal to the number of degrees of freedom, i.e., $m \leq n$. Finally, the RRPM (Redundantly Restrained Parallel Manipulator), in which the platform's position, in this case, is completely determined by the number of wires, having $m > n + 1$ and thus more than one redundant cable.

Verhoeven, 2004, also classified robots actuated by cables according to the number of controllable degrees of freedom, and the type of end effector movement as displayed in Tab. 1. This classification is also shown in Fig. 2.

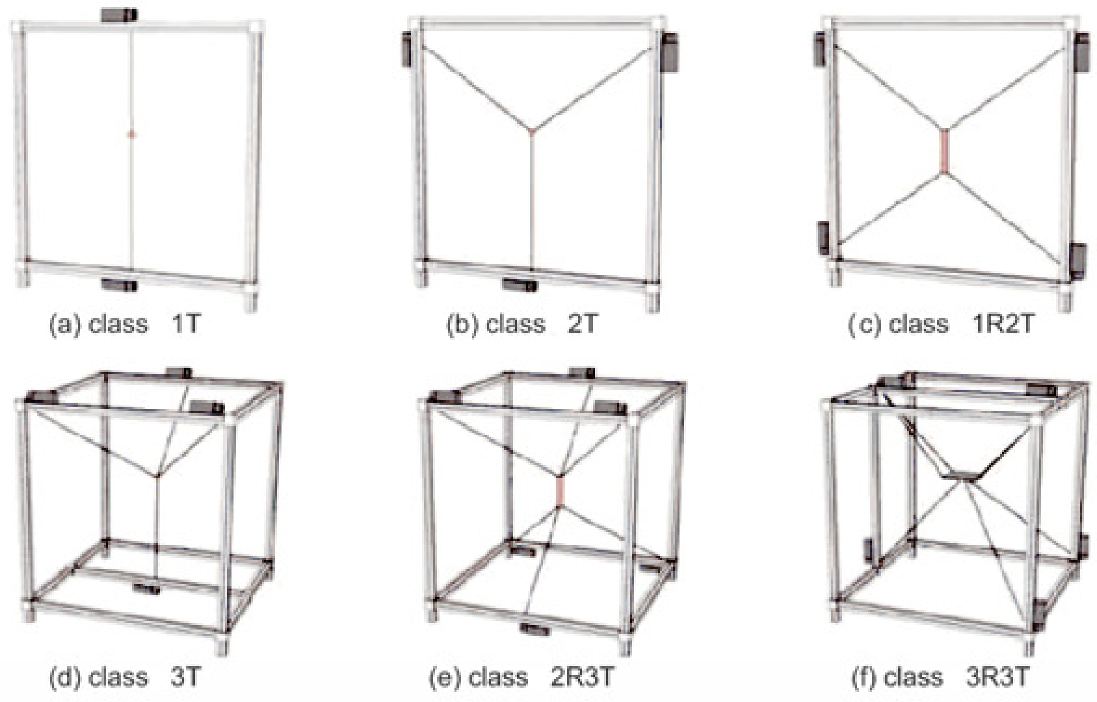

Figure 2: Classification according to the type of motion of the platform by Verhoeven, 2004.

Table 1: Classification with respect to controllable degrees of freedom according to Verhoeven (2004).

Class	DoFs	Type of Motion	Class	DoFs	Type of Motion
1T	1	Linear motionofbody.	**3T**	4	Spatialmotionof point.
2T	2	Planar motionof point.	**2R3T**	5	Spatialmotionofbeam.
1R2T	3	Planar motionofbody.	**3R3T**	6	Spatial motion of a body.

The workspace of a robot actuated by cables is limited just in terms of minimum and maximum forces applied to the cables and is an important factor for the correct functioning. However, they may also be considered in the workspace study the rigidity of the base and the collision between the cables.

In Verhoeven studies, one can find the workspace definition proposed by him, also in 2004. As shown in Fig. 3, the cable length can be calculated using the vectors $l_1,\dots,l_\mu$ once such cables are always taut. Coordinate systems presented as O_{p} and O_B are respectively the location reference system of the mobile platform and the inertial reference system fixed base. The vectors $p_1,\dots,p_\mu$ are used to connect the platform reference system to cable anchor points on the platform. The vectors $b_1,\dots,b_\mu$ connecting the inertial reference system based on the points where the cables enter into the workspace. The tensions on the cables are represented by vectors $f_1,\dots,f_\mu$ while f_p e τ_p and represent the result of all external forces applied to the platform, such as the force of gravity. Although the figure has the r vector, that connects the fixed reference base and the mobile platform.

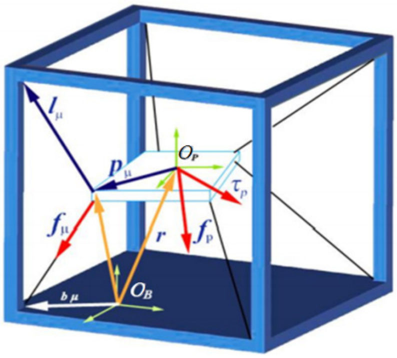

Figure 3: Workspace defined by Verhoeven, 2004.

The model studied in this work is reported as IRPM, when it comes to the difference between the number of cords and the number of degrees of freedom. Already, according to its movement, it is classified as 2R3T, has decided Verhoeven.

2.2 WORKSAPCE

Workspace is the set of possible positions to be reached by the end actuator, which in this case is the mobile platform. The workspacestudy of a cable actuated robot is still an ongoing problem in the area, however it is essential for practical applications (Bruckmann et al. 2008). As much as he is considered limited compared to serial robots (Travi, 2009), it is not so limited as the classic parallel robot in rigid structure. In fact, it can change the length of the powertrain through the winding drum of cables and in many situations the robot can also overcome obstacles (Bruckmann et al. 2008).

In any case, the workspace of robot actuated by cables haveas the main limiting factor is the capacity of motors (Bruckmann et al. 2008). In addition, an important feature of a robot of this type is that to work correctly, the cables must always be stressed. This characteristic imposestension restrictions, that is, should be taken as minimum tension allowed one which maintains the cablestractioned, and maximum tension as the one that is compatible with the engine power and with the technical specifications of the cables. Also other criteria, such as the stiffness of the cable or collision between them can be considered.

Thus a posture of the carriage belongs to the workspace if the tension distributed in the cables is between a minimum tension $\underline{\tau} \in \mathbb{R}^m$and a maximum voltage, $\overline{\tau} \in \mathbb{R}^m$, where m is the number of the robot's cables.

3. KINEMATIC AND STATICS ANALYSIS

The mechanisms modeling is composed of the static and kinematic analysis, allowing to determine in one the joint effort, or wrenches and another position and velocity related to movements of joints which are represented by twists.

The kinematic analysis comprises both the study of the position (kinematic position) as the speed (kinematic differential) mechanisms. In the forward kinematics position, the linear or angular position of active joints is known and the goal is to obtain the position of a link or a specific point of the mechanism. In serial robots, this point generally corresponds to the effector. In parallel robots, this point is also called effector and generally corresponds to the center of the mobile robot platform. In the direct differential kinematics, the linear or angular velocity the active joints is known and the goal is to get the speed of a link or of a specific point of the mechanism. In inverse kinematics, the position (or speed) of a specific point of the mechanism is known and the goal is to find the position (or speed) of the actuated joints. It is common to systematize the forward kinematics through Denavit-Hartemberg method (Simas, 2008). The kinematic model can also be made by the method of successive screws, using Davies' method or using geometric and algebraic intuition, which method is called analytical and commonly used to model the inverse kinematics. Another method used for the inverse kinematics is based on the integration of velocities of the joints, which are calculated by the inverse matrix of the Jacobian. This methodology is known as inverse kinematics differential.However, for parallel manipulators, the resolution of the kinematic model consists only in of determining the cable length and its relation to the platform posture (Travi, 2009). In this case, considering that the cables are always stressed, you can represent them by vectors and thus knowing the dimensions of the platforms and imposing your posture (position and orientation) can easily determine the length of the cables through analytical approach.

In static analysis engines, the goal is to determine the existing requests in the joints, and when there is contact with the environment, existing efforts in the interface. On first analysis it does not cover the study of internal efforts traction, compression, torsion, tension or shear in the existing links, but known efforts in the joints, existing internal efforts in the links can be determined and used in dimensional system design (Weihmann, 2011). The traditional approach to solving the static serial or parallel arrangements is the use of the equilibrium diagram of the cart body. The Davies method, which involves knowledge of graphs, Kirchoff's laws and screw theory, can also be used to resolve the static. It is a tool for the static equations of a robot in a matrix form (Weihmann et al., 2011).

4. KINEMATIC AND STATIC PROPOSED MODELS

Since the mechanism proposed here is actuated by cables, and therefore, parallel, direct kinematic analysis becomes complex and can be obtained up to 40 different solutions (Travi, 2009). So it will be used an analytical approach based on knowledge of vectors which is precise and specific for each manipulator. This methodology was based on the proposal by Bruckmann, in 2008.

The Figure 4a shows the kinematic structure of the mechanism proposed. It can be seen that each cable is represented by a prismatic joint, which is connected to the fixed base by a universal joint, and the mobile platform via a spherical joint.The vector representation is used to solve the inverse kinematics of the mechanism is fully diagrammed in Fig. 4b.

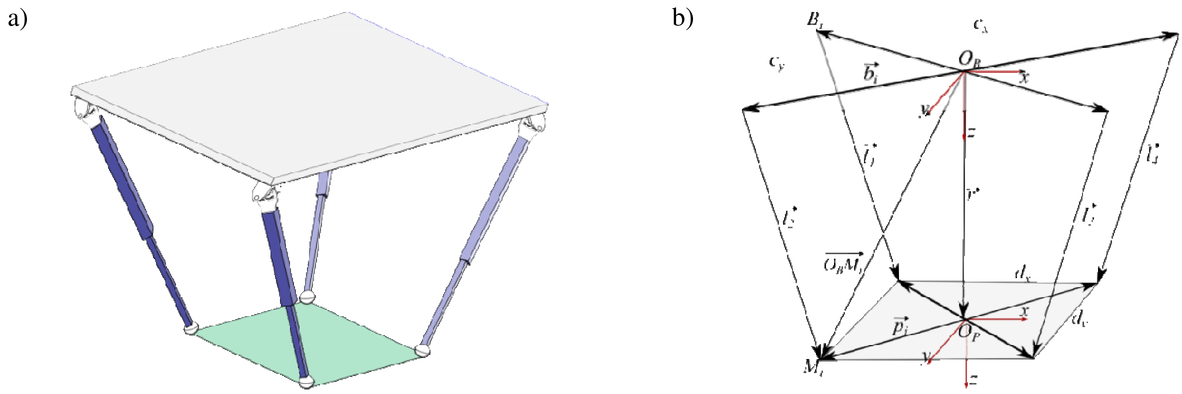

Figure 4: Mechanism representation:a) Kinematic structure; b). Vector representation.

Each cable is represented by a vector $\vec{l_i}$, which can be written as

$$\vec{l_i} = \vec{p_i}^B - \vec{b_i}. \tag{1}$$

The vectors $\vec{p_i}$, connecting the reference points for anchoring the cable to the mobile platform, are written with respect to reference coordinates of the own O_P the center of the mobile platform, while all other vectors are written in the reference coordinate O_B the fixed base center.

In this case, you must write the vectors $\vec{p_i}$ through O_B coordinates. It is easy to see that

$$\vec{p_i}^B = \overrightarrow{O_B M_i}, \tag{2}$$

i.e.,

$$\vec{l_i} = \overrightarrow{O_B M_i} - \vec{b_i}. \tag{3}$$

Provided the angles θ_x, θ_y e θ_z of orientation of the mobile platform and the position of the center of the same in space (through $\vec{r}$ vector), you can get the length of each cable, which is given by

$$|\vec{l_i}| = |\overrightarrow{O_B M_i} - \vec{b_i}|. \tag{4}$$

It is important to note that for the calculation $\overrightarrow{O_B M_i}$uses the rotation matrix *Roll-Pitch-Yow*, denoted by R, since data the angles θ_x, θ_y e $\theta_z$which guiding the mobile platform, each vector $\vec{p_i}$must also undergo the same rotation. Thus, it has

$$\overrightarrow{O_B M_i} = R\vec{p_i} + \vec{r}, \tag{5}$$

wherein

$$R = \begin{bmatrix} cos\theta_y cos\theta_z & cos\theta_z sin\theta_x sin\theta_y - cos\theta_x sin\theta_z & sin\theta_x sin\theta_z + cos\theta_x cos\theta_z sin\theta_y \\ cos\theta_y sin\theta_z & cos\theta_x cos\theta_z + sin\theta_x sin\theta_y sin\theta_z & cos\theta_x sin\theta_y sin\theta_z - cos\theta_z sin\theta_x \\ -sin\theta_y & cos\theta_y sin\theta_x & cos\theta_x cos\theta_y \end{bmatrix}. \tag{6}$$

So,

$$|\vec{l_i}| = |R\vec{p_i} + \vec{r} - \vec{b_i}|. \tag{7}$$

Once the vectors representing the cables are determined, it is possible to generate accurately the coordinates of each fixing point of the cable to the mobile platform, and use such information to resolve the static model of the mechanism, since it is not possible to obtain algebraic equations because their characters exceed the number of characters allowed by Matlab® program, in which the simulations were performed.

The static model was solved using Davies' method, the following nine steps outlined by Cazangi (2008). In static analysis of parallel robots, the main objective is to determine the traction forces in engines winding and unwinding the cables, according to the force applied to the mobile platform, for each position of the same. Such an approach appears in many publications and further explanation can be found in the literature (Davies, 2006; Weihmann et al, 2011; Mejia et al, 2015).

Using graph theory (Davies, 2006) determines the degree of restriction of gross handler that is given by

$$C = \sum_{i=1}^{e} c_{p_i} + \sum_{j=1}^{e_a} c_{a_j} = 130, \tag{8}$$

where$e$ is the total number of direct couplings, $e_a$the number of active engagements, c_p is the number of unit restrictions on direct couplings and $c_a$is the number of unit restrictions generated by actuators in actuated joints. Moreover, the degree of net restriction is $C_N = 4$ representing the number of primary variables, namely the number of the free variables required to set the system statically (Weihmann, 2011). Each variable is a static system is a wrench that acts on the mobile platform of the mechanism and the primary variables considered were the strengths and the known moments from the mobile platform interaction with the environment. Thus, the equation that solves the static is

$$\left[\hat{A}_{N_S} \vdots \hat{A}_{N_P}\right]_{126\times130} \begin{bmatrix} \Psi_S \\ \dots \\ \Psi_P \end{bmatrix}_{130\times1} = \vec{0}, \tag{9}$$

i.e.,

$$[\Psi_S]_{126\times1} = \left[-\hat{A}_{N_S}^{-1}\right]_{126\times126} \left[\hat{A}_{N_P}\right]_{126\times4} [\Psi_P]_{4\times1}, \tag{10}$$

where Ψ_S is the vector of magnitudes of the secondary variables, $\hat{A}_{N_S}$is the matrix of unit shares of the secondary variables, $\hat{A}_{N_P}$ is the unit actionsmatrix of the primary variables and Ψ_P variable is the vector of magnitudes of the variables primaries.

What we want to know are the tractions forces on the actuators of each leg of the robot, which are represented by the force of prismatic joint on its leg. So, finally,

$$\begin{bmatrix} F_{1_{Pz}} \\ F_{2_{Pz}} \\ F_{3_{Pz}} \\ F_{4_{Pz}} \end{bmatrix}_{126\times1} = \left[-\widehat{A}_{N_S}^{-1}\right]_{126\times126} \left[\widehat{A}_{N_P}\right]_{126\times4} \begin{bmatrix} F_{g_x} \\ F_{g_y} \\ F_{g_z} \\ M_{g_z} \end{bmatrix}. \tag{11}$$

It is important to note that the matrix $\widehat{A}_{N_S}$was assembled from wrenches determined by Screw Theory, and the information on position and orientation of each wrench were obtained by previously presented kinematic analysis.

5. RESULTS

Through an algorithm developed for the Matlab Matrix Laboratory, can analyze certain positions of the mobile platform by verifying the results obtained in the kinematic analysis and static analysis. For the simulations, it is considered, without loss of generality, a patient 100kg, which generates a weight force of 1000N applied to the center of the mobile platform Likewise, the dimensions of the platform are considered fixed for 1,5 by2 meters and the mobile platform are 0.9 by 1.8 meters. The distance set between the centers of reference is 1 meter.

The Figure 6a shows the mobile platform considered in the initial position. So from this position varies up θ_x angle between 0° and 90° to evaluate the stresses in the cables. This change must take place at times when the patient is lying down and need to sit down. The objective is to analyze if all the positions in which the moving platform passes in this situation belong to the workspace. An intermediate position of the movement is shown in Figure 6b and the graphics are generated in Figure 7a and Figure 7b.

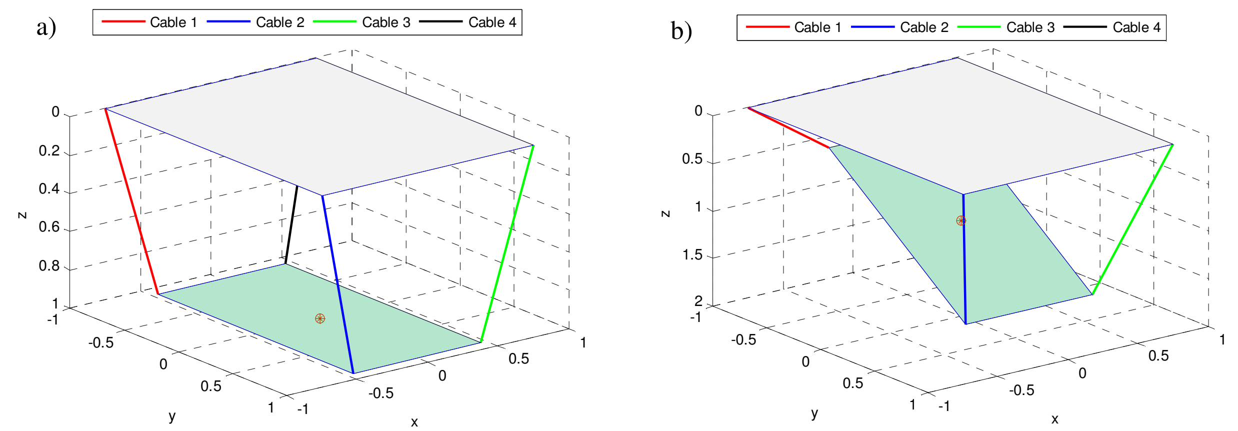

Figure 6: Postures of the mobile platform: a) Initial position of the mobile platform; b) Intermediate position with $\theta_x = 45°$.

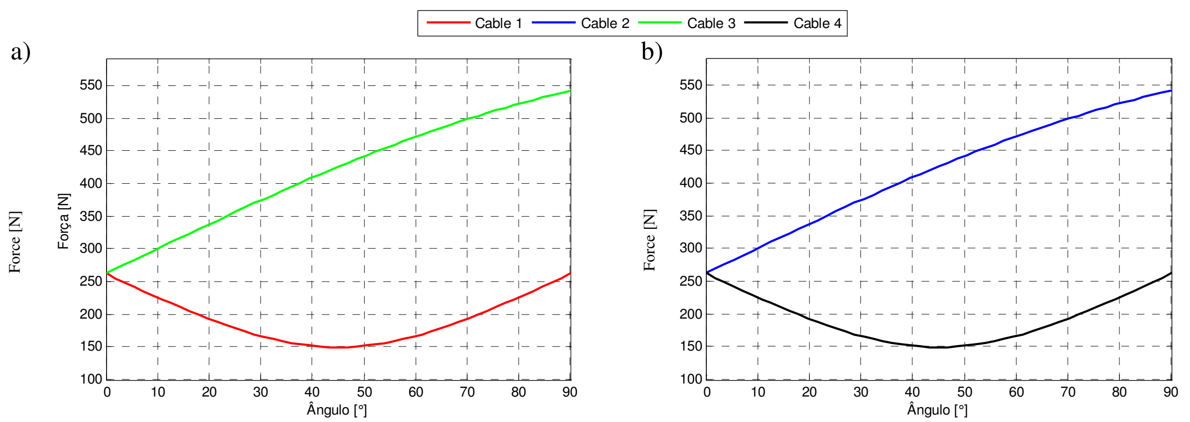

Figure 7: Variation Angle [°] sion on the cables as a function of angle θ_x: a) Cable: Angle [°] b) Cables 2 and 4.

Similarly, remaining fixed $\theta_x = 0$ and only vary the angle θ_y the same initial conditions. Such movement of the mobile platform must be made in situations that require change the orientation of the patient in the supine position, but keeping it flat. It is also possible to vary the distance $|\vec{r}|$ between the platform's referencial to evaluate tensions, as seen in Figure 8.

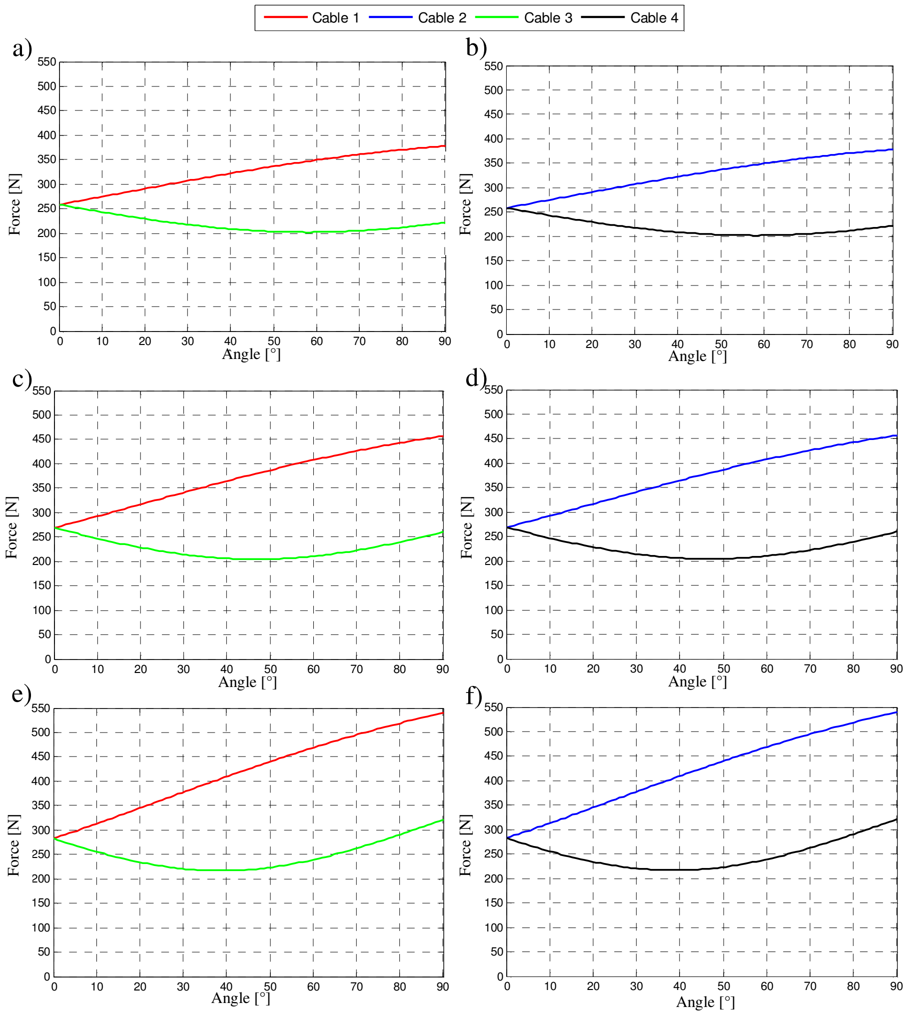

Figure 8: Tension in the cable in function of the angle θ_y: a)Cables 1 and 3 to $|\vec{r}| = 1{,}2$ m; b) Cables 2 and 4 to $|\vec{r}| = 1{,}2$ m; c) Cables1 and 3 to $|\vec{r}| = 0{,}8$ m; d) Cables 2 and 4 to $|\vec{r}| = 0{,}8$ m; e) Cables 1 and 3 to $|\vec{r}| = 0{,}6$ m; f) Cables 2 and 4 to $|\vec{r}| = 0{,}6$ m.

An analysis like this, it is necessary to vary the orientation angles of θ_x and θ_y and evaluate all cases. Thus, setting, for example, θ_x angle = 30° and varying θ_y, we obtain the graph of Figure 9a. Thus, a posture example that does not belong to the workspace is shown in Figure 9b.

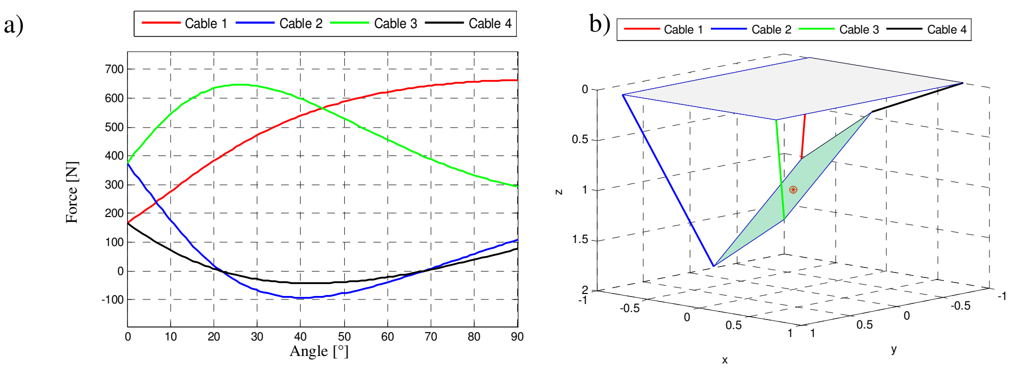

Figure 9: a) Tension in the cable in function of the angle θ_y, with $\theta_x = 30°$; b) Posture determined by $\theta_x = 30°$and $\theta_y = 40°$.

6. CONCLUSIONS

It is easy to see that in Figure 7 the cables 1 and 4 have the same tensions, as well as tensions in the cables 2 and 3. This situation stems from the fact that the line through the cable attachment points 1 and 4 to the mobile platform are parallel to the rotational axis, as the line passing through the connection points of the cables 2 and 3 to the mobile platform.

In Figure 8, it is noted that all the curves are smooth, and as the distance between core centers decreases, the traction forces on the cables are greater, considering the same angles of rotation. In addition to the angle of variations performed, it may be interesting to vary the load carried by the mobile platform, which certainly generates tensions proportional to it in the cables. Simulations and analysis of this type can also be used to determine both the working space and to define characteristics such as engine output to be used, or even the technical specifications of the cables.

A robot actuated by cables has structural advantages over rigid structure parallel robots, including security of which is transported, the smoothness of movements and ease the transfer of the same (Bruckmann*et al*, 2008). These features are very important to a mechanism which carries and move bedridden patients in hospitals.

7. ACKNOWLEDGEMENTS

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9. RESPONSIBILITY NOTICE

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