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# ALGEBRAIC TENSION CONDITIONS IN CABLE-DRIVEN MECHANISMS

**Thaís Muraro**
Federal University of Santa Catarina
Department of Mechanical Engineering
Florianópolis, Brazil
muraro.thais@gmail.com

**Daniel Martins**
Federal University of Santa Catarina
Department of Mechanical Engineering
Florianópolis, Brazil
daniel.martins@ufsc.br

**Leonardo Koller Sacht**
Federal University of Santa Catarina
Department of Mathematics
Florianópolis, Brazil
leonardo.sacht@ufsc.br

***Abstract.*** *The cable-driven parallel mechanisms have an important feature regarding the tension forces in the cables, because the cables can only pull and can not push the end effector, because of this cable tensions must always be positive. Thus, the tensions on cables should be evaluated and, then, restricted. This is done by using the Davies method for the statics and by solving the linear equations system through the null space of the matrix.*

***Keywords:*** *Cable-driven, Tension conditions, Davies method, Linear equations, Null space*

## 1. INTRODUCTION

The cable-driven mechanisms have economical and structural advantages (Barrete and Gosselin, 2005; Bosscher et al, 2007; Merlet, 2004), which made them be more studied and used since the 1980's. Moreover, they can be separated in two classes: the cable-suspended parallel mechanisms (CSPMs) and the fully-constrained mechanisms (FCMs) (Gosselin, 2014). This separation was motivated by the distribution of the tensions in the cables.

The development of this paper is motivated by problems about the platform position control, more specifically the fact of that the cables can not be loose (Pusey et al, 2004; Bosscher, Riechel and Ebert-Uphoff, 2006; Muraro, 2015; Muraro, Martins and Sacht, 2017), in other words, they must be always tensioned. For this, we used a way to evaluate the tensions in the cables and also to generate graphics that show a vector representation of the cable forces. This approach shown by Muraro, Martins and Sacht (2015) is an adaptation of the Davies method (Davies, 2006) to obtain a system of linear equations in which the variables are all the mechanical system forces and its moments. And once the system is determined, it will be solved by the null space of the matrix.

Then, the main contribution of this paper is to present tension maps for a cable in a four-bar mechanism using a vectorial way previously purposed in (Muraro, Martins and Sacht, 2017). It is done in order to evaluate the tensions in the cable and then to avoid the sagged cable.

## 2. CABLE-DRIVEN PARALLEL MECHANISMS

Like the parallel mechanisms of rigid structure, the cable-driven mechanisms have also been the object of much interest and study in the last decades. They are derived from Stewart Platform (1965) because, in 1985, Landsberger and Sheridan proposed replacing the rigid linear actuators of the Stewart Platform by cables. In this sense, the cable-driven robots are also parallel structures, in which, cables take the place of the rigid legs. However, they have some advantages compared to the classic parallel robots (Bruckmann et al, 2008). For example, the cable-driven parallel mechanisms are lighter then mechanisms with rigid structure, that is to say, they are easily transportable, or also a great number of cables can be had, which increases the supported load. Besides that, the workspace of a cable-driven is larger than a similar rigid structure.

A cable-driven parallel mechanism (CDPM) has constructive features similar to those of the Stewart platform. In fact, a cable-driven mechanism is constituted by a mobile platform, where the end-effector is positioned, a base, or fixed platform, whose purpose is to sustain the load moved and give the necessary rigidity to the robot, the cables, that allow the realization of the movement, and the engine or actuators that drive the cables movement.

This type of mechanism type has become more studied since the last three decades, mainly due to its large workspace and its structural simplicity (Bosscher et al, 2008), together with the reduced cost of production (Barrete and Gosselin, 2005). Its application is more focused on situations where rigid and heavy manipulators are not the best choice. Although it has similar characteristics to the classic parallel robots, there are certain important differences (Bruckmann et al, 2008). Some of them can be characterized as advantages, such as the fact that the cables can be rolled up by the drums very quickly, while the moving mass of the robot is very small. This allows the robot to achieve acceleration and very high speeds in the end-effector (Bruckmann et al, 2008; Muraro, 2015). Also because the mass of the moving parts is very small, these robots become more energy efficient and thus suitable for the movement of heavier loads, acting as cranes. In addition, by increasing the number of cables, the workspace can be modified, the load capacity can increase and even improve the safety of what is being transported. Thus, a greater number of cables is allowed than the number of degrees of freedom of the end-effector and furthermore, if the position of these cables is favorable, the end-effector can also still overcome some obstacles.

Although a CDPM has a number of advantages over the classic rigid and conventional robots, it also presents some problems in its use. The main of these problems was precisely inherited from the rigid parallel robots, witch have restricted workspace (Muraro, 2015). It can be said that this disadvantage is aggravated, because the cables can only be pulled (Gosselin, 2014; Muraro, 2015) and not push the mobile platform. However, it is possible to change the length of the kinematic chain through the cable winding drum, which overcomes the geometric limitation of the classic parallel robot workspace (Bruckmann et al, 2008), or even reposition the cable attachment points to the rigid structure, making it reconfigurable (Merlet, 2004).

The motion control of this type of robot is also nontrivial, since there may be redundancy of traction, that is, there may be more cables than controllable degrees of freedom, and thus the distribution of cable tension must be evaluated and how its elasticity influences movement (Bruckmann et al, 2008). The kinematics of these manipulators is also complex and to control them it is very important to find a strategy where real-time computation is efficient (Gosselin, 2014).

## 3. THE DAVIES METHOD

The Davies method is mainly used to solve the kinematic and static analysis in mechanisms, but new applications are been developed (Carboni, 2015). This method is based on screw theory, graph theory, and Kirchhoff's laws. It generates results in the matrix form, requiring, in this way, a previous knowledge about the matrix algebra to apply it. Regarding the use of Kirchhof's laws, the method is based on the Circuits Law for kinematics, while for performing static analysis it is based on the Nodes Law (Davies, 2006).

The objective in the static analysis of mechanisms is to determine the existing requests in the joints and, when there is contact with the environment, the efforts existing in the end-effector. To cable-driven mechanisms, the main objective to the same analysis is to evaluate the distribution of tension in the cables according to the load carried, and with the pose of the end effector or the mobile platform.

Although the main objective of the static analysis of cable driven mechanisms, for example, is the determination of the tensions in the cables, the Davies method allows to determine at once all the requests existing in all the joints of the mechanism, thus configuring an advantage of this method. While tension in the cables can be used to analyze the workspace, the efforts of the other joints are necessary for the complete design of the mechanism. In addition, the solution by the Davies method is obtained from the solution of systems of linear equations, which provides the visualization of the results through a vector approach.

The Davies method consists, according to Cazangi (2008) of nine steps. However, we can summarize the nine steps of this method into four general steps (Muraro, Martins and Sacht, 2017). The first one is about the graphic and graph representations of the mechanism. That is, the schematic and the topological representations of the mechanism are made, with representation and identification of the joints and the links and also with the positioning of a coordinate system. Then the representation through an oriented graph is made. From the representations, the second step includes all the characteristics of the system, which are determined, such as the number of actions C, and the parameters of the wrenches: orientation $\vec{S}$, position $\overrightarrow{S_0}$ and the pitch $h$. Also the features related to graphs are made, such as the number of chords $I$, and of cuts $k$ through the equations

$$I = e - \nu + 1, \quad (1)$$

and

$$k = \nu - 1, \tag{2}$$

where $\nu$ is the number of vertices in the action graph and $e$ is the number of mechanism couplings.

The third step consists in the matrix representation of the system. That is, the wrenches – in this case $\$_{aFx}$, $\$_{aFy}$, $\$_{aMz}$, $\$_{bFx}$, $\$_{bFy}$, $\$_{cFx}$, $\$_{cFy}$, $\$_{dFx}$, $\$_{dFy}$, $\$_{dMz}$, $\$_{pFx}$, $\$_{pFy}$ and $\$_{pMz}$– are described. Besides that, the Cut-set Matrix $[Q_A]_{k\times C}$, which relates the actions to the cuts, is constructed. From these mathematical entities the Actions Matrix $[A_D]_{\lambda\times C}$ and also the Network Unitary Actions Matrix $[\hat{A}_N]_{\lambda.k\times C}$ are determined. Note that λ is the order of the system i.e. in the planar case $\lambda = 3$ and in the spatial case $\lambda = 6$. And finally, in the last step, the laws of Kirchhoff are applied, generating the homogeneous system

$$\hat{A}_N \vec{\Psi} = \vec{0}, \tag{3}$$

where $\vec{\Psi}$ is the wrenches magnitudes vector.

The system must be solved by separating the variables between the primary ones (generally known and that determine the system completely) and the secondary ones (that one wishes to know). Thus, the system becomes non-homogeneous and the matrix of coefficients becomes square. In this way, only solution can be determined.

More information about the Davies method (details and examples) can be found in Cazangi (2008), Davies (2000) and Davies (2006).

## 4. SCREW THEORY

The Screw Theory was formulated by Mozzi in 1763 and systematized by Ball in 1876. It is an important tool used to represent the instantaneous state of motion (kinematics) and a motion of a rigid body in the space (statics) (Cazangi, 2008; Frantz, 2015; Muraro, 2015). A Screw, denoted by \$, could be considered a geometric entity from the mid-nineteenth century, when Julius Plücker proposed coordinates for a line (axis). Thus, a screw has six coordinates of its own: the coordinates of Plücker (Weihmann, Marins and Coelho, 2011; Muraro, 2015; Frantz, 2015) and it is completely determined by a directed straight, called the screw axis, and by a step denoted by $h$. It is said that a screw is normalized when its axis is represented by a unitary vector. Then it is denoted by $\hat{\$}$.

A screw can represent both the state of motions and the state of actions of a rigid body, being called twist and wrench respectively. In twist, used in kinematic analysis of mechanisms, the first three coordinates represent the angular velocity of the body and the other three coordinates represent its linear velocity. The wrench is used in the static analysis of mechanisms and the first three components indicate the moments and the last three, the resulting force (Muraro, 2015; Frantz, 2015; Cazangi, 2008; Ball, 1876).

## 5. METODOLOGY

To evaluate the tension in the cables, we solved test problems that consist in simple problems, whose illustrate others, more complicated. A first problem about a truss was solved in a previous paper, when the vectorial way was proposed. In this paper, we use that vectorial way to solve another problem about the tension conditions in a cable, witch is part of the four-bar mechanism. In another words, it will be introduced the four-bar mechanism, in that a rigid link was replaced by a cable. This way it is possible to evaluate the tensions and to determine the feasible intervals for them. The feasible intervals are sets that contain only positive forces.

In order to survey the problem of the sagged-cables, six steps were proposed (Muraro, Martins and Sacht, 2017). The first one consists in the schematic representation of the mechanism, replacing, for this, the cable by two rigid links connected to the prismatic joint. These links will be connected to the system through the revolution joints, because it is a planar system. Secondly we use the Davies method (Davies, 2006) for statics until to obtain the homogeneous system of linear equations, that is, until to the fifth step described by Cazangi in 2008, in which is determined the network unit action matrix. This method is based in graph theory and screw theory and also in the Kirchhoff's laws (Davies, 2006; Cazangi, 2008). It is through the application of the node's law that the homogeneous system of linear equation is generated. Subsequently, this homogeneous system is solved through the null space of matrix. Then, the next step is to find convenient relations between the system variables. In the fifth step, graphical representations are made, plotting, in this case, the components, $F_x$ and $F_y$, of the force in the cable. Finally, the last step consists of properly restraining forces to avoid sagged-cables.

### 5.1 Case study

The problem to be shown here is a four-bar mechanism connected by rotating joints $a$, $b$, $c$ and $d$, with motions in the $xy$ plane. In this specific case, one of the bars - between the joints $b$ and $c$ – is replaced by an inextensible cable, as shown in the Figure 1 - a) and in addition, joints $a$ and $d$ are considered to be actuated. So, the cable is modeled as a prismatic joint for the application of the Davies method for static analysis. Then, the first step proposed in the methodology is shown in the Fig. 10: while the Fig. 1 – a) is only the visual representation of the studied mechanism, the Fig. 1 – b) shows the schematic representation of the mechanism with the positioning in the coordinate system, as well the denomination of each link and joint.

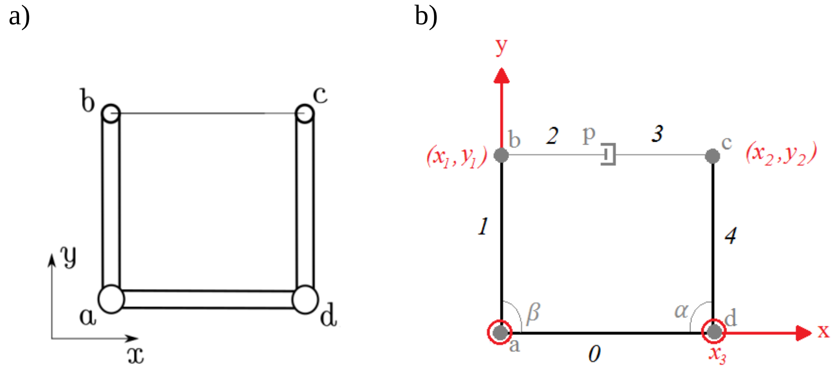


Figure 1 – Four-bar mechanism: a) Mechanism representation b) Schematic representation of the mechanism with the positioning in the coordinate system and denomination of the links and joints.

Now, in the second step, we need to describe the mechanism as a graph, in order to use the Davies method in the solution of this case. So, the couplings graph can be seen in the Fig. 2 - a) and the actions graph in the Fig. 2 - b).

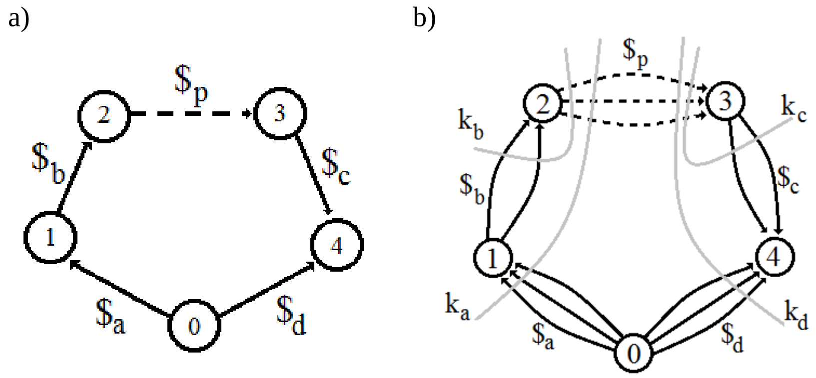


Figure 2 – Graph representations: a) Couplings graph. b) Actions graph.

For the graph representation it was necessary to determine the chords number, $l = 1$, and the cuts number, $k = 4$, which were calculated through equations 1 and 2 respectively. These numbers are also necessary to determine the cut-set matrix, which is

$$Q_A = \begin{array}{c} \begin{array}{ccccccccccccc} F_{p_x} & F_{p_y} & M_{p_z} & F_{a_x} & F_{a_y} & M_{a_z} & F_{b_x} & F_{b_y} & F_{c_x} & F_{c_y} & F_{d_x} & F_{d_y} & M_{d_z} \end{array} \\ \left[\begin{array}{ccc:ccc:cc:cc:ccc} -1 & -1 & -1 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ -1 & -1 & -1 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 & 0 & 0 \\ -1 & -1 & -1 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 \\ 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 \end{array}\right] \end{array} . \tag{4}$$

And the network unit actions matrix, defined from the cut-set matrix and the construction of wrenches is given by

$$\hat{A}_N = \left[\begin{array}{ccc|ccc|cc|cc|ccc}
y_1 & -x_1 & -1 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
-1 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & -1 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
\hline
y_1 & -x_1 & -1 & 0 & 0 & 0 & -y_1 & x_1 & 0 & 0 & 0 & 0 & 0 \\
-1 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & -1 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\
\hline
y_1 & -x_1 & -1 & 0 & 0 & 0 & 0 & 0 & -y_2 & x_2 & 0 & 0 & 0 \\
-1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\
0 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\
\hline
-y_1 & x_1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & x_3 & 1 \\
1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\
0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0
\end{array}\right] . \tag{5}$$

Now, applying the Kirchhoff's Nods Law, the homogeneous system of equation 3 can be solved, being the network unit actions matrix seen in the equation 5 and the magnitudes vector given by

$$\vec{\Psi}^t = \left[\begin{array}{ccc|ccc|cc|cc|ccc} F_{p_x} & F_{p_y} & M_{p_z} & F_{a_x} & F_{a_y} & M_{a_z} & F_{b_x} & F_{b_y} & F_{c_x} & F_{c_y} & F_{d_x} & F_{d_y} & M_{d_z} \end{array}\right] \tag{6}$$

which is the vector with the 13 variables of the linear system.

In the third step, by using the "*nullspace*" function in the computational program Maxima®, the linear system solution was obtained. The solution, $N$, is a vectorial space generated by only one vector with 13 components, as can be seen

$$N = span\left\{\begin{pmatrix} x_1 - x_2 \\ y_1 - y_2 \\ 0 \\ x_1 - x_2 \\ y_1 - y_2 \\ x_2 y_1 - x_1 y_2 \\ x_1 - x_2 \\ y_1 - y_2 \\ x_1 - x_2 \\ y_1 - y_2 \\ x_2 - x_1 \\ y_2 - y_1 \\ (x_1 - x_3) y_2 + (x_3 - x_2) y_1 \end{pmatrix}\right\}, \tag{7}$$

Then, using the equivalences

$$x_1 = |ab| \cos \beta, \tag{8}$$

$$y_1 = |ab| \, sen \, \beta, \tag{9}$$

$$x_2 = x_3 - |cd| \cos \alpha, \tag{10}$$

and

$$y_2 = |cd| \, sen \, \alpha, \tag{11}$$

where $x_3$ is a constant, we obtain algebraic expressions for each variable of the linear homogeneous system. In this way, the solution vectors for the homogeneous system are written as

$$\begin{pmatrix} F_{p_x} \\ F_{p_y} \\ M_{p_z} \\ F_{a_x} \\ F_{a_y} \\ M_{a_z} \\ F_{b_x} \\ F_{b_y} \\ F_{c_x} \\ F_{c_y} \\ F_{d_x} \\ F_{d_y} \\ M_{d_z} \end{pmatrix} = \delta \begin{pmatrix} |ab|\, cos\, \beta - x_3 + |cd|\, cos\, \alpha \\ |ab|\, sen\, \beta - |cd|\, sen\, \alpha \\ 0 \\ |ab|\, cos\, \beta - x_3 + |cd|\, cos\, \alpha \\ |ab|\, sen\, \beta - |cd|\, sen\, \alpha \\ x_3|ab|\, sen\, \beta - |ab||cd|\, sen(\alpha + \beta) \\ |ab|\, cos\, \beta - x_3 + |cd|\, cos\, \alpha \\ |ab|\, sen\, \beta - |cd|\, sen\, \alpha \\ |ab|\, cos\, \beta - x_3 + |cd|\, cos\, \alpha \\ |ab|\, sen\, \beta - |cd|\, sen\, \alpha \\ x_3 - |cd|\, cos\, \alpha - |ab|\, cos\, \beta \\ |cd|\, sen\, \alpha - |ab|\, sen\, \beta \\ -x_3|cd|\, sen\, \alpha + |ab||cd|\, sen(\alpha + \beta) \end{pmatrix}, \quad (12)$$

where $\delta \in \mathbb{R}$.

Now, the solution is related to the constant $\delta$ and also to the angles $\alpha$ e $\beta$, which are given according with the geometry of the problem. Thus, by determining a value for any force or moment, with the exception of $M_{p_z}$ since it is null, the system is completely determined.

Then, the tension force $F_p$ can be evaluated in the cable. For analysis of results, it is always considered that a force smaller than zero represents the compression, while a force greater or equal to zero represents the tension in the cable. We can also perform a vector force evaluation, which will be presented in the next section, where the results are presented and discussed through graphs generated in the Matlab® program.

## 6. RESULTS AND DISCUSSION

The results obtained are algebraic expressions for the force magnitude in the cables and graphics that show the force components of the cable tension. The math sentences may be obtained through Eq. 12 and the graphics are shown in Fig. 3 to Fig. 7.

The graphs in the Fig. 3, Fig. 4, Fig. 5, Fig. 6 and Fig. 7 introduce a vectorial representation of the tensions, which is relevant for several applications, from the theoretical studies about the force capability or the workspace, to the choice of engines during the mechanical design. Besides that, the approach should evolve to solve other problems that include spatial cases, and not just planar cases.

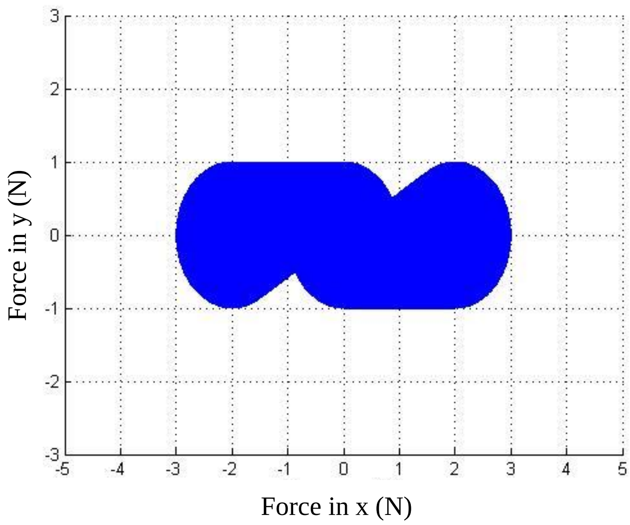


Figure 3 – Cable tension with $x_3 = 1$, $|ab| = 1$ e $|cd| = 1$.

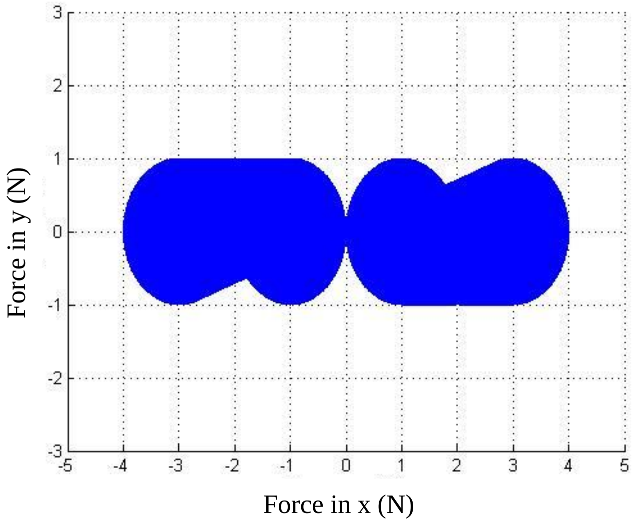


Figure 4 – Cable tension with $x_3 = 2$, $|ab| = 1$ e $|cd| = 1$.

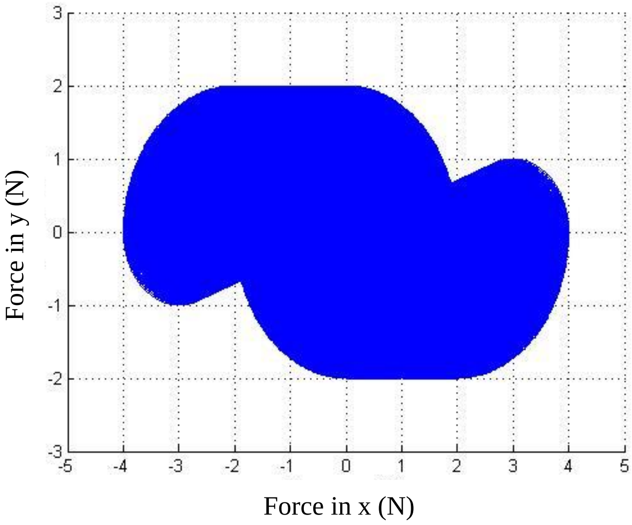


Figure 5 – Cable tension with $x_3 = 1$, $|ab| = 2$ e $|cd| = 1$.

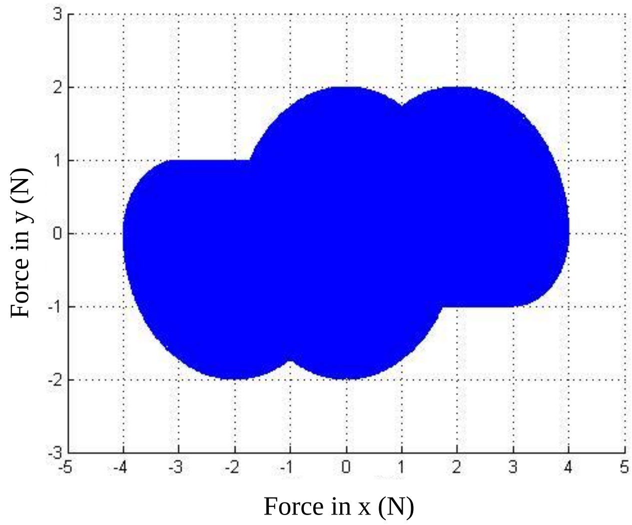


Figure 6 – Cable tension with $x_3 = 1$, $|ab| = 1$ e $|cd| = 2$.

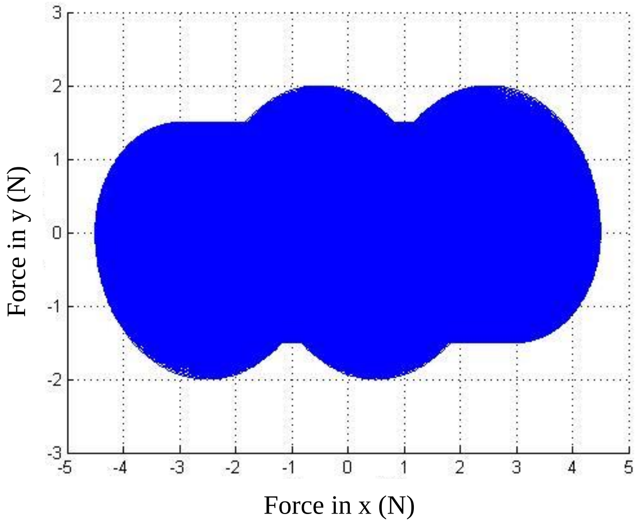


Figure 7 – Cable tension with $x_3 = 1$, $|ab| = 1{,}5$ e $|cd| = 2$.

In this specific case, we obtain a null space that is generated by only one vector. The vector's components are related to two angles to be determined (see equation 12). Considering all the feasible geometries in relation to the angles, that is, considering all combinations of $0 \leq \alpha \leq 180°$ and $0 \leq \beta \leq 180°$, with intervals of one degree, and fixing the measurements of the links (in meters), the constant $\delta$ was varied between $-1 \leq \delta \leq 1$ in order to obtain the force maps shown in the figures 3 to 7.

Note that the cable considered is inextensible, which means, mechanically, that the prismatic joint can not be expanded, it can only be contracted, configuring, in the second situation, a "sagged cable". Thus, given the lengths of the rigid links and the measurements of the angles $\alpha$ and $\beta$, it is possible to determine the length of the cable.

## 7. CONCLUSIONS

In this paper it was presented a way to study and evaluate cable tensions through the Davies method and then the resolution of linear systems. This approach generates algebraic expressions and vectorial representations for the tensions in the cable. These results can be useful to studies about force capability or workspace determination. Besides that, the obtained results can facilitate the trajectory control and the engines choice or another design features. But, the most important objective for this approach is to avoid the sagged-cables in cable-driven robots and mechanisms.

Furthermore, as a future work, we will apply this methodology in other mechanisms, with more cables, and with spatial movements. The resolution of different problems is the key idea of the problem: evaluate and compare the results for several mechanisms in order to obtain the better way for study the cable tension conditions and the cable tension distribution in any cable-driven mechanism.

## 8. ACKNOWLEDGEMENTS

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