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Design of a Cable-Driven Parallel Robot with Grasping Device

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Abstract

Cable-Driven Parallel Robots (CDPRs) are composed of a base frame and a moving-platform. A set of cables actuated by winches and guided by pulleys on the base frame are attached to the moving-platform. Those cables are used to generate motions or to apply forces to the moving-platform throughout its workspace. CDPRs are being increasingly used in industry due to several advantages provided by the cables such as a large translational workspace, a high payload-to-weight ratio and high velocities and accelerations. However since the cables can only pull the moving-platform, the latter cannot go out of the robot base frame bounded by the pulleys. An example is the treatment of large structures by using a CDPR. The structure itself can be used to hold the pulleys of the CDPR and the moving-platform would therefore need to go out of the robot volume to reach it. To overcome this issue a grasping device is mounted onto the moving-platform to grab the structure. It should be noted that when the structure is grabbed, the model of the overall system changes as the motions of the moving-platform is not only controlled by cables anymore, but the contact between the grasping device and the structure should be considered. This paper deals with the conceptual design of a grasping device for CDPRs and the definition of two workspaces. The first workspace characterizes the area covered by the moving-platform when the latter is free of contact with the environment. The second workspace is the region that the gripper can follow during gripping phase. It turns out that the robot workspace increases while considering the structure grasping into the system modeling.

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1. Introduction

Because of their large workspace, Cable-Driven Parallel Robots (CDPRs) seem well suited for the maintenance of large structures such as bridges or buildings. Several workspaces have been studied in the literature, such as the *Wrench Closure Workspace* [1,2] or *Wrench Feasible Workspace* [3] for the static equilibrium of CDPR. In most cases, those workspaces are included inside the volume enclosed by the pulleys guiding the cables. Indeed the cables can only pull and not push the moving-platform, therefore limiting the pose it can reach outside of the volume of the pulleys. One technique for the moving-platform to go out from the area delimited by the pulleys is to take advantage of the dynamic behavior of the CDPR [4]. Accordingly, Barrette *et al.* defined the *Dynamic Workspace* [5] of CDPRs. However, it is not realistic from an industrial viewpoint to use this approach to make the moving-platform move along tubes outside the CDPR wrench-closure workspace.

To the best of the author's knowledge, two solutions exist to operate along large structures. The first one consists on the discrete reconfiguration of CDPRs [6,7] to cover the entire structure to treat. Gagliardini *et al.* defined a reconfiguration strategy to find a way to cover the entire structure with the smallest number of reconfigurations in [8]. However, some manual operations are still required to change the robot from one configuration to another. The second approach aims at embedding a serial manipulator onto the moving-platform to extend the workspace locally [9,10].

To avoid those drawbacks, a multi-link CDPR, namely, a CDPR with poly-articulated moving-platform, can be used. This concept was studied through the analysis of the *Force-Closure Workspace* in [11] or the *Tensionable Workspace* in [12], but there are still few applications [13]. The main one is the modeling of the human neck by Lau *et al.* who developed a generalized model of multi-link CDPR in [14,15].

This paper introduces a planar CDPR with a two-link

moving-platform, which is used as a gripper. The contact between the grasping device and the structure modifies the model of the robot, which increases the part of the structure covered by the robot. The mechanism under study and its targeted applications are described in Sec. 2. Section 3 deals with the geometrico-static modeling of the mechanism at hand in both free phase, i.e, non grasping phase, and grasping phase. The manipulator workspace is analyzed in Sec. 4. Finally, some conclusions are drawn in Sec. 5.

2. Mechanism under study

Fig. 1. represents a planar CDPR with six cables, which come out of winches placed on the corner of a rectangle represented in blue. Those cables are attached to a four degree-of-freedom moving-platform. The latter is a grasping device composed of two jaws, the upper one in red and the lower one in blue. Those jaws are linked together by a revolute joint. This revolute joint gives a fourth degree-of-freedom to the gripper, in addition to the two usual translation and the rotation of the planar moving-platform. The grasping device should grab the guide and translate it along the rib.

The static workspace of CDPR is usually contained in the volume defined as the convex hull of the pulleys. In the case where those pulleys are fixed to the external structure to be treated, one need to ensure that the moving-platform can reach it even if it is located outside of this volume. To do so, the solution studied here consists of grasping the structure. It should be noted that the geometrico-static model of the robot differs from the free phase to the grasping phase.

A guide is placed inside this rib and is connected to it with a prismatic joint along the direction of the rib. The goal is to manage to move the guide along the entire rib by using the CDPR. To do so, two phases are considered. The first one, called *free phase*, corresponds to the motion of the moving-platform when it is only actuated by the cables. In this phase, the moving-platform is moved in the workspace of the CDPR to reach the guide and grasp it. The model of the robot changes since not only the cables generate forces on the moving-platform, but also the reaction forces between the guide and the jaws of the gripper. In the second phase, named *grasping phase*, the robot should be able to grab and move the guide all along the rib.

3. Geometrico-static modeling of a planar CDPR with an articulated moving-platform

3.1. Free phase

The moving-platform consists of a grasping device presented in Fig.2. It is composed of two jaws, the upper one is red and the lower one is blue, linked together in a point P by a revolute joint. The cables are attached to each jaw. The exit point (anchor point, resp.) of the i th cable connected to the upper jaw is named A_{ui} , (B_{ui} , resp.) $i = 1, \dots, 3$. The exit point (anchor point, resp.) of the

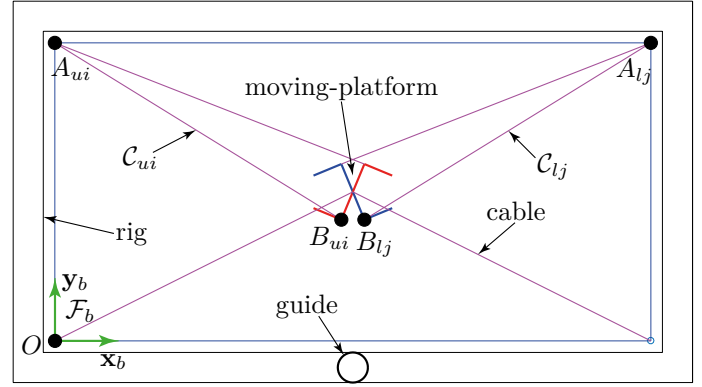


Fig. 1. Planar CDPR with an articulated gripper

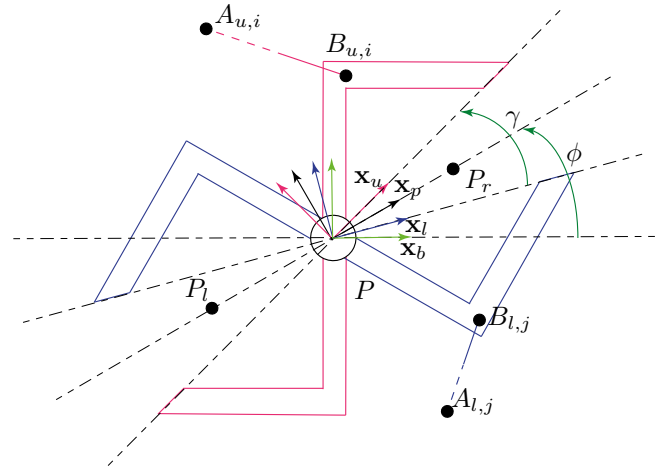


Fig. 2. A one degree-of-freedom gripper

j th cable connected to the lower jaw is named A_{lj} , (B_{lj} , resp.) $j = 1, \dots, 3$.

Therefore the moving-platform has four degrees of freedom in this planar case, the two usual translations and one rotation along with the opening/closing of the jaws. The frame attached to the moving-platform is denoted $\mathcal{F}_p = (P, \mathbf{x}_p, \mathbf{y}_p)$ and ϕ is the rotation angle between axis x_b and axis x_p . $\mathcal{F}_u = (P, \mathbf{x}_u, \mathbf{y}_u)$ is the frame attached to the upper jaw and $\mathcal{F}_l = (P, \mathbf{x}_l, \mathbf{y}_l)$ the one attached to the lower jaw. The angle between axis x_l and axis x_u is denoted γ and the frame \mathcal{F}_p is chosen so that each jaw is placed symmetrically around it. Therefore the angle between \mathcal{F}_p and \mathcal{F}_u or between \mathcal{F}_p and \mathcal{F}_l is $\frac{\gamma}{2}$. The loop-closure equations associated to the cables attached to the upper and lower jaws are the following:

$${}^b\mathbf{c}_{ui} = {}^b\mathbf{a}_{ui} - {}^b\mathbf{p} - \mathbf{R}^p\mathbf{b}_{ui} \quad (1a)$$

$${}^b\mathbf{c}_{lj} = {}^b\mathbf{a}_{lj} - {}^b\mathbf{p} - \mathbf{R}^p\mathbf{b}_{lj} \quad (1b)$$

\mathbf{u}_{ui} and \mathbf{u}_{lj} are the unit vectors of cables \mathcal{C}_{ui} and \mathcal{C}_{lj} , respectively:

$$\mathbf{u}_{ui} = \frac{\mathbf{c}_{ui}}{\|\mathbf{c}_{ui}\|_2} \quad (2a)$$

$$\mathbf{u}_{lj} = \frac{\mathbf{c}_{lj}}{\|\mathbf{c}_{lj}\|_2} \quad (2b)$$

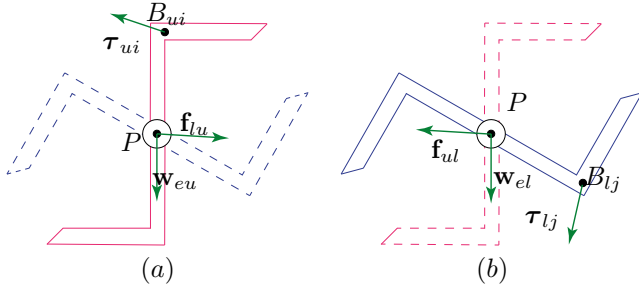


Fig. 3. Free body diagram of the upper jaw (a) and the lower jaw (b)

\mathbf{W}_u (\mathbf{W}_l , resp.) denotes the wrench matrix associated to the upper jaw and maps the tensions exerted in cables C_{ui} , $i = 1, \dots, 3$, (C_{lj} , $j = 1, \dots, 3$ resp.) into the three dimensional wrench space. \mathbf{W}_u and \mathbf{W}_l take the following form:

$$\mathbf{W}_u = \begin{pmatrix} {}^b\mathbf{u}_{u1} & {}^b\mathbf{u}_{u2} & {}^b\mathbf{u}_{u3} \\ {}^b\mathbf{u}_{u1}^T \mathbf{E}^T \mathbf{R}^p \mathbf{b}_{u1} & {}^b\mathbf{u}_{u2}^T \mathbf{E}^T \mathbf{R}^p \mathbf{b}_{u2} & {}^b\mathbf{u}_{u3}^T \mathbf{E}^T \mathbf{R}^p \mathbf{b}_{u3} \end{pmatrix}$$

$$\mathbf{W}_l = \begin{pmatrix} {}^b\mathbf{u}_{l1} & {}^b\mathbf{u}_{l2} & {}^b\mathbf{u}_{l3} \\ {}^b\mathbf{u}_{l1}^T \mathbf{E}^T \mathbf{R}^p \mathbf{b}_{l1} & {}^b\mathbf{u}_{l2}^T \mathbf{E}^T \mathbf{R}^p \mathbf{b}_{l2} & {}^b\mathbf{u}_{l3}^T \mathbf{E}^T \mathbf{R}^p \mathbf{b}_{l3} \end{pmatrix} \quad (3)$$

where

$$\mathbf{E} = \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix} \quad (4)$$

and \mathbf{R} is the rotation matrix from \mathcal{F}_b to \mathcal{F}_p , namely:

$$\mathbf{R} = \begin{pmatrix} \cos(\phi) & -\sin(\phi) \\ \sin(\phi) & \cos(\phi) \end{pmatrix} \quad (5)$$

The free body diagram of the upper jaw and of the lower jaw are represented in Fig.3(a) and Fig.3(b), respectively. To keep the moving-platform in static equilibrium, the vector of the tension in the cables $\boldsymbol{\tau}_u$ and $\boldsymbol{\tau}_l$ need to balance the external wrenches \mathbf{w}_{eu} and \mathbf{w}_{el} applied to the upper and lower jaw, respectively. The center of mass of both jaws is supposed to be located in point P . \mathbf{f}_{ul} denotes the wrenches applied by the lower jaw onto the upper one, and \mathbf{f}_{lu} the opposite. Therefore the relation Eq.(6) stands.

$$\mathbf{f}_{ul} = -\mathbf{f}_{lu} \quad (6)$$

The equation for the static equilibrium of both jaws expressed in point P are:

$$\mathbf{W}_u \boldsymbol{\tau}_u + \mathbf{f}_{ul} + \mathbf{w}_{eu} = \mathbf{0}_3 \quad (7a)$$

$$\mathbf{W}_l \boldsymbol{\tau}_l + \mathbf{f}_{lu} + \mathbf{w}_{el} = \mathbf{0}_3 \quad (7b)$$

To control the opening and closing of the grasping device, the relative angle between both jaws needs to be consid-

ered. With this structure, only the cables control the opening/closing of the grasping device if the pivot is considered without friction. A positive resulting moment generated by the cables on the upper jaw leads to an opening of the pliers, and one on the lower jaw leads to its closing. Therefore Eq.(8) needs to be verified to keep constant the relative angle between both jaws.

$$\mathbf{z}_b^T (\mathbf{W}_u \boldsymbol{\tau}_u - \mathbf{W}_l \boldsymbol{\tau}_l) = 0 \quad (8)$$

The static equilibrium of the grasping device is obtained by adding Eq.(7a) to Eq.(7b) with respect to Eq.(6), and taking into account Eq.(8):

$$\mathbf{W} \boldsymbol{\tau} + \mathbf{w}_e = \mathbf{0}_4 \quad (9)$$

where $\boldsymbol{\tau} = [\boldsymbol{\tau}_u; \boldsymbol{\tau}_l]$, $\mathbf{w}_e = [\mathbf{w}_{eu} + \mathbf{w}_{el}; 0]$ and:

$$\mathbf{W} = \begin{bmatrix} \mathbf{W}_u & \mathbf{W}_l \\ \mathbf{z}_b^T \mathbf{W}_u & -\mathbf{z}_b^T \mathbf{W}_l \end{bmatrix} \quad (10)$$

3.2. Grasping phase

When the moving-platform grasps the guide, the model of the robot changes due to the contact between both jaws and the guide. The free body diagram of the grasping device is shown in Fig.4. In addition to the six cables attached to the moving-platform, the contact between the guide and the jaws are considered in four contact points. The modeling methodology is similar to the one shown previously. \mathbf{W}_{cu} and \mathbf{W}_{cl} are the wrench matrices associated to the contact points between the guide and the upper jaw and the lower jaw, respectively. Those matrices are defined as in Eq.(3a) and Eq.(3b), but for the contact points C_{u1} and C_{u2} or C_{l1} and C_{l2} respectively. By taking into account the effect of the contact to the opening/closing of the jaws, we obtain the global wrench matrix for the contact points \mathbf{W}_c :

$$\mathbf{W}_c = \begin{bmatrix} \mathbf{W}_{cu} & \mathbf{W}_{cl} \\ \mathbf{z}_b^T \mathbf{W}_{cu} & -\mathbf{z}_b^T \mathbf{W}_{cl} \end{bmatrix} \quad (11)$$

and the static equilibrium of the moving-platform becomes:

$$\mathbf{W} \boldsymbol{\tau} + \mathbf{W}_c \boldsymbol{\tau}_c + \mathbf{w}_e = \mathbf{0}_4 \quad (12)$$

where $\boldsymbol{\tau}_c = [f_{u1}; f_{u2}; f_{l1}; f_{l2}]$ is the vector containing the contact forces. The contact is maintained as long as $\boldsymbol{\tau}_c \geq \mathbf{0}_4$. In addition, the static equilibrium of the guide needs to be considered. The guide in the rib is represented in Fig.5. The prismatic joint between the guide and the rib balances the forces applied to the guide in the direction normal to

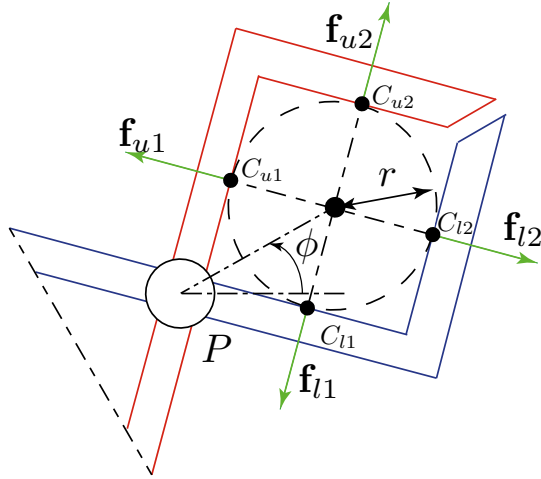


Fig. 4. Free body diagram of the moving-platform grasping the guide

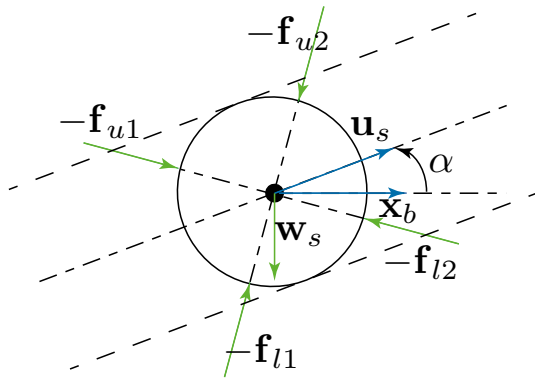


Fig. 5. Free body diagram of the stud inside the rib

the sliding direction \mathbf{u}_s . However if the joint is considered ideal, the only forces applied along direction \mathbf{u}_s are the contact forces between the guide and the moving-platform and the effect of gravity on the guide. Therefore to remain in static equilibrium the following equation needs to be verified:

$$-\mathbf{u}_s^T \mathbf{W}_c \boldsymbol{\tau}_c + \mathbf{u}_s^T \mathbf{w}_s = 0. \quad (13)$$

4. Workspace analysis

4.1. Free phase

This section deals with the workspace analysis of this CDPR. More precisely, we wish to evaluate the impact of the grasp on the workspace size. The workspace studied is the *Weight Feasible Workspace* which contains every pose of the moving platform for which the tension available in the cables can balance the effect of gravity on the moving-platform.

$\boldsymbol{\tau} = [\tau_1, \dots, \tau_6]^T$ denotes the vector of the tensions applied to the six cables. The tension τ_i in each cable i can vary between $\underline{\tau} = 5N$ and $\bar{\tau} = 50N$, $5N$ being the minimal value required to keep the cable in tension and $50N$ being the maximal tension the actuating system can provide. Therefore, the six-dimensional box of feasible tensions is

defined as:

$$\mathcal{T} = \{\boldsymbol{\tau} \in \mathbb{R}^6 : \underline{\boldsymbol{\tau}} \prec \boldsymbol{\tau} \prec \bar{\boldsymbol{\tau}}\} \quad (14)$$

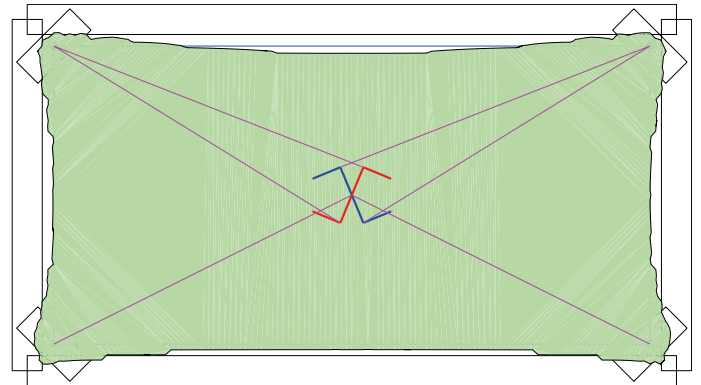
The side of the grasping device which is taken into account is chosen in the set of configurations \mathcal{S} defined by:

$$\mathcal{S} = \{r; l\} \quad (15)$$

where r denotes the right side of the grasping device and l the left side. The external forces applied on the moving-platform are generated by its weight only. A mass of $m_p = 1kg$ is considered for this study, therefore the vector of external forces is $\mathbf{w}_e = [0; -m_p g; 0]^T$ applied in point P . The workspace considered when the CDPR is in its free phase consists of every pose that P_r or P_l can reach, and for which the grasping device can perform an opening/closing operation in static equilibrium. The mathematical definition associated is:

$$\mathcal{F}_1 = \{\mathbf{p} \in \mathbb{R}^2 : \exists c \in \mathcal{S}, \exists \phi \in [\underline{\phi}; \bar{\phi}], \forall \gamma \in [0; \bar{\gamma}], \exists \boldsymbol{\tau} \in \mathcal{T}, \mathbf{W}\boldsymbol{\tau} + \mathbf{w}_e = \mathbf{0}_4\} \quad (16)$$

In this case, the boundaries considered are $\underline{\phi} = -\frac{\pi}{2}$, $\bar{\phi} = \frac{\pi}{2}$ for the orientation of the moving-platform and $\bar{\gamma} = \frac{\pi}{8}$ for its opening. This value allows it to perform a grasping operation without colliding with the guide. The workspace obtained is shown in Fig.6. One can see that the moving-platform can reach the external structure only in its corners.

Fig. 6. *Weight Feasible Workspace* of the CDPR in its free phase

4.2. Grasping phase

When the moving-platform is grasping the guide, the model of the robot is different and therefore the definition of the previous workspace is not suited for its study. In addition to the mass of the moving-platform, the mass of the guide, arbitrarily set to $m_s = 1kg$, is also considered. This time, the workspace consists of every pose that P_r or P_l can reach while grasping the guide, and maintain the static equilibrium of both the moving-platform and the

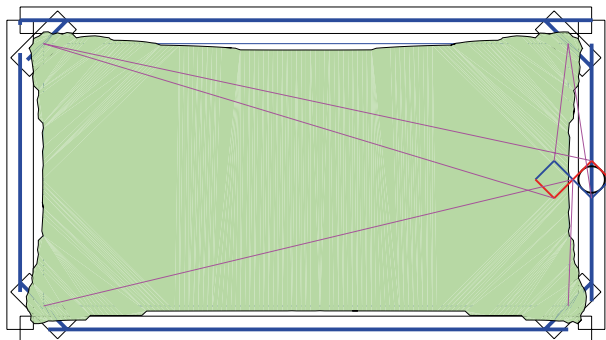


Fig. 7. Workspace of the CDPR grasping the guide

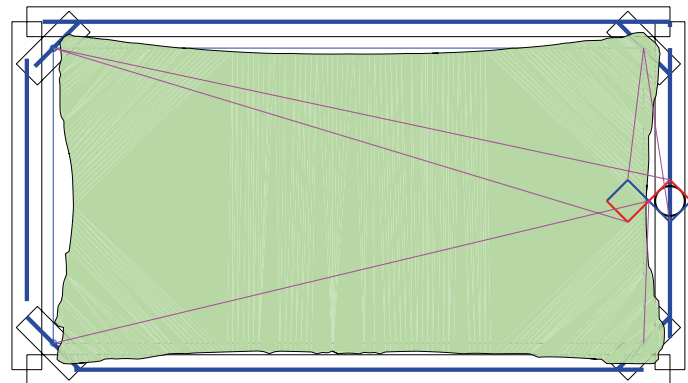


Fig. 8. Workspace of the right plier grasping the guide

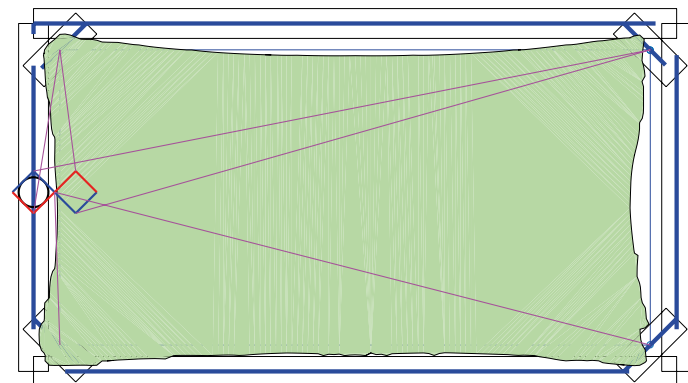


Fig. 9. Workspace of the left pliers grasping the guide

guide. Its mathematical definition is:

$$\mathcal{F}_2 = \{\mathbf{p} \in \mathbb{R}^2 : \exists c \in \mathcal{S}, \exists \phi \in [\underline{\phi}; \overline{\phi}], \exists \boldsymbol{\tau} \in \mathcal{T}, \exists \boldsymbol{\tau}_c \geq \mathbf{0}_4 \left\{ \begin{array}{l} \mathbf{W}\boldsymbol{\tau} + \mathbf{W}_c\boldsymbol{\tau}_c + \mathbf{w}_e = \mathbf{0}_4 \\ \mathbf{u}_s^T \mathbf{W}_c\boldsymbol{\tau}_c + \mathbf{u}_s^T \mathbf{w}_s = 0 \end{array} \right\} \} \quad (17)$$

The resulting workspace is represented in blue in Fig.7. One can see that the portion of the external structure covered by the robot is greatly increased by grasping the guide.

4.3. Analysis

On the example shown in Fig.7, the rib on the right was not covered at all in the free phase, since the cables could not pull the moving-platform further enough on the right side. Indeed, one can see that the cables coming from the right cannot generate forces in this direction since they are close to being vertical. However a large portion can be covered when the guide is grasped. This means that the contact forces between the grasping device and the guide can balance the effect of the cables pulling it back to the center of the workspace, and that the cables can maintain the jaws closed onto the guide.

To cover the largest portion of the external structure, one need to follow the steps:

- Move the grasping device in its *free phase* to a grasping point belonging to both \mathcal{F}_1 and \mathcal{F}_2 to reach the guide. Those poses correspond to the corners of the external structure in this example.
- Close the jaws to grasp the guide.
- Move along the ribs to cover the external structure in the *grasping phase*.
- Return to one of the grasping points.
- Repeat to cover the largest portion possible.

It is to note that the workspace is different depending on which plier grasps the guide. Figure 8 represents the workspace of the robot when the right plier grasp the guide, and Fig.9 the one when the left plier grasps the guide. It is necessary to find the position where both pliers can grasp the guide to switch between them.

5. Conclusion/Future work

This paper presents a planar CDPR with a new moving-platform with two degrees of freedom. This moving-platform consists of a grasping device that will grab a guide sliding on an external structure. The interaction with the guide can be considered as online reconfiguration since it changes the model of the robot. This reconfiguration increases the workspace of the CDPR, allowing it to move along a structure it could not reach from its standard configuration.

First, the static model of the robot equipped with the new moving-platform is developed in its free phase, and in its grasping phase. Two new workspaces are then defined to fit with the study of this concept. The first one is suited for the study of CDPR using a moving-platform with several degrees of freedom and the second for the study of CDPR interacting with an external object or structure. The analysis of those workspaces show the interest of the interaction between the moving-platform of a CDPR and its environment to improve its properties such as increase its workspace.

Those promising results are the first steps of an ongoing work in this area, that is focused on the experimental validation of the results, the study of new designs of the grasping device and to extend this work to spatial cases.

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