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Optimizing Cable-Routing for Reconfigurable Cable-Driven Parallel Robots

Utkarsh A. Mishra¹, Stéphane Caro^{2,*} and Marc Gouttefarde³

¹ Indian Institute of Technology Roorkee, Uttarakhand 247667, India
umishra@me.iitr.ac.in

² CNRS, Laboratoire des Sciences du Numérique de Nantes, UMR CNRS 6004,
1, rue de la Noë, 44321 Nantes, France
stephane.caro@ls2n.fr

³ LIRMM, Univ Montpellier, CNRS, Montpellier, France
marc.gouttefarde@lirmm.fr

Abstract. Reconfigurable cable-driven parallel robots have proved to be very effective in tasks involving complex and cluttered environments. This paper presents a methodology for determining an appropriate cable routing between the cable exit points and the winches. The cable exit points are defined beforehand and the pulleys can be discretely positioned on the robot frame. A six-degree-of-freedom (6-DOF) reconfigurable cable-driven parallel robot is used as an illustrative example. The locations and connections between all pulleys are obtained based on structural and mechanical constraints, mainly imposed by the pulleys. Two specific cases are studied and the optimal configuration for each case is presented in an illustrative and quantitative manner.

Keywords: Cable-Driven Parallel Robots, Cable Routing, Optimization

1 Introduction

Cable-Driven Parallel Robots (CDPRs) have gained a lot of popularity in a wide range of applications. In such robots, cables are used to manipulate a Moving Platform (MP) and connect it to a fixed base frame. Hereafter, the connection points between the cables and the base frame will be referred to as exit points. The use of cables instead of rigid links to make the MP move brings to CDPRs several advantages such as low inertia, very large workspace, and a higher payload to weight ratio as compared to their serial and parallel counterparts. Various tasks like large scale 3D printing [1], rehabilitation mechanisms [5], transfer robots for the elderly [6], rescue robots [7] as well as large-scale telescopes [10] have exploited these advantages. However, there are some potential drawbacks associated with CDPRs. Due to the use of a significant number of cables, the probability of collisions between the cables and the surrounding environment increases. Furthermore, the static equilibrium of the MP is influenced by the non-rigid nature of the cables as they can pull, but not push on the MP.

* Address all correspondance to this author.

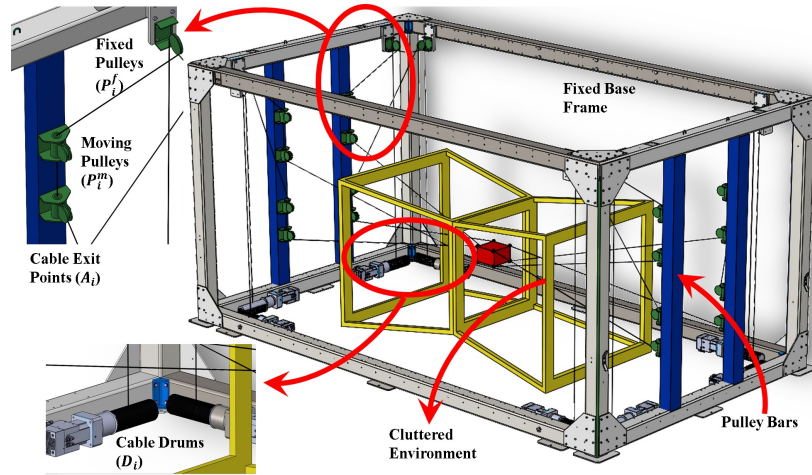


Fig. 1: A Reconfigurable Cable-Driven Parallel Robot evolving in a cluttered environment

Generally, the design of a CDPR is such that the layout of the cable exit points is fixed [4]. In such a case, the CDPR can hardly operate efficiently in a cluttered environment where it is not entirely possible to avoid cable collisions. Using multiple CDPRs working together in a single environment might resolve this issue, but significantly increases the complexity and cost of the process. Keeping all these issues in mind, the idea of reconfiguration with fixed base frame was explored in [2] and extended in [3] to allow the possibility of multiple task-specific configurations in a large workspace. For relatively small workspaces, CDPRs with mobile base frames [8,9] have been proposed. Such CDPRs are referred to as Reconfigurable CDPRs (RCDPRs), and the presented work primarily deals with such robots with fixed base frames. In this context, the algorithm proposed in [3] efficiently determines the cable exit positions on the base frame based on the required task constraints using a graph-based formulation. It allows one to find suitable cable layouts for the RCDPR while minimizing the number of reconfigurations and optimizing some performance functions. However, the authors did not study the management of the cable routing between the cable exit points and the winches. The cable being routed over multiple pulleys and each cable having multiple segments, it becomes very likely that the cable routing from the exit points to the winch drums is infeasible, violating pulley physical constraints and collision conditions.

In this paper, we explore the possibilities of optimizing cable routing for RCDPRs. While most previous works have contributed to reconfiguration planning, the methodology of connecting winch drums to the cable exit points obtained from the reconfiguration planner has not been addressed. Cable routing configurations might not always be feasible when physical constraints of the pulley are taken into concern. Furthermore, as each cable is segmented into multiple parts, the occurrence of cable collisions become more likely. Considering such constraints, an objective function is formulated in

this paper to provide a feasible and optimal routing configuration. Two case studies are discussed with a cluttered environment inspired from authors' previous works [2, 3]. First, the MP moves inside a lattice. Then, the MP moves outside the lattice. Symmetry is used to simplify the problem and resulting configurations are calculated using ©MATLAB and represented with ©SOLIDWORKS models.

The modeling of the manipulator and the associated nomenclature are discussed in Section 2. Section 3 describes all the constraints considered for the determination of the cable routing. Section 4 formulates the problem statement as an integer optimization problem. Section 5 gives the results obtained using the proposed approach. Those results are discussed in Section 6. Conclusions and future work are drawn in Section 7.

2 Problem Formulation and Parametrization

Let us consider a 6-DOF fully-constrained RCDPR with 8 cables. Its i th closed loop is shown in Fig. 2, $i = 1, \dots, 8$. The frame \mathcal{F}_b of origin O is attached to the base. The frame \mathcal{F}_p of origin P is attached to the MP. The figure shows drums D_i 's (position vector \mathbf{d}_i), fixed pulleys P_i^f 's (position vector \mathbf{p}_i^f), positioned directly above each of the drums and movable pulleys P_i^m (position vector \mathbf{p}_i^m). The cable anchor points, B_i 's (\mathbf{b}_i denotes the position vector of anchor point B_i expressed in \mathcal{F}_p), on the moving platform, are connected to each of the corresponding base frame exit pulleys denoted by A_i 's. Ideally, based on [3], P_i^m and A_i are located on the same reconfigurable pulley bar. All pulley and drum position vectors are expressed in \mathcal{F}_b .

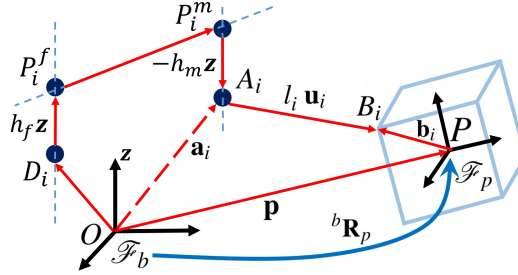


Fig. 2: i^{th} -closed loop of the CDPR

The distances h_f and h_m denote the distances between drum and fixed pulley, and moving pulley and cable exit points, respectively. Their signs are with respect to the direction of the vectors as shown in Fig. 2. Here, h_f is constant for all the drum and fixed pulley pairs, whereas h_m is chosen for each A_i based on a discretized setting where $h_m = z_i \Delta h_m$ and Δh_m is the discretization step along each bar of the RCDPR frame. z_i is an integer bounded by the structural constraints that the moving pulley should remain on the pulley bar.

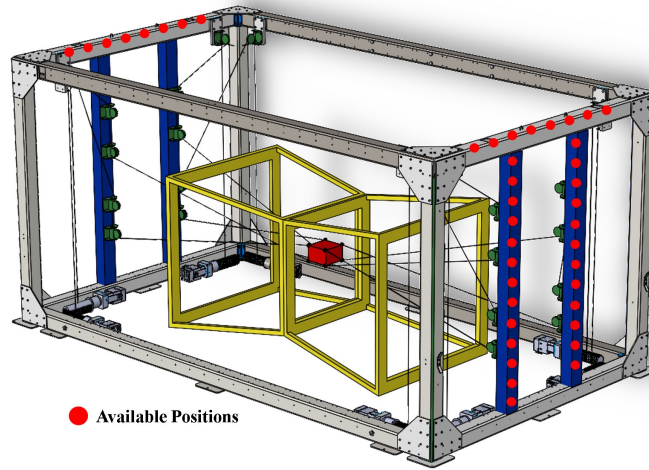


Fig. 3: Possible locations for the pulleys and mobile pulley bars

In Fig. 2, the cable exit points are obtained with the algorithm described in [3]. Hence, we already know A_i corresponding to each of the cable anchor points, B_i . Moreover, this is a direct inference that once we choose a drum, D_i , for a given cable exit point A_i , P_i^f is by default the fixed pulley located over the drum since connecting to any other fixed pulley does not make proper sense.

Given all the required information as stated above, the aim of this work is to find a proper cable routing which abides by all the structural, pulley and collision constraints as well as optimizes the cumulative cable length of all the eight cables. Hereafter, it should be noted that all reconfigurations are discrete and the available positions for each reconfigurable unit (pulley bars and moving pulleys) are discretized as shown in Fig. 3.

3 Constraints

The problem definition gives rise to a number of constraints and for the sake of simplicity, some assumptions are made in order to find a suitable cable routing configuration. The following three types of constraints are considered.

3.1 Structural Constraints

The structural constraints are imposed by the reconfiguration design. The drums, D_i and pulleys above them, P_i^f , are fixed and hence the distance between them is fixed. This reduces the problem to finding an optimal P_i^f for each A_i . Furthermore, a similar constraint is applicable for all the moving pulleys, P_i^m , i.e. the moving pulley should always be above or under the exit point, A_i , the latter being given. Indeed, both the

moving pulley P_i^m and cable exit point A_i are located on the same pulley bar. However, the distance between A_i and P_i^m can vary and is an optimization variable denoted as z_i as defined in Section 2. P_i^m can be above or below A_i . In addition, from Fig. 1, it is apparent that a pulley bar may contain four pulleys, two of which being the exit points and the other two being the moving pulleys. This imposes further constraints that there should not be any overlapping between the $A_l-P_l^m$ and $A_u-P_u^m$ cable segments, where subscripts l and u denote lower and upper respectively.

3.2 Pulley Constraints

Pulleys play a vital role in changing the directions of the cables. The pulleys considered in this work typically have two types of entries and exits (from both top and bottom), namely through the “pulley groove” and the “pulley wheel”. These pulleys are accompanied by their own set of structural constraints being restricted by their range of rotation about their axis and imposing rules on cables entering or exiting through the pulley wheel as illustrated in Fig. 4.

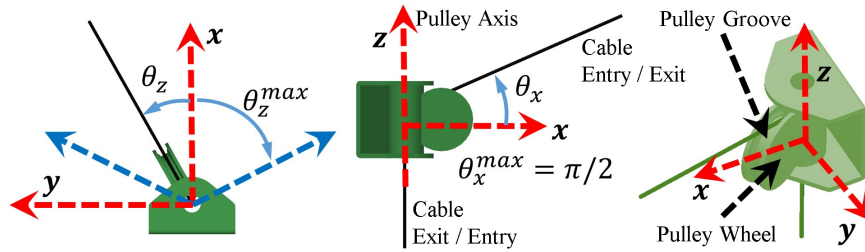


Fig. 4: Pulley-cable constraints

If the cable exits one pulley through wheel and enters another pulley through wheel, then the two pulleys must be co-planar. In such a case, the rotation of the corresponding pulleys and the exit angles between the cable and the pulley is bounded. However, if any of the entry or exit happens through the groove, the co-planarity constraint is not required for that entry or exit.

3.3 Collision Constraints

The cable routing in case of a RCDPR discretizes the cable into multiple segments as compared to a single cable for standard CDPRs. Such segments are generally formed between the cable anchor point on the MP, cable exit point, moving pulley, fixed pulley and the drum. This not only increases the probability of collision between cables but also between two different segments of a single cable. Hence, collisions between all the possible pairs of such segments including pairs belonging to the same cable should

be checked. Apart from collision between cables, all the segments should also avoid collisions with the environment obstacles as well as the MP itself.

4 Methodology

The problem formulation as described in Section 2 has two different settings to be optimized. First, a suitable drum D_i has to be chosen for every A_i and then the position of the moving pulleys as determined by z_i has to be optimized such that all the constraints are satisfied. Now, as the complete setting is discrete, an integer optimization based approach is considered and solved using an optimization algorithm. The overall objective function is to minimize the cumulative cable length due to the routing configuration i.e. from the cable exit point to the drum. This results in the following optimization problem:

$$\min_{z_i, P_i^f} \sum_{i=1}^{i=8} l_i + \text{secondary objectives}$$

subject to:

1. Cable Constraints:

$$\mathbf{p}_i^m = \mathbf{a}_i + z_i \Delta h_m \mathbf{z}, \quad \mathbf{y}_P = \text{Pulley Normal Axis}$$

$$\left| \frac{\pi}{2} - \cos^{-1} \left(\frac{(\mathbf{p}_i^m - \mathbf{p}_i^f)^T \mathbf{y}_P}{\|\mathbf{p}_i^m - \mathbf{p}_i^f\|_2} \right) \right| \leq \theta_z^{max}$$

2. Collision Constraints: Satisfied

and

$$\begin{aligned} l_i &= \sqrt{(\mathbf{a}_i - \mathbf{p}_i^m)^T (\mathbf{a}_i - \mathbf{p}_i^m)} + \sqrt{(\mathbf{p}_i^m - \mathbf{p}_i^f)^T (\mathbf{p}_i^m - \mathbf{p}_i^f)} + \sqrt{(\mathbf{p}_i^f - \mathbf{d}_i)^T (\mathbf{p}_i^f - \mathbf{d}_i)} \\ &= |z_i \Delta h_m| + \sqrt{(\mathbf{p}_i^m - \mathbf{p}_i^f)^T (\mathbf{p}_i^m - \mathbf{p}_i^f)} + h_f \end{aligned}$$

which directly implies that the absolute value of z_i should be as small as possible. However, the pulley constraints play a vital role in their selection. Apart from the primary cable length objective, various secondary objectives are possible in order to create a more accurate analysis. Examples of such objectives can be minimizing pulley bending and pulley friction loss. Such objective functions are not considered in this section, but briefly discussed in Section 6.

In order to simplify the number of explorable solutions, we strictly take the advantage of all the possible symmetries in the configuration of the cable exit points with respect to the position of the fixed pulleys. Using the symmetry, the number of optimization variables is reduced by $1/2^k$ for k symmetry planes. some examples of symmetry are shown in Fig. 6. With a reduced number of optimization variables, complete search over all the space of reconfigurations can be performed in order to find the best possible routing. The methodology is illustrated in the form of a flowchart in Fig. 5.

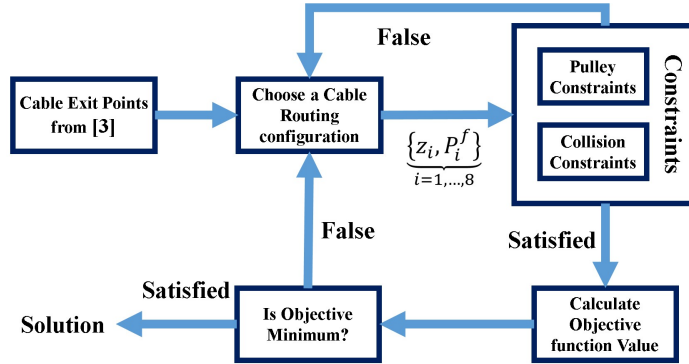


Fig. 5: Methodology to determine cable routing

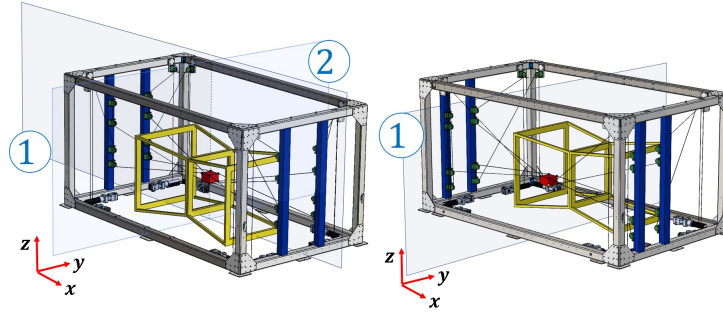


Fig. 6: Two Symmetry Planes

5 Simulation Results

The foregoing methodology is used to determine the cable routings associated with two configurations of a RCDPR similar to [3]. For the first case, the MP was placed inside the hollow obstacle as shown in Fig. 1 which addresses the tasks of painting and inspecting the obstacle from inside. The configuration is considered first because it addresses usage of all the movable pulleys available for reconfiguration and also allows us to consider two planes of symmetry as in Fig. 6 (left). Whereas in the second case, the MP was placed outside the obstacle as shown in Fig. 7. In this configuration, significant differences are created because of the presence of a single symmetry plane as shown in Fig. 6 (right) and there are some cables for which the exit points are the fixed pulleys themselves. In Fig. 7, two cables are directly connected to the fixed pulleys and hence they do not require the pulley bar which further reduces the number of variables in the cable routing optimization.

The symmetry planes reduced the problem of solving for only one corner, i.e. two fixed pulleys, two moving pulleys and two exit points. The solution is expected to give

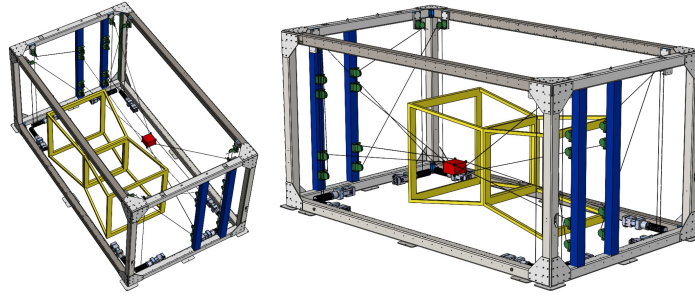


Fig. 7: Optimized cable routing configuration for case 2: when MP is outside (on one side) of the obstacle

values for z_1 and z_2 to determine the position of the moving pulleys w.r.t. exit points and then choose suitable fixed and moving pulley pairs to be connected. The routing solution obtained for one corner is illustrated in Fig. 8 (left) where the respective pulley pairs are (P_1^f, A_2) and (P_2^f, A_1) . The values of z_1 and z_2 are -3 and -2 respectively. The negative values mean that the moving pulleys are above the cable exit points based on the parametrization in Fig. 2.

For the second case, based on the symmetry plane, the solution for routing configuration consists of three pulley pairs and the corresponding three z values. One fixed pulley is the exit point and is not included in the optimization process. This is to be noted that all exit points were previously obtained using the algorithm of [3]. The obtained configuration shown in Fig. 8 consists of the pulley pairs (P_1^f, A_2) , (P_2^f, A_1) and (P_3^f, A_3) . The corresponding values of z_1, z_2 and z_3 are $-1, 2$ and 2 , respectively.

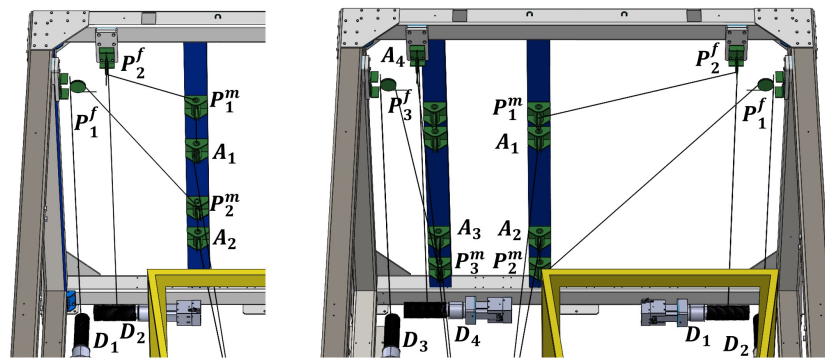


Fig. 8: Optimized cable routing configuration for case 1 (left) and case 2 (right) based on variable reduction with symmetry

Table 1 gives some quantitative results for cases 1 and 2. The reduced number of variables are presented after considering the symmetry planes. The calculations were carried out with an Intel ®i7-7500U CPU@2.70GHz processor.

Table 1: Results for configurations 1 and 2

Parameter	Case 1	Case 2
Original no of optimization variables	16	12
Original no of cable routings	$8! \times 6^8 \approx 68$ billions	$6! \times 4^6 \approx 3$ millions
No. of symmetry planes	2	1
Reduced no of optimization variables	4	6
Reduced no of cable routings	$2! \times 6^2 = 72$	$3! \times 4^3 = 384$
Total Computation Time	31 s	214 s

6 Discussion

The methodology discussed in the present paper is modular and is open to addition of constraints and secondary objectives which will eventually result in a more accurate and practical results. The architecture of the RCDPR is chosen such that the number of pulleys between an exit point and a drum is odd [3]. The introduction of multiple number of pulleys play a vital role in introducing various other conditions which should be considered while planning for such robots. Simple pulley rotation constraint is considered in this work but multiple criteria like pulley bending and losses due to pulley friction will definitely play a significant role. While the former can be added directly to the process of optimizing cable routing after the cable exit points are obtained, the latter will modulate the decision on cable tensions (as pulley friction depends on cable tension) as well as affect the choice of the most optimal cable exit points. This will couple static equilibrium, exit point selection and optimal cable routing.

7 Conclusions and Future Work

Cable routing between the winch drum and the cable exit point is an important criterion to be defined for RCDPRs. While RCDPRs are helpful for operation in complex and highly cluttered environments, their performance can be further optimized by considering an optimal cable routing configuration as well. This paper exhibits two cases of planning in RCDPRs as discussed in previous works and introduces an insight on how such cable routing can be performed in an efficient manner. Cable routings are obtained, assessed and illustrated. Future work will deal with experimental studies and introduce more objective functions and constraints in the optimization problems as discussed in Section 6.

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