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Discrete reconfiguration planning for Cable-Driven Parallel Robots

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ABSTRACT

Cable-Driven Parallel Robots (CDPRs) are a class of parallel robots whose legs consist of cables. In most previous studies, the positions of the cable connection points on the moving platform and on the base frame are fixed, these positions being determined during the CDPR design. However, such fixed-configuration CDPRs are not always suitable and some situations require reconfiguration capabilities, e.g. a cluttered environment where cable collisions with objects in the CDPR workspace cannot be completely avoided without reconfigurations. This paper deals with Reconfigurable Cable-Driven Parallel Robots (RCDPRs) whose cable connection points on the base frame can be positioned at a possibly large but discrete set of possible locations. Means to select and optimize the sequence of discrete reconfigurations allowing the RCDPR moving platform to follow a prescribed path are introduced. A so-called feasibility map is first generated. For each possible configuration of the RCDPR, this map stores the feasible or unfeasible character of each point of the discretized prescribed path, according to user-defined constraints which ensure a proper functioning of the RCDPR. The feasibility map is next analyzed in order to determine minimum sets of configurations which allow the RCDPR to follow the whole prescribed path. Finally, the corresponding discrete reconfiguration planning problem is represented as a graph whose nodes correspond to feasible RCDPR reconfigurations. The arcs of the graph are weighted by a user-defined cost function so that the graph can be searched for an optimal reconfiguration strategy using Dijkstra's algorithm.

1. Introduction

Several industrial sectors, e.g. the naval and renewable energy industries, are facing the necessity to manufacture novel products of large dimensions and having complex shapes. In order to improve such manufacturing processes, the IRT Jules Verne promoted the investigation of new technologies. In this context, CAROCA[1] project aims at investigating the performance of *Cable Driven Parallel Robots* (CDPRs) to manufacture large products in cluttered industrial environments [1]. CDPRs are a particular class of parallel robots whose moving platform is connected to the robot fixed base frame by a number of cables as

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[1] Evaluation des CApacités de la RObotique à CÂbles dans un contexte industriel.

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illustrated in Fig. 1. Hereafter, the connection points between the cables and the base frame will be referred to as exit points. CDPRs have several advantages such as a high payload-to-weight ratio, a potentially very large workspace, and reconfiguration capabilities. Therefore, they can be used in several applications, e.g. heavy payload handling and airplane painting [2], cargo handling [3], warehouse applications [4], and large-scale assembly operations [5]. Other possible applications include the broadcasting of sport events, haptic devices [6–8], support structure for giant telescopes [9,10], and search and rescue deployable platforms [11,12].

In the sequel, a CDPR *configuration* refers to the positions of the cable exit points, the positions of the cable anchor points on the moving platform, and the cable layout between these two sets of points. In most previous studies, the CDPR has a fixed configuration which is determined during its design, e.g. [13]. While fixed-configuration CDPRs are relevant in many cases, some more demanding applications require reconfiguration capabilities. One notable case is a cluttered environment where cable collisions with objects in the CDPR workspace cannot be completely avoided so that reconfigurations are necessary. This case is dealt with in this paper where the considered applications involve low force operations over the surface of a large (metallic) structure, e.g. painting and sandblasting. The CDPR environment is cluttered because the structure is located into the workspace and occupies a significant part of it, as illustrated in Fig. 1. The task to be performed is simplified to that of following a prescribed path which is defined by the user in such a way that the entire surface of the structure is eventually treated. The platform orientation is constant. Tools and/or active devices have to be embarked on the CDPR moving platform but the corresponding issues are out of the scope of this paper.

Because of cable collisions, several CDPRs would need to be installed around the structure, typically one per structure face [1]. Alternatively, to reduce the number of winches and thus the installation and maintenance costs, a limited number of winches can be used when reconfigurations are allowed. The most efficient way of avoiding cable collisions is to permit CDPR cable exit point reconfigurations. Exit point reconfigurations can be performed in a continuous or in a discrete manner. The first one consists in cable exit points mounted on mobile bases, e.g. a trolley on a rail [14] or a flying platform [15–17]. Such a *Reconfigurable Cable-Driven Parallel Robot* (RCDPR) has a *continuous* set of possible configurations. On the contrary, the set of possible reconfigurations is *discrete* when the cable exit points can be positioned at a possibly large but finite number of locations, such as those of a grid of possible exit point positions. From a technical point of view, modifying a cable exit point amounts to move or change the last pulley which directs the cable toward the moving platform, as shown in Fig. 1. A possible reconfiguration procedure is detailed in [18].

Preliminary studies on RCDPRs have already been performed by the NIST as a part of the *NIST RoboCrane* project [19]. Izard et al. [20] also studied a family of RCDPRs, named *ReelAx*, in order to investigate the potentialities of CDPRs in industrial contexts. However, no reconfiguration strategy has been proposed by the authors. More detailed studies have been performed by Rosati et al. [21,22], which focused on planar RCDPRs. They suggested to use movable exit points in order to maximize a local performance index across the CDPR workspace. The corresponding continuous reconfiguration problem is solved by means of an analytical description of the desired optimal cable configuration which can however hardly be extended to spatial RCDPRs. In 2012, Zhou et al. [23] suggested to increase the number of Degrees of Freedom (DOFs) of CDPRs by mounting the winches on mobile bases, which results in a type of RCDPRs. In [24,25], Zhou used an alternative concept for RCDPRs. A set of cables with constant lengths are connected to linear motors. The cables are either attached to the platform [25] or pull the platform by means of idler pulleys [24]. In both cases, a planar case study has been investigated to show the concept advantages.

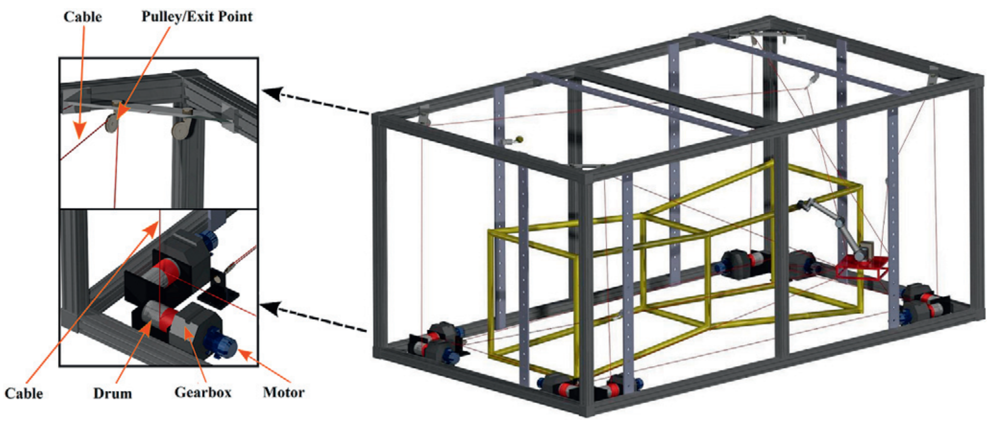

Fig. 1. Example of a Reconfigurable Cable-Driven Parallel Robot (RCDPR) design. The robot shown in the picture is a concept created in the framework of the CAROCA project and is intended to paint tubular structures.