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Cable-Driven Parallel Robots, theoretical challenges and industrial applications

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***Abstract*—This paper analyzes some of the theoretical and industrial challenges arising in the study of Cable-Driven Parallel Robots, and the solutions proposed by the University of Bologna.**

***Index Terms*—Cable Parallel Robots, Industrial Applications**

I. INTRODUCTION

Cable-Driven Parallel Robots (*CDPRs*) form a class of parallel robots, introduced in the 80', which employ cables in place of rigid-body extensible legs in order to control the end-effector (*EE*) pose (Fig. 1). Despite the fact that cables can only provide tensile force, that is, they can pull but not push, they present specific advantages over traditional parallel robots: (i) cables can be coiled and uncoiled onto motorized winches, so that the robot workspace can be remarkably large, (ii) cable mass is often practically negligible, thus increasing the robot dynamic performance, and (iii) actuator and transmission elements, that is, winches and pulleys, can easily be rearranged, thus machine reconfigurability is enhanced.

A *CDPR* which aims at controlling f degrees of freedom (*DoFs*) of an *EE*, regardless of the intensity of external actions, should have at least $n = f + 1$ cables. Indeed, since cables may only exert tensile axial forces, a constraint redundancy on the *EE* may generally avoid cable slackness and *EE* instability [1]. This cable arrangement allows for stiff, dexterous and highly dynamic manipulator, but it requires force control, it demands a considerable nominal power, and it limits workspace accessibility (Fig. 1).

Power consumption, robot cost, and workspace limitations can be reduced by constraining the robot *EE* with $n = f$ cables, which are routed from an elevated position. On the other hand, cable slackness is avoided only if an external force (i.e. gravity) steadily acts upon the *EE*. *CDPRs* with $n < f$ cables (Fig. 2), which are underactuated by design, are also justified in several applications, in which the task to be performed requires a limited number of controlled freedoms or a limitation of mobility is acceptable in order to further enhance accessibility, decrease complexity, and ultimately cost. However, only a sub-set of the *EE* generalized coordinates can be directly controlled, while the others are determined by the system mechanical equilibrium [2].

II. THEORETICAL CHALLENGES

Our research efforts has been focused on *CDPRs* with $n = f$ cables, and underactuated *CDPR* with $n < f$ cables.

Trajectory planning is one of the major challenges in the study of completely-constrained *CDPRs*: the inertial actions acting on the robot *EE* greatly influence cable tensions and ultimately the system stability and accuracy. Classes of dynamically-feasible trajectories for this class of *CDPRs*, and the robot capability to move outside its static workspace, were developed in [3]–[5]. In addition, the kinematic performances of purely-translational completely-constrained *CDPRs* were assessed in [6]. Underactuated *CDPR* present additional challenges, since the *EE* mechanical equilibrium not only influences cable tensions, but also the *EE* pose. The solutions to the so-called geometrico-static problems [7]–[9], as well as the equilibrium stability [2], were addressed in detail. Additionally, if an arbitrary motion is prescribed to a suitable subset of the *EE* coordinates, the robot constraint deficiency leads to *EE* oscillations and the impossibility of bringing the system at rest in a prescribed time. The problem of limiting *EE* oscillations of 3-cable robots was addressed in [10] by

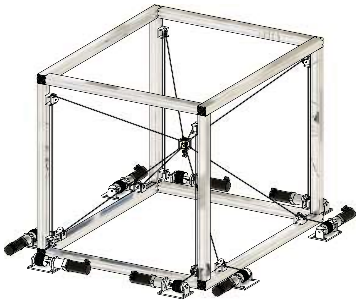

Fig. 1: Redundantly constrained cable-driven robot

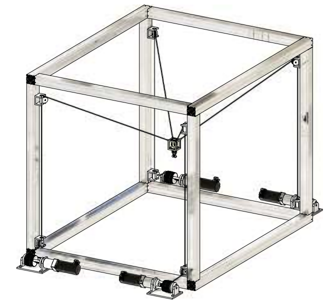

Fig. 2: Suspended under-constrained cable-driven robot

(a) Closed (b) Deployed (c) Tilted

Fig. 3: Cable-driven laser scanner prototype

combining input-shaping filters and dynamically-scaled trajectories; its generalization to generic underactuated *CDPRs*, which necessitates the non-trivial computation of the system natural oscillation frequencies, has recently been tackled in [11]. On the other hand, the possibility to completely stop the *EE* after an arbitrary trajectory was considered by designing so-called rest-to-rest trajectories in [12]. This latter type of trajectories need to be computed off-line relying on a precise knowledge of robot parameters.

The improvement of underactuated *CDPR* performances is one of our current focuses. Achieving a high *EE* accuracy is only possible if a suitable feedback controller on its pose is developed. On the other hand, before the *EE* pose can be regulated, it needs to be estimated. The use of standard direct kinematic approaches for pose-estimation is unfeasible due to actuation deficiencies, thus novel techniques dedicated to precise pose-estimation based on low-cost redundant proprioceptive measurements [13], exteroceptive sensors (such as standard IP cams) and extended Kalman filter are being considered.

III. INDUSTRIAL APPLICATIONS

We focus here on two representative industrial applications: laser scanning, and automated curtain wall assembly.

We designed a cable-driven laser scanner composed by a fixed laser distance-measuring device, whose laser beam is reflected by an optical mirror mounted on the *EE* of a completely-constrained suspended *CDPR* [14]. The aim of the machine is to collect data points corresponding to the inner surface of fuel-storage tanks, in order to reconstruct its shape, and thus its volume. To this end, the *EE* is completely self-deployable, meaning that it can automatically fold on itself, and it can freely tilt in any direction up to 85° (Fig. 3). Curtain wall installation and maintenance was performed in the european project HEPHAESTUS by employing a redundantly constrained *CDPR* with 8 cables, whose pose was continuously estimated by means of a camera mounted on the robot *EE* [15]. The large workspace of this class of manipulators allows the robot to freely operate on the whole façade under construction (Fig. 4), and the *EE*-mounted vision system provided the absolute accuracy needed for assembly operations.

Fig. 4: Demonstration of a panel installation with a *CDPR*

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