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Cable-Driven Parallel Robots

Marc Gouttefarde and Tobias Bruckmann

Synonyms

Cable-driven parallel mechanisms/manipulators; wire-driven robots; wire robots; cable-suspended robots; cable robots; tendon-based Stewart platforms.

Definition

A Cable-Driven Parallel Robot (CDPR) is a special type of parallel robot where cables replace rigid links. Alternatively, a CDPR can be viewed as a dexterous lifting machine which uses several cables to avoid, at least partially, a sway of the payload. CDPRs generally consist of a supporting structure, winches winding up the cables, and a payload (mobile platform) where the cables are attached.

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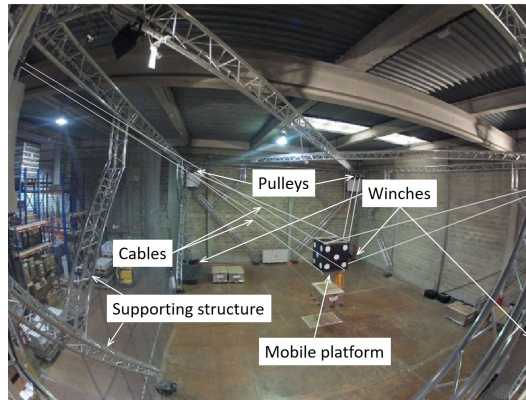


Fig. 1 The LIRMM/Tecnalia 6-DOF CDPR CoGiRo (Gouttefarde et al 2015a).

Overview

This section presents a brief overview of the CDPR state of the art. Further analyses and descriptions can notably be found in (Bruckmann et al 2008a,b; Gosselin 2014; Pott 2018).

Working principle and components of a CDPR

As illustrated in Fig. 1 and 2, the mobile platform of a CDPR is connected to a number of winches by means of cables. The winches are generally fixed to a supporting structure, to the ground, or to posts. The cables are stored on the winch drums and may be routed to the mobile platform by means of one or several pulleys. They are either directly attached to the mobile platform or connected to it by means of universal joints. Various types of cables or wires can be used, steel wire ropes and synthetic fiber ropes being the most common ones.

The mobile platform position and orientation can be adjusted by modifying the cable lengths between the winches and the platform. A motion of the mobile platform can also be induced by varying the cable forces. The winches can thus

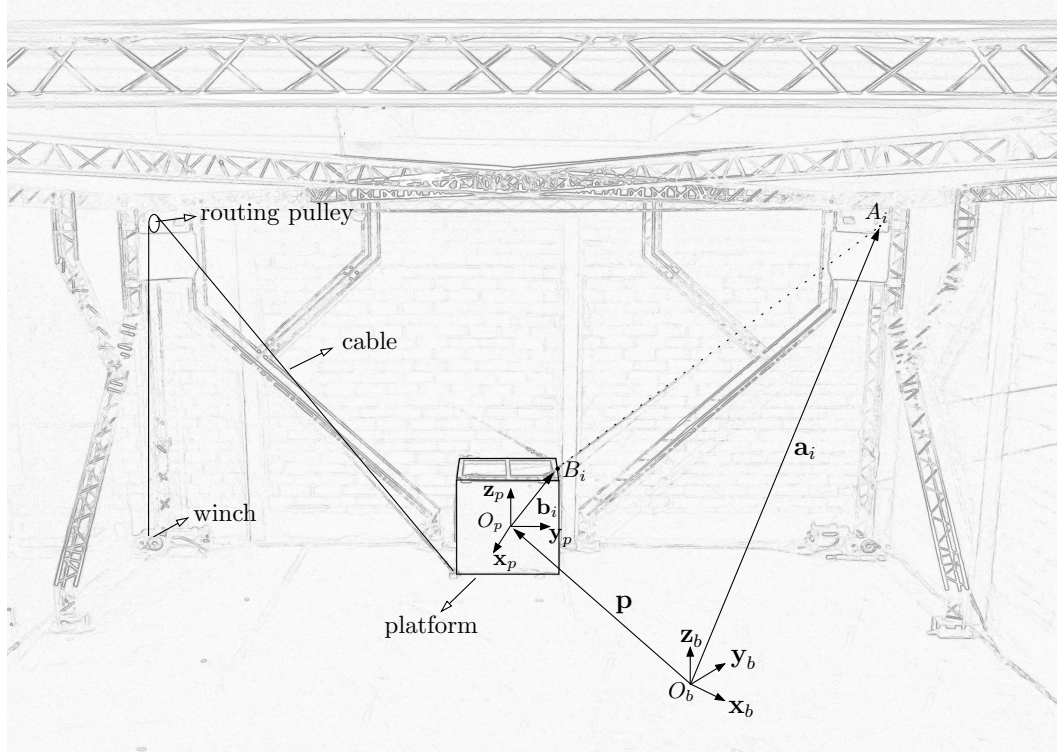


Fig. 2 Notations to describe the kinematics of a CDPR.

control the mobile platform position and orientation by appropriately adjusting the cable lengths or tensions. Besides, the wrenches (forces and moments) applied by the cables on the mobile platform depend on the cable tensions and, thereby, can also be adjusted. Force sensors may be placed at one of the routing pulleys, or in between the cables and the mobile platform, to measure the cable tensions, either for tension monitoring purposes or to regulate the cable tensions in a closed-loop control.

For example, Fig. 1 and 2 show the CDPR Co-GiRo whose mobile platform has six degrees of freedom (DOF) and is driven by eight steel cables wound on winch drums. The eight winches are secured to steel plates fixed at the bottom of the supporting structure. Each cable is routed from the winch drum to the mobile platform attachment point B_i by means of a swiveling pulley

located near the top of the supporting structure. As illustrated in Fig. 3, such an output pulley is pivoting around the vertical axis so that, when the mobile platform moves, it remains aligned with the vertical plane containing the cable.

General classification of CDPRs

Depending on the number m of cables, on their arrangement at the mobile platform and on the number n of mobile platform DOF, different types of CDPRs can be distinguished.

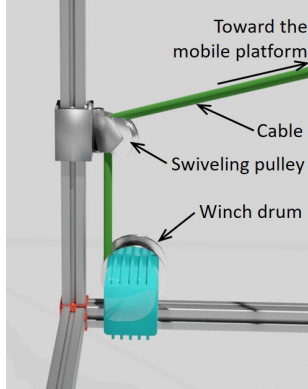


Fig. 3 Swiveling output pulley directing the cable toward the mobile platform of a CDPR.



Fig. 4 CABLAR: A fully-constrained CDPR for warehouse logistics. Image source: (Gouttefarde et al 2015b)

CDPRs having more cables than DOF: $m > n$

Fully-constrained CDPRs are a first type of CDPR having more cables than DOF. A *pose*, i.e., position and orientation, of the mobile platform of a CDPR is said to have wrench closure if, ignoring cable tension maximum limits, any wrench can be generated at the mobile platform by pulling on it with the cables (non-negative ca-

ble tensions). In such a wrench-closure pose, the mobile platform is fully constrained (completely restrained) by the cables since any wrench can be balanced by tensile cable forces. A CDPR is defined as being fully constrained when its set of wrench-closure poses, i.e., its wrench-closure workspace (Gouttefarde and Gosselin 2006), is non-empty. In practice, a CDPR is said to be fully-constrained when its wrench-closure workspace is non-empty and covers its whole prescribed workspace or, at least, a (significant) part of it. The prescribed workspace is generally defined by the CDPR designer or end-user according to the specifications of a given application. A CDPR can be fully constrained only if the number m of cables is greater than the number n of mobile platform DOF. Indeed, a well-known necessary (but not sufficient) condition for wrench-closure is $m > n$, e.g., (Kurtz and Hayward 1991). Moreover, in a fully-constrained CDPR configuration, the cables typically “surround” the mobile platform. Such a cable arrangement is necessary because the cables can pull on the mobile platform but not push on it. A fully-constrained CDPR example is shown in Fig. 4. Other examples are presented in (Kawamura and Ito 1993; Hiller et al 2005a; Pott et al 2013).

Other redundantly actuated CDPRs ($m > n$) are such that all the cable base points A_i are located above the mobile platform when the latter lies within its prescribed workspace. Hence, the net weight of the mobile platform and the payload is used to keep the cables taut. The mobile platform is suspended on the cables so that these CDPRs are often referred to as *suspended CDPRs*. An example of a 6-DOF 8-cable suspended CDPR is shown in Fig. 1 and 2. Although redundantly-actuated suspended CDPRs have more cables than DOF, wrench-closure poses do not exist for this type of CDPR because all the cable base points A_i are located above the mobile platform. For instance, a perturbation force directed upward and sufficiently large to overcome the platform weight cannot be balanced by the cable forces.

Nevertheless, the mobile platform is to some extent fully constrained when its pose is such that the cables can balance, within a certain range, forces and moments in all directions.

Note that a fully-constrained CDPR may leave its wrench-closure workspace and then operates in a suspended mode, e.g., under the action of external loads such as gravity or by simply unwinding the cables until the platform is entirely located below the lowest base point A_i . Contrary to fully-constrained CDPRs, the lower part of the workspace of suspended CDPRs is free of cables which is useful in applications where cable collisions with workers or objects on the ground may be an issue. However, because they rely on gravity to keep the cables taut, suspended CDPRs can balance a limited set of external wrenches and are also generally less stiff in horizontal directions, the actual stiffness depending on the cable arrangement and on the overall mass suspended on the cables.

Finally, when $m > n$, note that CDPRs which are neither fully-constrained nor suspended are uncommon.

is under-constrained by the cables and the CDPR is usually referred to as being under-constrained or under-actuated. The actual pose of the mobile platform of an under-constrained CDPR depends not only on the cable lengths but also on its statics or dynamics. This characteristic makes the kinematics of under-constrained CDPRs a kinetostatic problem which can be challenging to solve (Abbasnejad and Carricato 2015; Berti et al 2016; Carricato 2013; Carricato and Merlet 2013; Merlet 2014). Most under-constrained CDPRs presented in the literature are in a suspended configuration, i.e., all cable base points A_i are located above the mobile platform, but a CDPR can be under-constrained without being cable-suspended.

Besides, the mobile platform of a CDPR with $m \geq n$ is under-constrained by the cables when, out of its m cables, at least $m - n + 1$ are slack, and also that such a situation may occur in practice (Merlet 2012). As this situation is normally unintended, a proper control approach should be able to avoid cable slackness within the workspace, at least for fully-constrained CDPRs.

CDPRs having as many cables as DOF: $m = n$

When $m = n$, i.e., the number of cables is equal to the number of DOF of the mobile platform, the CDPR generally resembles an upside-down Gough-Stewart platform. A well-known 6-DOF 6-cable suspended CDPR is the NIST ROBOCRANE (Albus et al 1993). Other examples can be found in (Merlet 2014; Pusey et al 2004; Tang and Yao 2011). Compared to redundantly actuated cable-suspended CDPRs ($m > n$), the position workspace of cable-suspended CDPRs is generally smaller when $m = n$.

Under-constrained CDPRs: $m < n$

In the case $m < n$, i.e., when the number of cables is smaller than the number of DOF, the platform

Reconfigurable CDPRs

The positions of the mobile platform cable attachment points B_i and the positions of the base points A_i are generally fixed. Since such fixed-configuration CDPRs are not always suitable, reconfigurable CDPRs were proposed, e.g., to optimize performances or to avoid cable collisions in a cluttered environment. Reconfigurations can be performed in a continuous or discrete manner (Rosati et al 2011; Zanotto et al 2014; Nguyen and Gouttefarde 2014; Zhou et al 2014; Boumann et al 2020; Alamdari and Krovi 2016; Gagliardini et al 2016).

Multibody cable-driven manipulators

In most CDPRs, all cables are attached to a single rigid body, namely, the mobile platform. An

extension of this idea consists in actuating a (serial) kinematic chain by means of cables yielding a multibody (or multilink) cable-driven manipulator. Various cable routings can be used such as in (Rezazadeh and Behzadipour 2011) where each cable is connected to one and only one link of the chain, or in (Lau et al 2013; Mustafa and Agrawal 2012) where cables are allowed to pass through several links of the chain.

Other types of CDPRs

Two other examples of cable-actuated robotic systems include, on the one hand, kinematically constrained CDPRs (also called reduced-DOF CDPRs), e.g., (Dekker et al 2006), where specific cable arrangements are used to eliminate some of the mobile platform DOF (typically the rotations) and, on the other hand, hybrid actuation CDPRs where both cables and rigid links are connected to the mobile platform, e.g., (Landsberger and Sheridan 1987). In the latter, the rigid links are used either to drive the platform or to maintain tension in the cables. Besides, in (Khakpour et al 2014), cable differentials are introduced as a means to enlarge the CDPR workspace.

Advantages and disadvantages of CDPRs

The pros and cons of a CDPR may depend on a particular application context but the following general advantages and disadvantages can be formulated. On the one hand, CDPRs have many desirable characteristics such as high payload-to-weight ratio, reconfiguration capabilities, simple mechanical design, intrinsic modularity and a relatively low cost. Moreover, distinctive advantages of CDPRs are scalability, a potentially very large workspace and the ability to handle very heavy payloads. Besides, cables being lightweight, CDPRs can be designed to be

extremely fast. On the other hand, because of cable flexibility and compliance, the positioning accuracy, stiffness and vibration of CDPRs are common issues. Additionally, the cables can pull but not push on the mobile platform. This unidirectional nature of cable actuation requires specific attention in design, path planning and control. Besides, issues related to cable collisions may also be a concern.

Key Research Findings

Basic modeling, design and control techniques of CDPRs are summarized in this section.

Modeling

Kinematics

Provided that the cable deformation due to its mass and elasticity is neglected and also that all cables are taut, the length l_i of the straight line segment A_iB_i ,

$$l_i = \left\| \overrightarrow{B_iA_i} \right\| = \left\| \mathbf{a}_i - \mathbf{p} - \mathbf{Q}\mathbf{b}_i \right\|, \quad i = 1, 2, \dots, m. \quad (1)$$

corresponds to the cable length between the base point A_i and the the platform attachment point B_i (Bruckmann et al 2008a). The notations used in (1) are illustrated in Fig. 2. The rotation matrix \mathbf{Q} defines the orientation of the mobile platform. Then, (1) is the closed-form solution to the *inverse kinematics* (IK) which determines the cable lengths being given the mobile platform position \mathbf{p} and orientation \mathbf{Q} . While the inverse kinematics is straightforward, the determination of the platform position and orientation being given the cable lengths, i.e., the *direct kinematics*, is significantly more difficult and can possess numerous solutions, e.g., (Pott 2018; Berti et al 2016).

Cable tensions and wrench matrix

The relationship between the cable tensions and the wrench \mathbf{w}_c —force and moment—applied by the cables on the platform can be written as (Roberts et al 1998; Hiller et al 2005b)

$$\mathbf{W}\mathbf{t} = \mathbf{w}_c \quad (2)$$

where

$$\mathbf{t} = [\mathbf{t}_1 \ \mathbf{t}_2 \ \dots \ \mathbf{t}_m]^T \quad (3)$$

is the cable tension vector and the $n \times m$ matrix \mathbf{W} is the *wrench matrix*. \mathbf{W} is also often called the *structure matrix*. The mobile platform static equilibrium equations are then:

$$\mathbf{w}_c + \mathbf{w}_e = \mathbf{W}\mathbf{t} + \mathbf{w}_e = \mathbf{0}, \quad \mathbf{t} \geq \mathbf{0} \quad (4)$$

where \mathbf{w}_c is wrench applied by the cables on the mobile platform and \mathbf{w}_e is the sum of the other wrenches acting on the platform, including its weight. The inequality $\mathbf{t} \geq \mathbf{0}$ means that each element of \mathbf{t} must be non-negative. This notation is also used in the following.

Differential kinematics

The differential kinematic equations:

$$\dot{\mathbf{i}} = \mathbf{J} \begin{bmatrix} \dot{\mathbf{p}} \\ \dot{\boldsymbol{\omega}} \end{bmatrix} \quad (5)$$

provides the relationship between, on the one hand, the mobile platform linear velocity vector $\dot{\mathbf{p}}$ and angular velocity vector $\dot{\boldsymbol{\omega}}$, and, on the other hand, the vector $\dot{\mathbf{i}} = [\dot{i}_1, \dot{i}_2, \dots, \dot{i}_m]^T$ of the cable length time derivatives. The principle of virtual work can be used to show that $\mathbf{J} = -\mathbf{W}^T$.

Dynamics

When the cable mass is neglected, the Newton-Euler equations of the mobile platform and the dynamic equations of the winches can be readily

assembled to yield the CDPR dynamic model. This model is identical to that of a standard robotic manipulator. When the cable mass is not neglected, the dynamic modeling of the CDPR is significantly more difficult to obtain (e.g. (Du and Agrawal 2015)).

Stiffness and Vibrations

Several previous works presented stiffness analyses of CDPRs, e.g. (Behzadipour and Khajepour 2006; Surdilovich et al 2013), where the cable tension is generally considered to be proportional to the cable extension (linear elasticity). Based on this stiffness modeling, CDPR mobile platform vibrations caused by cable flexibility can be analyzed, e.g. (Diao and Ma 2009). Besides, vibration suppression and control methodologies were also proposed, e.g. (Lesellier et al 2018; Begey et al 2019; Rushton et al 2019; Baklouti et al 2019; Cuvillon et al 2020).

Cable modeling and pulley kinematics

When the cable mass and elasticity are taken into account, the modeling of a CDPR can be significantly more complex. For instance, the kinematics and statics of CDPRs with cables modeled by means of the well-known elastic catenary (Irvine 1981) can be found in (Kozak et al 2006; Gouttefarde et al 2012; Arsenault 2013; Merlet 2016). Moreover, issues related to possibly slack cables are solved in (Berti et al 2016; Merlet 2014), and the dynamics or vibration analysis of CDPRs with cables of non-negligible mass are discussed in (Nahon et al 2002; Caverly and Forbes 2014; Yuan et al 2015; Du and Agrawal 2015; Yuan et al 2017). Besides, especially for large CDPRs, the output pulley kinematics may be non negligible and methods presented, e.g., in (Bruckmann et al 2008a; Gouttefarde et al 2014; Pott 2018; Idà et al 2019), can be used to take a non-zero pulley diameter into account in the CDPR modeling.

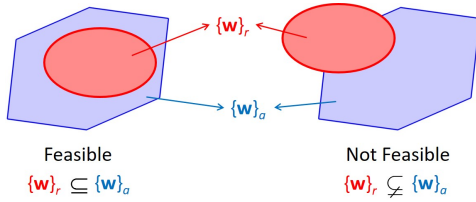


Fig. 5 Illustration of wrench feasibility.

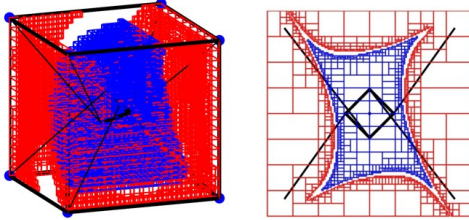


Fig. 6 The WFW of a spatial 6-DOF CDPR (left) and of a planar 3-DOF CDPR (right) determined by means of interval analysis for a constant orientation of the mobile platform (Gouttefarde et al 2011).

Feasible Cable Tensions and Workspace Definitions

Since cables can pull but not push, all components of the cable tension vector \mathbf{t} must be non-negative, i.e., $\mathbf{t} \geq \mathbf{0}$, since otherwise some cables are slack. In addition, to limit cable sagging due to low tension, strictly positive values are often used, i.e., $\mathbf{t} \geq \mathbf{t}_{\min}$ where $\mathbf{t}_{\min} > \mathbf{0}$ is the minimum tension vector. Moreover, to account for the capabilities and limitations of the CDPR cables, winches, supports, etc., \mathbf{t} must satisfy $\mathbf{t} \leq \mathbf{t}_{\max}$ where \mathbf{t}_{\max} is the vector of maximum allowed tensions ($\mathbf{t}_{\max} > \mathbf{t}_{\min}$).

On the one hand, the available wrench set $\{\mathbf{w}\}_a$ is the set of wrenches that can be generated at the mobile platform by the cables. $\{\mathbf{w}\}_a$ is known to be a particular polytope called a zonotope (Bouchard et al 2010; Gouttefarde and Krut 2010). On the other hand, the *required wrench set* $\{\mathbf{w}\}_r$ is defined as the set of wrenches \mathbf{w}_c that the cables must be able to generate at the mobile platform. The exact definition of $\{\mathbf{w}\}_r$ depends on the task(s) to be accomplished by the

CDPR and thus of a particular application context. A given mobile platform pose is said to be *wrench feasible* when the required wrench set $\{\mathbf{w}\}_r$ is entirely contained within the available wrench set $\{\mathbf{w}\}_a$ as illustrated in Fig. 5.

The Wrench-Feasible Workspace (WFW) (Bosscher et al 2006) is then defined as the set of wrench-feasible poses. The WFW can be determined by various methods (Gouttefarde et al 2011) such as illustrated in Fig. 6. Since cables of large lengths can be used, the workspace of a CDPR is generally not limited by the cable lengths but by wrench-feasibility issues. The size and shape of the WFW is thus an important property of a CDPR, being given that a large WFW is generally desired. The Static Workspace (SW) is a particular case of the WFW where the required wrench set $\{\mathbf{w}\}_r$ is reduced to the opposite of the wrench induced by the mobile platform weight. Another important workspace for CDPRs is the Wrench-Closure Workspace (WCW) (Gouttefarde and Gosselin 2006; Abbasnejad et al 2018), also known as force-closure or controllable workspace. The WCW is the set of poses at which the mobile platform is fully constrained by the cables. Other workspace definitions include dynamic workspaces (Barrette and Gosselin 2005; Eden et al 2016) and the twist-feasible workspace (Lessanibahri et al 2017). A detailed discussion on CDPR workspace definitions and computation can notably be found in (Pott 2018) (Chapter 5).

Cable Collisions

Besides wrench feasibility, another issue that may limit the actual workspace of CDPRs is cable collisions. A cable may collide with another cable, with the mobile platform or with objects in the CDPR environment. Examples of specific studies on cable collisions for CDPRs include (Merlet 2004; Perreault et al 2010; Zhang et al 2020). Furthermore, CDPRs might be

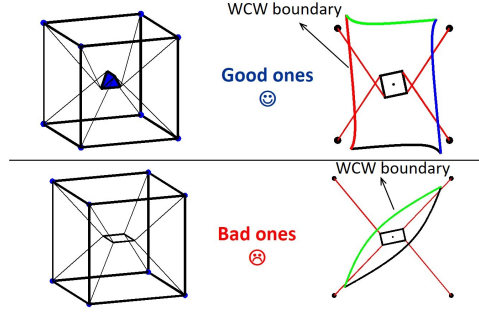


Fig. 7 The right part of the figure shows two 3-DOF CDPR cable configurations together with their constant-orientation WCW. The left part shows two 6-DOF CDPR cable configurations (WCW not shown for clarity). The two CDPRs in the upper part of the figure have a large WCW while, on the contrary, the two CDPRs in the lower part have a limited WCW.

enhanced by actively allowing cable collisions (Wischnitzer et al 2008).

Design

The design of a CDPR includes the design of its winches, the routing pulleys, the supporting structure, the mobile platform and the means to secure the cables to the mobile platform. The choice of the cables, the drives, the control system and sensors are also dealt with at the design stage. These various choices and designs can be done according to standards and by means of state-of-the-art methods and technologies, e.g., those related to lifting appliances.

Nevertheless, a fundamental problem specific to CDPRs and directly linked to wrench feasibility is the synthesis of the CDPR geometry. The latter can be divided in two main steps. The first one consists in selecting the CDPR type (fully-constrained, suspended, under-constrained) and choosing the number of cables. The second one consists in designing the cable configuration, i.e., determining the positions of the cable attachment points B_i , the positions of the cable exit points A_i , and the arrangement of the cables

between these points. The cable configuration should be carefully designed since it influences significantly the CDPR performances. Such as illustrated in Fig. 7, the size and shape of the workspace are notably sensitive to the cable configuration. In some previous works where cable configurations are introduced, e.g., (Kawamura et al 1995; Gallina and Rosati 2002; Hiller et al 2005b; Pott et al 2013), the cable configuration process is not discussed. On the contrary, specific methodologies often based on optimization techniques have been presented, e.g., in (Tadokoro et al 1996; Perreault and Gosselin 2008; Zhou et al 2012; Azizian and Cardou 2012; Gouttefarde et al 2015a; Hussein et al 2021).

Besides, design optimization typically needs to take into account multiple criteria and constraints to reflect specific application requirements such as workspace, desired platform dynamics and stiffness, e.g., as presented in (Reichert and Bruckmann 2019) for the warehousing application shown in Fig. 4.

Cable Tension Calculation

For an n -DOF CDPR actuated by $m \geq n$ cables, the resolution of actuation redundancy generally consists in calculating feasible cable tensions \mathbf{t} along a prescribed trajectory. Such feasible cable tensions can be calculated by solving a constrained optimization problem where, for instance, the p -norm of the cable tension vector, $\|\mathbf{t}\|_p$, is minimized. The value $p = 2$ is most often selected (Hassan and Khajepour 2011; Taghirad and Bedoustani 2011) but other values can be used, e.g. $p = 4$ (Gosselin and Grenier 2011), being noted that $p = 1$ and $p = \infty$ may lead to discontinuous cable tensions along the trajectory, e.g. (Oh and Agrawal 2005). Efficient methods working in part of the CDPR workspace (Pott 2013) or for particular cases, e.g. for $m = n + 2$ (Gouttefarde et al 2015b), have also been pro-

posed in order to ensure real-time computation capabilities (Mikelsons et al 2008).

Control Schemes

Various control schemes and strategies can be used for position or force control of CDPRs, e.g., (Fang et al 2004; Oh and Agrawal 2005; Kino et al 2007; Lambert et al 2007; Kraus et al 2014; Khosravi and Taghirad 2014; Fortin-Côté et al 2014; Korayem et al 2017).

For instance, the position control scheme shown in Fig. 8 is presented in (Lamaury et al 2013). It can be implemented by means of CDPR kinematic and dynamic modeling presented in the previous sections and can be used to control redundantly actuated CDPRs since it includes a tension distribution block. This control scheme was notably used to control large suspended CDPRs displacing heavy payloads (ANR Project CoGiRo 2012).

The only measurements used in the control scheme of Fig. 8 are actuator angular positions and velocities (joint-space controller), which are generally readily available. However, since the control scheme has no feedback on the actual pose of the mobile platform, the positioning accuracy and trajectory tracking capabilities may be limited. Calibration techniques, e.g., (Wang et al 2017; Lau 2017), and pose measurements and control in Cartesian space, e.g., (Begey et al 2019; Dallej et al 2019; Merlet 2017; Garant et al 2017; Zake et al 2019), were thus investigated.

Examples of Applications

Applications of CDPRs include, but are not limited to, mobile aerial camera systems (SKY-CAM 2021), lifting equipment and robotic cranes (TensileTruss 2021; CRANEBOT 2021; FREERIDER 2021), haptic interfaces and force feedback devices (Ishii and Sato 1994; Haption

2021), giant telescopes (R. Nan et al 2011; Hypertelescope 2021), motion simulators (CableRobot Simulator 2015; TAIT 2016), drawing and 3D printing (Scribit 2021; Hangprinter 2016), maintenance systems (Aerones 2020), and training and rehabilitation (The FLOAT 2021). Several of these applications notably benefit from CDPR scalability and potentially very large workspace.

Current and Future Research Directions and Applications

New and possible future applications of CDPRs may be found in the construction sector, e.g. facade operations (Hephaestus 2020), automated masonry construction (Bruckmann et al 2017), large-scale 3D printing of concrete or other material (Izard et al 2017; HINDCON 2019), in inspection and maintenance for the displacement and positioning of sensors, in the marine sector including marine litter removal (MAELSTROM 2021) and underwater construction, in the renewable-energy industry (MOSAIC 2021), in the entertainment industry, and in agriculture (Sun et al 2019).

These applications should motivate developments related to CDPR design for increased reliability and lower cost, modeling and sensing for improved positioning accuracy and trajectory tracking, design and control for better safety and physical interactions, as well as on-board devices and reconfigurability to enable more challenging requirements such as complex accessibility, cluttered workspace, or large orientation ranges.

Cross-References

Parallel Robots: Architecture, Modeling, and Design

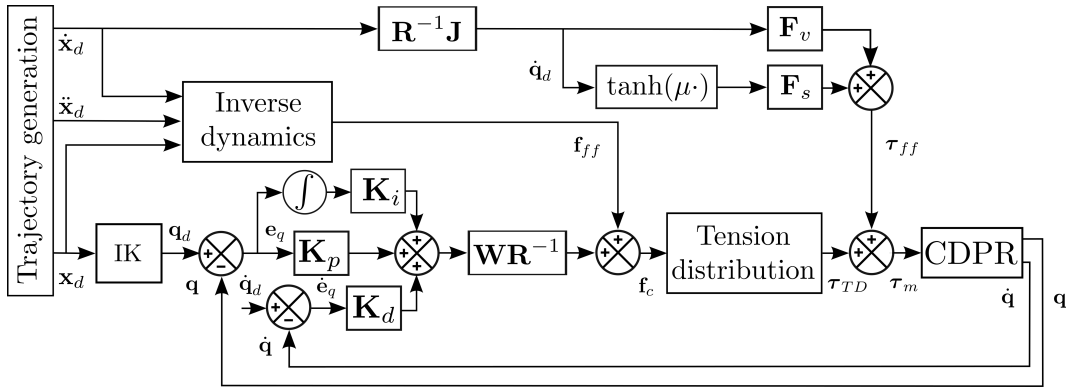


Fig. 8 Control scheme using feedforward terms, a PID joint-space controller and a tension distribution algorithm. \mathbf{R} is a diagonal matrix containing the winding ratios of the winches. \mathbf{F}_s and \mathbf{F}_v denote the dry and viscous friction in the winches. \mathbf{K}_p , \mathbf{K}_d and \mathbf{K}_i are diagonal positive definite gain matrices of a PID controller.

Kinematics

Dynamics of Parallel Robots

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