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Cable-driven parallel mechanisms: state of the art and perspectives

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Abstract
This paper presents a review of the state of the art in the area of cable-driven parallel mechanisms. The basic kinematic architecture of cable-driven parallel mechanisms is first recalled and the associated kinematic and static model is briefly exposed. Fundamental problems are formulated, including the definition of the wrench matrix, the wrench-closure workspace and the wrench-feasible workspace. Advances that have been made in the determination of such workspaces are reported. The dynamics and control of cable-driven parallel mechanisms are then considered, first for fully constrained cable-driven parallel mechanisms and secondly for cable-suspended parallel mechanisms. Calibration and identification issues are also addressed and various alternative architectures of cable-driven parallel mechanisms are reported. Finally, applications are considered and open issues are mentioned.

Key words : Cable-driven mechanisms, Cable-driven parallel mechanisms, Wire-driven robots, Cable-driven robots, Cable-suspended robots

1. Introduction

Parallel mechanisms have been part of the robotics landscape for several decades. Their mechanical properties make them most appropriate for tasks that require large payload to weight ratios or very demanding dynamic trajectories (e.g. high-speed robots) [1, 2]. It is remarkable that many of the most successful designs of parallel mechanisms involve some links that are subjected to only tensile and compressive loads. The most common example of this principle is the Gough-Stewart-Cappel platform [3–6], which involves six legs mounted on Hooke joints and spherical joints at their ends. The Gough-Stewart-Cappel platform is used in numerous applications and is considered by many as the archetypal parallel mechanism. It is well-known in structural engineering that designs involving links that are subjected to only tension and compression constitute an optimal use of materials. Such designs lead to lightweight components and very large payload to mass ratios.

Given the above observations related to parallel mechanisms in general, it is only natural to extend the reasoning one step further and consider parallel mechanisms that involve members loaded solely in tension, thereby leading to the concept of cable-driven parallel mechanisms — also referred to as wire-driven parallel mechanisms or tendon-driven parallel mechanisms — introduced in [7, 8]. Cables are flexible members that can support very large tensile loads per unit weight. Compared to struts, they represent an even more effective use of materials which explains why they have been employed in construction and in machines since antiquity [9]. Cable-driven parallel mechanisms combine the principles of parallel mechanisms with the properties of cables, leading to potentially very effective mechanisms. Moreover, in addition to providing very high load transmission capabilities, cables can be wound on spools — as opposed to struts and prismatic joints, which must be retracted — , thereby providing potentially very large workspaces. Nevertheless, several issues arise in the analysis, design, control and practical implementation of cable-driven parallel mechanisms and many of these issues have been addressed by researchers over the last two decades.

This paper aims to provide an overview of the research that has been conducted in the area of cable-driven parallel mechanisms until now. In Section 2, the geometric, kinematic and static problems are defined. Solutions to the main problems are provided and the different workspace concepts are introduced. Section 3 deals with the dynamic modelling

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and control, which is another important issue, especially in high-speed robots. Section 4 discusses the use of other architectures of cable-driven mechanisms, including tensegrity-based cable-driven parallel mechanisms. Finally, Section 5 discusses a few applications of cable-driven parallel mechanisms while Section 6 provides concluding remarks and some perspective.

2. Geometric, kinematic and static analysis

2.1. Modelling and notation

The most common architecture of a cable-driven parallel mechanism (CDPM) consists of a single rigid body platform to which (m) cables are attached. Each of the cables is, at its other end, connected to a spool mounted on the ground link and which is used to wind or unwind the cable. By controlling the extension of the cables, the pose — position and orientation — of the platform can be controlled. An example of a fully constrained planar 4-cable 3-dof CDPM is shown in Fig. 1(a) and an example of a spatial 6-cable cable suspended parallel mechanism is shown in Fig. 1(b). Many other architectures of cable-driven mechanisms are obviously possible and will be considered in Section 4 of this paper. However, because of its importance in the literature and its archetypal nature, the basic architecture described above is first considered.

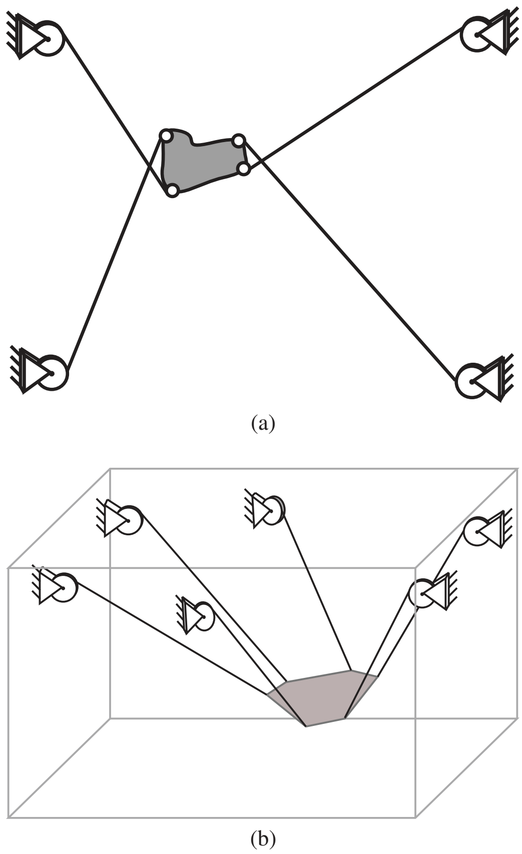

Fig. 1 Schematic representation of (a) a fully constrained planar 4-cable 3-dof CDPM and (b) a spatial 6-dof 6-cable cable suspended parallel mechanism.

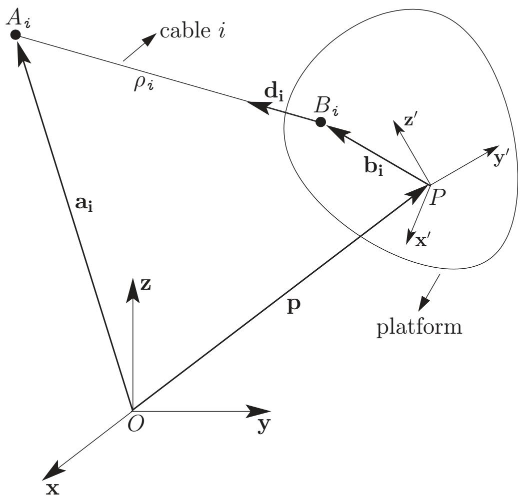

Fig. 2 Kinematic modelling of a CDPM.

As illustrated in Figure 2, a fixed reference frame $(O, \mathbf{x}, \mathbf{y}, \mathbf{z})$ is attached to the base of a CDPM and is referred to as the base frame, while a moving reference frame $(P, \mathbf{x}', \mathbf{y}', \mathbf{z}')$ is attached to the mobile platform, where P is the reference point of the platform to be positioned by the mechanism. The orientation of the moving frame with respect to the base frame represents the orientation of the mobile platform with respect to the base of the mechanism and is given by rotation matrix $\mathbf{Q}$. Point A_i is the point at which the ith cable ($i = 1, 2, \ldots, m$) winds around its reel, and is assumed to be fixed relative to the base. Similarly, the ith cable is attached at point B_i on the mobile platform and this attachment point is assumed to be fixed relative to the mobile platform. In most works, the ith cable is assumed to be taut between points A_i and B_i and therefore considered a straight segment (A_iB_i), with its length denoted ρ_i. The attachment points A_i and B_i are

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generally modelled as spherical joints. Then, $\mathbf{a}_i$ and $\mathbf{b}_i$ are respectively defined as the vector connecting point O to point A_i and the vector connecting point P of the platform to point B_i, both vectors being expressed in the base frame. The position $\mathbf{p}$ of the mobile platform is given by the vector connecting point O to point P, expressed in the base frame. Also, the unit vector along cable i, pointing from B_i to A_i is noted $\mathbf{d}_i$ and can be calculated using

$$\mathbf{d}_i = (\mathbf{a}_i - \mathbf{b}_i - \mathbf{p})/\rho_i \tag{1}$$

The above basic geometric model was established in the early works on CDPM including for instance in [10], [11] and [12]. It is pointed out that the above analysis is purely geometric and nothing was said concerning the ability of the mechanism to maintain tension in the cables. This issue is addressed in the next subsection using the concept of wrench matrix.

2.2. Wrench matrix

The statics of CDPMs is now considered, in order to introduce the unilateral tension constraint induced by the cables. When tension is applied, cable i exerts at point B_i a pure force $t_i\mathbf{d}_i$ on the mobile platform, where t_i is the magnitude of the tension in the cable. Since cables can only be loaded in tension, t_i is always nonnegative. This pure force generates a moment $\mathbf{b}_i \times t_i\mathbf{d}_i$ at the reference point P of the mobile platform and the wrench (force/moment pair) applied at P by the ith cable is $t_i\mathbf{w}_i$, with wrench $\mathbf{w}_i$ defined as

$$\mathbf{w}_i = \begin{bmatrix} \mathbf{d}_i \\ \mathbf{b}_i \times \mathbf{d}_i \end{bmatrix}. \tag{2}$$

If $\mathbf{w}_p$ denotes the total wrench applied at point P by the m cables of the mechanism, the relationship between the tensions t_i in the cables and the wrench $\mathbf{w}_p$ can be written in matrix form as

$$\mathbf{Wt} = \mathbf{w}_p \tag{3}$$

with

$$\mathbf{W} = \begin{bmatrix} \mathbf{w}_1 & \mathbf{w}_2 & \dots & \mathbf{w}_m \end{bmatrix} \tag{4}$$

and

$$\mathbf{t} = \begin{bmatrix} t_1 & t_2 & \dots & t_m \end{bmatrix}^T \tag{5}$$

where $\mathbf{t}$ is the vector of cable tensions and $\mathbf{W}$ the $6 \times m$ pose dependent wrench matrix.

Equation (3) is a key relationship in the kinematics, statics and dynamics of CDPMs. Indeed, most of the analytical results proposed in the literature are based on the latter equation and its implications. A variety of situations can be covered by properly defining vector $\mathbf{w}_p$. For instance, under static conditions, the platform wrench $\mathbf{w}_p$ represents the wrench induced by gravity on the platform. If dynamics are considered, then vector $\mathbf{w}_p$ represents the wrench induced by gravity plus the inertial effects associated with the platform motion. In haptics applications, wrench $\mathbf{w}_p$ also includes the external forces and moments applied to the platform by the user.

2.3. Workspaces and force capabilities

Using eq.(3), researchers have addressed fundamental problems related to the analysis, design and control of parallel mechanisms. Among other properties, several studies have targeted the determination of the workspace of CDPMs for a set of given geometric parameters. Several definitions of the workspace have been proposed. One particularly relevant concept is that of wrench closure workspace, which can be defined as the *set of poses of the platform for which any wrench applied on the platform* $\mathbf{w}_p$ *can be balanced by a set of positive cable tensions*. Based on eq.(3), the wrench closure workspace can be defined mathematically as the set of platform poses for which, for any wrench applied on the platform $\mathbf{w}_p$, there exists at least one vector of cable tensions, $\mathbf{t} \in \mathbb{R}^m$ such that $\mathbf{Wt} = \mathbf{w}_p$ and $\mathbf{t} \geq \mathbf{0}$, where $\geq$ denotes the componentwise inequality. In other words, a pose belongs to the wrench closure workspace if $\mathrm{rank}(\mathbf{W}) = 6$ and $\exists \mathbf{z} \in \mathcal{N}(\mathbf{W})$ such that $\mathbf{z} > \mathbf{0}$, where $\mathcal{N}(\mathbf{W})$ stands for the nullspace of $\mathbf{W}$ [13]. Finding the conditions for the existence of such a vector in the nullspace of the wrench matrix is a difficult problem, especially if the dimension of the nullspace is greater than 1, i.e., if the number of cables exceeds the dimension of the Cartesian workspace by at least two. When the dimension of the nullspace is equal to one, algebraic derivations can be used [13]. Also, planar mechanisms lead

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to tracktable results even if the dimension of the nullspace is greater than one [14]. However, for more general cases, other techniques must be resorted to. In [15], Stiemke's theorem is used to provide an effective way of determining the boundaries of the wrench closure workspace. This approach leads itself to other numerical implementations using techniques such as interval analysis [16] and others [17].

It has also been observed by several researchers that the wrench closure workspace is a rather restrictive property and that it is not necessarily the best design criterion. Indeed, when information on the tasks to be performed by a robot is available, it may be preferable to use the wrench feasible workspace, which is defined as the set of poses in which the cables can balance any platform wrench $\mathbf{w}_p$ belonging to a set of prescribed wrenches [18–22]. Using this approach, the design of a CDPM can be better tailored to a given set of tasks.

Other workspace definitions can be found in the literature, such as the dynamic workspace [23] or the force closure workspace [24]. In most cases, a mathematical description of the boundaries of the workspaces can be obtained for simple architectures but it is difficult to extend such results to more general cases, which requires more advanced methods [16].

Assuming that a CDPM is at a feasible pose, it is also of interest to determine its force capabilities for given actuator limits [19, 25, 26]. In other words, determine the set of wrenches that the CDPM is capable of applying to its environment via its platform given its geometry and the limitations of its actuators or transmissions. This problem can be tackled based on the mapping of the cable force vector onto the platform wrench space, using eq.(3). As pointed out in [25], the result is a zonotope in the platform force space, which provides a very effective description of the force capabilities of a given mechanism in a given pose. A zonotope is a polytope composed of pairs of parallel faces.

Although some CDPMs have been built using cables distributed 'around' the moving platform in order to fully constrain it, others have been built using the suspension paradigm and are often referred to as cable-suspended parallel mechanisms (CSPMs). In fact, one of the first CDPMs built, the NIST Robocrane [10], was based on this approach, which was also used in [27, 28] and in many other designs. Cable-suspended parallel mechanisms are characterized by the use of gravity — the weight of the platform — to maintain the cables in tension. In fact, in CSPMs, gravity is sometimes considered as an additional cable that always acts downwards on the moving platform. CSPMs do not generally have a wrench closure workspace. However, they possess the advantage of not requiring redundant actuation since the number of cables does not have to exceed the number of degrees of freedom. However, their acceleration capabilities are limited since the downwards vertical acceleration is produced solely by gravity. CSPMs can also be underactuated, leading to pendulum-type mechanisms whose degrees of freedom are not all controlled [29–33]. Underactuated CSPMs also raise the interesting issue of the determination of their static pose for a given geometry of the attachment points and given cable lengths. This problem involves geometric and static conditions and leads to a set of very complex algebraic equations. A simplified case was solved in [34] for applications in cooperating flying vehicles. The general case of a body suspended on three cables was treated in [35], where the complexity of the problem is fully revealed. Indeed, in the latter reference, the problem is shown to be equivalent to finding the roots of a univariate polynomial equation of degree 156. The case with four cables is studied in [36] and leads to a polynomial equation of degree 216. The three-cable problem is also addressed in [37] using interval analysis. In [38], the determination of the static pose of a CSPM with an arbitrary number of cables was formulated as an optimization problem having well-defined properties, which was solved globally to yield the equilibrium with the lowest potential energy, the others being left unfound. An example involving a platform suspended on 1000 cables is solved in the paper to illustrate the generality and the effectiveness of the method.

Most of the above mentioned references deal mainly with the analysis problems, i.e., the determination of the workspaces, force capabilities or other properties of given architectures of mechanisms. The synthesis problem, on the other hand, received much less attention. In fact, most of the prototypes that have been built are based mainly on the intuition of the designers, with nevertheless justifications for the design choices [39, 40]. In [41, 42], the synthesis of planar CDPMs was formulated mathematically using optimization formalisms. In [43], numerical optimization was used to synthesize CDPMs while ensuring wrench capabilities and avoiding mechanical interferences.

Analysis and synthesis problems related to CDPMs also include the determination of potential interferences between cables or between cables and other bodies. Indeed, CDPMs are by nature prone to mechanical interferences since cables define straight lines between the fixed base and the moving platform. It is therefore apparent that intersections between the lines easily occur when the platform undergoes translations or rotations. In [44], the determination of the interference-free regions of the workspace is addressed. A simplified approach was proposed in [45], leading to a very efficient algorithm for the determination of the workspace regions that are free from interferences for a given orientation of the platform. As opposed to parallel mechanisms based on rigid links, CDPMs may also be able to tolerate some cable interferences, due to the flexibility of the latter. In [46], this approach was taken in order to handle the potential interferences that may occur

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in a locomotion interface based on two adjacent platforms each driven by eight cables.

3. Dynamics and control

3.1. Fully constrained CDPMs

As mentioned above, CDPMs have several advantages over rigid-link mechanisms. One of these advantages is the reduced weight of the components. Therefore, when the platform is fully constrained, CDPMs are very appropriate for high-speed and high-performance applications, as evidenced by the early design proposed in [39].

In high-speed applications, the inertial effects of the moving platform become significant and must be considered in eq.(3), i.e., they must be included in the computation of $\mathbf{w}_p$. If the mass of the cables is neglected — which is the case in most studies on CDPMs — , the computation of the inertial effects is simple since it amounts to applying the Newton-Euler equations on a single moving rigid body on which pure forces (directed along the cables) are exerted. Nevertheless, similarly to what was mentioned for the static case, if the number of cables exceeds the number of degrees of freedom of the platform, eq.(3) leads to an overdetermined system of equations and in general there exist infinitely many solutions for the cable tensions. This allows the use of optimization in order to generate a proper distribution of the cable tensions for given platform trajectories and avoid large internal forces. Possible approaches to generate an optimal solution of eq.(3) include linear programming [47, 48] and quadratic programming [49, 50]. Although linear programming is a simple and systematic procedure, it cannot guarantee the continuity of the solution, which may lead to instabilities. On the other hand, quadratic programming provides continuity but at the expense of less predictable computation time. The situation becomes more complex when the number of cables is increased. In [51], the authors use Dykstra's alternating-projection algorithm to find the minimum-norm solution. This technique is also computationally intensive. In [52, 53], real-time continuous algorithms are proposed. In [54], a fast tension distribution algorithm is proposed based on Mikelsons' barycentre approach for systems in which the number of cables is equal to $n + 2$, where n is the degree of freedom of the platform. In practice, the determination of the tension distribution in real-time is of great interest.

Actuation redundancy also makes the control and implementation of CDPMs more complex. Indeed, controlling the distribution of the forces in the cables requires that these forces be monitored, which may not be trivial in practice. Several means of measuring the tension in the cables have been proposed in the literature [55]. An alternative approach consists in relying on the compliance of the cables and attachments to produce a proper force distribution [56]. This approach simplifies the control but limits the force control capabilities. Given the dynamics of a CDPM, several control strategies have been proposed in the literature. In [57], a controller that deals with cable tensions was first proposed. The computation of the optimal solution is performed off-line and the solution is used by the real-time controller. In [58], a fuzzy controller is proposed while [59] uses a backstepping approach to control a 3-dof CDPM. Sliding mode control was used in [60] and the stability of the approach is demonstrated using Lyapunov's second principle. In [61,62], the flexibility of the cables is considered in the development of a complex dynamic model that could be used for control. In [63], the use of an H_∞ controller is proposed in order to alleviate the effects of the flexibility of the cables in a CDPM. Similar or other techniques are also proposed, for instance in [64].

3.2. Cable-suspended parallel mechanisms

In CSPMs, the dynamics and control challenge is different. Indeed, in such mechanisms, there generally exists no configuration in which internal forces can be generated, i.e., these systems are not tensionable [65]. In [66], the positive tension constraints are formulated as a set of linear inequalities and a technique is proposed to plan trajectories such that these constraints are always satisfied. The tension distribution problem has also been studied in the context of very large CSPMs [67, 68].

In [69, 70], a technique is proposed to design dynamic trajectories that can guarantee that the cables remain tensioned. This technique, which is validated experimentally, reveals the existence of special frequencies for which periodic trajectories with theoretically unbounded amplitudes are feasible.

The dynamics of underactuated (pendulum-like) CSPMs has also been addressed in the literature. The concept was proposed in [29] and further developed in [30] and [33]. In [32], an architecture is proposed that is especially designed to provide differential flatness and integrability, thereby simplifying the control. Since the trajectory of underactuated CSPMs cannot be fully controlled, the trajectory planning and control techniques proposed in the literature focus on the prescription of target configurations to be reached. One of the key concepts is then the design of input functions that

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can either inject or extract energy from the underactuated mechanism, similarly to other engineering systems such as the famous censer (Botafumeiro) studied in [71].

Finally, some studies consider the mass of the cables as non-negligeable, mainly for applications in which very long cables are used [58, 72–76]. It was shown that the solution of the inverse kinematic problem of CDPMs while considering the mass of the cables requires the numerical solution of a set of nonlinear equations. Also, the dynamic model of a CDPM including cable mass, cable bending and cable torsional stiffness is proposed in [73]. The resolution of such models is computationally intensive and cannot be used in real-time controllers. However, the models are very useful for dynamic simulation and design.

3.3. Identification and calibration

The dynamic modelling and control strategies described in the preceding subsections require the knowledge of the kinematic and inertial parameters of the CDPMs. However, these parameters are often unknown or only estimated. Moreover, additional parameters such as friction characteristics, dynamic response of transmission components and others are unknown and often not even modelled. Therefore, calibration and identification must be used in order to ensure proper behaviour and kinematic accuracy. Calibration techniques tailored to CDPMs are proposed in [77–82]. Additionally, it was shown in [83] that a more accurate kinematic model — considering pulleys — can be implemented in real-time. In [84, 85], identification is addressed, including issues such as the determination of the optimal number of measurement points and the choice of identification reference frames. CDPMs are often said to be ideal candidates for portable reconfigurable systems that can be rapidly installed and operated. In such applications, calibration is key. Therefore, self-calibrating CDPMs have been proposed in the literature, for instance in [78].

4. Other architectures of cable-driven parallel mechanisms

In addition to the basic architecture described in Section 2 in which a moving platform is connected to the base frame via a set of cables wound on actuated spools, several other architectures have been proposed in the literature. In [86], the moving platform to which the cables are attached is mounted on a spherical joint, leading to a 3-dof spherical mechanism. This type of arrangement is also used in other robots where a constraining link is driven by cables such as in [87]. In [50], reduced degree-of-freedom CDPMs are designed by replacing some of the rigid links of parallel robots (such as the Delta robot) by cables and by introducing additional compressive passive links. In [88], a cable loop is used to drive a passive Cartesian robot. Using a similar approach, cable-loop-driven parallel mechanisms are proposed in [89] using a variety of routings, some of which lead to decoupled actuation. In some proposed designs, cable loops are used without requiring Cartesian passive links by using extension springs that compensate for the changes of length of the loops [90, 91]. Cable loops are also used in the design of the Marionet robot [92] which eliminates the need for spools and makes it possible to produce very large speeds.

Articulated mechanisms can also be driven by cables attached to the links and driven by actuators mounted on the base. Many routings are possible and analyzing general mechanisms built using this principle is challenging. In [93], reciprocal screw theory is used to propose tools that allow the modelling and analysis of arbitrary serial chains driven by cables routed along the chain. The topological modelling was further generalised in [94] using the concept of cable routing matrix. Based on these tools, the analysis, synthesis and design of cable-driven exoskeletons was presented in [95–98].

Finally, cables (tendons) are also used in many robotic hands to drive the opening and closing motions of fingers but this application is outside the scope of this paper.

5. Applications

Given their attractive properties, CDPMs lead themselves to many applications. It is remarkable that the first commercial application of CDPMs [99], known as the Skycam or Cablecam, preceded essentially all the research work mentioned in this paper. In this application, a large CDPM is used to move a camera above a stadium field for the filming of sports events or other performances. The large workspace provided by CDPMs makes them an ideal technology for this application. Additionally, cables are small and hardly visible. Therefore, the use of the cable-suspended camera system does not perturb the visibility for the local audience.

The second application to be proposed was that of construction cranes. In [10, 100], the NIST Robocrane was proposed as a crane with 6 controllable degrees of freedom in order to alleviate the drawbacks of the underactuated

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motions of conventional cranes. The prototype built at NIST, which consisted of a 6-dof 6-cable CSPM, was successfully demonstrated and generated other related research initiatives [27, 100–105].

The development of very large radio-telescopes provided another opportunity for the application of CSPMs. The five-hundred-metre aperture spherical radio telescope (FAST) currently being developed in China uses a CSPM as one of its main components. Therefore, significant research efforts have been deployed in order to design this very large cable-driven robot [58, 67, 74, 106–108]. A similar project was developed in Canada, in which an aerostat was used to tension a 6-cable parallel mechanism [40, 68, 73, 109, 110]. A 1/3 scale prototype of this two-hundred-metre Large Adaptive Reflector (LAR) was built and tested [111].

CDPMs have also been used in haptics. Haptic devices are often controlled using an impedance control scheme, in which the user can feel the inertia and friction induced by the device itself. Therefore, one of the key challenges in the design of haptic systems is to minimize the inertia and friction of the mechanism on which the user interaction port is mounted [112]. Haptic devices should also be stiff in order to allow high-bandwidth mechanical interaction and they should provide a workspace that is sufficient for the immersion to be convincing. The properties of CDPMs make them very attractive for such applications since they can provide high stiffness and very low inertia over a large workspace. One of the first examples of a haptic device based on a CDPM is the hand controller reported in [113]. Several other devices were also proposed and built [11, 56, 113–126] including a sword simulator [127] and a locomotion interface consisting of two 8-cable parallel mechanisms supporting the footplates [43, 128, 129]. Applications in teleoperation have also been proposed, such as in [130].

The challenges faced in the area of rehabilitation robotics are similar to those encountered in haptics. Therefore, CDPMs have also been proposed for rehabilitation systems. In [131], a fixed-base planar mechanism driven with cables was proposed for upper arm rehabilitation and the performance of CSPMs for rehabilitation is assessed in [132]. An active leg exoskeleton robot based on a CDPM is introduced in [95] and a wearable upper-limb exoskeleton system based on a CDPM is developed in [96–98] following a similar approach. In [133], a CDPM is used as a gait rehabilitation tool. The mechanism is used to apply controlled loads on a patient walking on a treadmill.

The lightweight characteristic of CDPMs also makes them ideal for high-speed motion. This was clearly demonstrated in [39, 134], where a very high-speed CDPM with six dofs and seven cables was developed. Another high-speed robot was presented in [92], where cable routings are used to amplify the speed of the linear actuators.

The very large translational workspace of CDPMs leads to obvious applications in material handling. One of the challenges in such applications is to avoid cable interferences with the environment while providing proper force transmission characteristics throughout the workspace. Example systems with large workspaces that can be used in warehouses and other similar applications have been proposed in [135–137] and [138–140]. A cable system suspended on a traditional overhead bridge is also proposed in [141, 142] and a cable system developed for use in spacecrafts was proposed in [143].

Several other applications of cable-driven parallel mechanisms have been proposed in the literature. For instance, applications of CSPMs in three-dimensional printing are starting to emerge [144] while cooperating flying vehicles are proposed in [145] and the dynamic trajectory planning of CSPMs described in [69, 70] is suitable for artistic performances. Cable-driven mechanisms are proposed in [146] for the mechanical teleoperation of surgical tools in MRI environments. The motivation for the latter work is to develop advanced teleoperation robots that comply with the contingencies of the MRI environment. Search and rescue operations are proposed as another application of CDPMs in [16, 85, 147–150]. CDPMs are also proposed as active systems for the manipulation of models in wind tunnels [151–153] and for the scanning of artefacts in order to construct digital models [28, 154]. In the latter application, a gravity-powered mechanism is employed to extend the rotational range of motion of the CSPM. A very large CDPM is proposed in [155] in order to inspect the facade of a building and to provide active interaction between the building and its occupants. Finally, CDPMs have also been proposed as motion simulators for a variety of applications [47, 49, 156–158] including the moving of a bed to study sleeping patterns [159].

It is obviously impossible to include schematics or photograhs of all the above mentioned prototypes or concepts in this paper. Therefore, only a few examples are shown here, mainly to help the reader appreciate the variety of scale, geometry and implementation context found in the literature. Despite these differences, the fundamental concepts remain applicable in all cases. Figure 3 shows a prototype of a 6-dof haptic device based on a CDPM and presented in [115]. This device uses 7 cables in order to fully constrain the platform and was reported to have a high force transmissibility and large practical workspace. An example of application in rehabilitation is shown in Fig. 4. This lightweight arm exoskeleton has five dofs, uses seven cables and is attached to the arm of the user with cuffs, providing a user-friendly rehabilitation environment [96–98]. An example of a CSPM with six cables is shown in Fig. 5. The latter prototype is used

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to scan artefacts (more accurately, take pictures of artefacts from a large number of camera poses) in order to construct a digital model. The rotational workspace of the mechanism (the yaw angle) is extended to a full rotation by including a gravity-powered rotational joint on the platform [28, 154] and objects of sizes ranging from a few centimetres to two metres were successfully scanned. One of the prototypes of a family of material handling robots proposed in [138–140] is shown in Fig. 6. The robot is driven by 8 cables and can produce relatively high velocities over a large workspace. A similar system, proposed in [135–137] is shown in Fig. 7. The latter also uses 8 cables, which appears as a good compromise between complexity, geometric balance and workspace capabilities. Large payloads can be handled. One of the prototypes described in [69, 70] is shown in Fig. 8. This 3-cable 3-dof system is used to produce dynamic trajectories that guarantee cable tensions while extending beyond the static workspace. Finally, Fig. 9 shows the very large 3-cable prototype developed in [40, 68, 73, 109, 110] for applications in radio-telescopes. This $\frac{1}{3}$ scale prototype has a foot print of approximately $0.5km^2$ and the cables connecting the ground winches to the aerostat have a length of approximately $400m$.

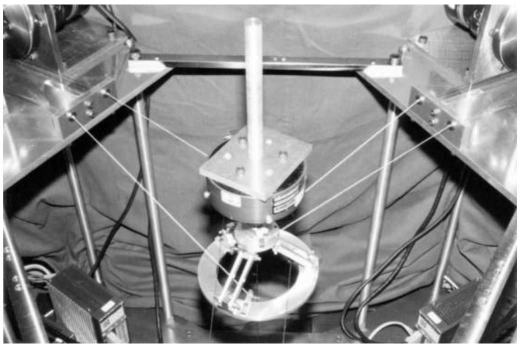

Fig. 3 Prototype of a 6-dof cable-driven haptic device developed at the Tokyo Institute of Technology (courtesy of Professor Yukio Takeda, TIT).

Fig. 4 Prototype of CAREX, a cable-driven arm exoskeleton for neural rehabilitation developed at Columbia University (courtesy of Professor Sunil Agrawal, Columbia University).

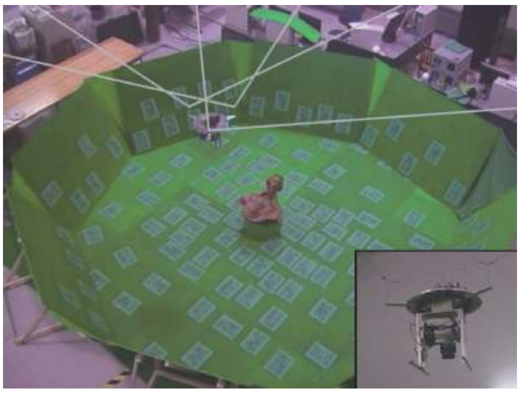

Fig. 5 Prototype of a 6-dof cable-suspended parallel mechanisms for the scanning of artefacts developed at Laval University.

Fig. 6 Prototype of IPAnema-1, an 8-cable 6-dof CDPM for material handling developed at the Fraunhofer Institute (courtesy of Dr. Andreas Pott, Fraunhofer IPA).

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Fig. 7 Prototype of the CoGiRo, an 8-cable 6-dof CDPM for material handling developed by LIRMM and Tecnalia (courtesy of Dr. Marc Gouttefarde, LIRMM).

Fig. 8 Prototype of a 3-cable 3-dof CSPM developed at Laval University for the performance of dynamic trajectories that extend beyond the static workspace.

(a)

(b)

Fig. 9 Prototype of a 3-cable 3-dof very large CDPM attached to an aerostat for a radio-telescope application built in Penticton, Canada: (a) view from one of the spools and (b) aerostat (courtesy of Prof. Meyer Nahon, McGill University).

6. Conclusion and perspectives

This paper provided an overview of the current state of the art in the area of cable-driven parallel mechanisms. It can be observed that several fundamental problems related to these mechanisms have been formulated systematically in the literature. For instance, eq.(3) and the definition of the wrench matrix are well understood. Several implications of this equation have been explored and used to develop analysis and synthesis tools, which have been reported in a significant body of published work that could not entirely be included in this paper. The variety of prototypes developed by researchers and practicians is impressive and reflects the large number of possibilities offered by cable-driven parallel mechanisms. Nevertheless, although the basic principles used in cable mechanisms are relatively well documented, their design and implementation remains challenging in many respects. Among other issues, the geometric synthesis of mechanisms with a prescribed workspace remains a very difficult problem, especially for mechanisms with more than three degrees of freedom. Also, several practical issues arise in the implementation of cable-driven parallel mechanisms such as the accurate control of cable lengths, the modelling of cable nonlinearities, the management of potential interferences and force distribution and the accurate pose determination of the platform, to name but a few. Therefore, it appears clearly that research in this area will continue to grow in the coming years and that the full potential of cable-driven parallel

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mechanisms has not yet been exploited. Future applications in several areas are to be expected which, in some cases, have the potential to rewrite the rules of robotic manipulation.

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