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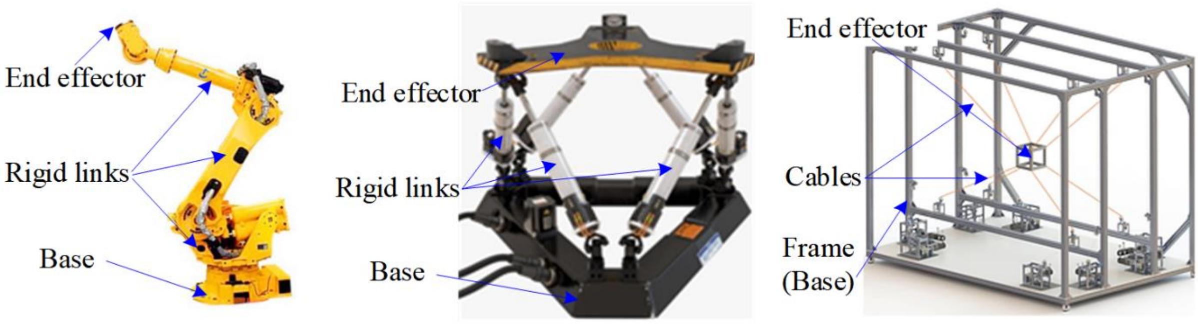
Abstract: A cable-driven parallel robot (CDPR) is a type of high-performance robot that integrates cable-driven kinematic chains and parallel mechanism theory. It inherits the high dynamics and heavy load capacities of the parallel mechanism and significantly improves the workspace, cost, and energy efficiency simultaneously. As a result, CDPRs have irreplaceable positions in industrial and technological fields, such as astronomy, aerospace, logistics, simulators, and rehabilitation. CDPRs follow the cutting-edge trend of rigid–flexible fusion, reflect advanced lightweight design concepts, and have become a frontier topic in robotics research. This paper summarizes the kernel theories and developments of CDPRs, covering configuration design, cable-force distribution, workspace and stiffness, performance evaluation, optimization, and motion control. Kinematic modeling, workspace analysis, and cable-force solution are illustrated. Stiffness and dynamic modeling and analysis methods are discussed. To further promote the development, researchers should strengthen the investigation in configuration innovation, rapid calculation of workspace, performance evaluation, stiffness control, and rigid–flexible coupling dynamics. In addition, engineering problems such as cable materials, reliability design, and a unified control framework require attention.

Keywords: Cable-Driven Parallel Robot, Kinematics, Optimization, Dynamics, Control.

1. Introduction

Robots influence every aspect of work and home and have the potential to positively transform lives and work practices, improving efficiency, safety, and service. Considering the arrangement of joints and links, robots can be divided into two categories: serial and parallel robots. Most industrial robots are similar to the human arm, adopting a serial configuration (Fig. 1(a)). It is an open-loop structure, with only one kinematic chain between the base and the end effector. Serial robots have the advantages of a large workspace and good flexibility, and the disadvantages of low load–weight ratio, low rigidity, and low accuracy.

In 1962, Gough designed a six degree-of-freedom (DOF) tire-testing machine with a parallel configuration [1]. Later, Stewart used a parallel mechanism for a flight simulator [2]. This mechanism is called the Gough–Stewart platform [3] and is now widely used as a motion simulator. Parallel mechanisms have two or more kinematic chains connecting the base and end effector simultaneously. It is a closed-loop mechanism with passive joints (Fig. 1(b)). Parallel robots can be intuitively understood as multiple serial robots carrying the end effector together, exhibiting the potential for large rigidity, heavy loads, and high accuracy [4]; parallel robots triggered the machine tool revolution in the 1990s [5]. The actuation units of the parallel robot are frequently fixed to the static base, which results in low motion inertia and good dynamics [6]. Parallel robots have achieved commercial applications as motion simulators [7], pick-and-place robots [8], and spindle heads [9].



(a) Serial robot (b) Parallel robot (c) Cable-driven parallel robot.

Fig. 1 Serial, parallel, and cable-driven parallel robots

Parallel robots have the disadvantage of a small workspace. To expand the workspace, researchers proposed cable-driven parallel robots (CDPRs), which adopt a parallel configuration and cables for kinematic chains instead of rigid links [10] (Fig. 1 (c)). Landsberger [11] first designed a 3-DOF CDPR for high-dynamic undersea operations in the 1980s and performed the mechanical analysis. In 1988, SkyCam [12] developed a camera system driven by four cables that could travel at 13 m/s in a hundred-meter-scale workspace. Brief comparisons of serial robots, parallel robots, and CDPRs are presented in Table 1. Based on the low cost, the outstanding advantages of CDPR lie in two aspects: large workspace with a high load capacity and high dynamics with a lightweight nature.

TABLE 1. Comparison of serial robots, parallel robots, and CDPRs

Performances	Serial robots	Parallel robots	CDPRs
Workspace	☆☆	☆	☆☆☆
Load capacity	☆☆	☆☆☆	☆☆☆
Stiffness	☆☆	☆☆☆	☆
Lightweight	☆	☆☆	☆☆☆
Acceleration	☆	☆☆	☆☆☆
Reconfigurability	☆	☆☆	☆☆☆

CDPRs have an important role in various fields. One of the earliest and most famous CDPRs is the RoboCrane robot developed by Albus et al. at the National Institute of Standards and Technology (NIST) [13] (Fig. 2). RoboCrane was extended to the fields of aircraft painting, port facilities, waste cleaning, and underwater applications [14]. With excellent performance, RoboCrane was awarded the "Best of What's New" award as one of the 100 top products, technologies, and scientific achievements in 1992 [15].

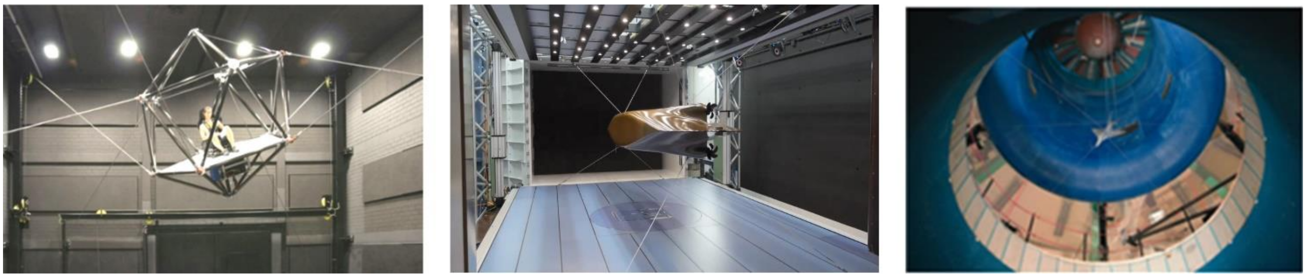
Fig. 2 RoboCrane and its applications

The largest CDPR now is the Five-hundred-meter Aperture Spherical radio Telescope (FAST) [16], the world's largest telescope built in China (Fig. 3(a)). The FAST feed support system is a six-cable CDPR with a span of 600 m [17]. CDPRs are also a good option for warehousing and logistics. El-Ghazaly et al. [18] designed and developed the CoGiRo robot to implement auxiliary automation, such as palletizing, handling, auxiliary assembly, and spraying (Fig. 3(b)). Bruckmann et al. [19] developed a cable-driven CABLAR system for warehouse material handling and retrieval (Fig. 3(c)). Owing to their reconfigurability, CDPRs have significant potential in building construction. Wu et al. [20] and Bruckmann et al. [21] proposed a CDPR prototype design for automatic wall construction.

(a) FAST [16] (b) CoGiRo [18] (c) CABLAR [19]

Fig. 3 CDPRs for lifting and handling

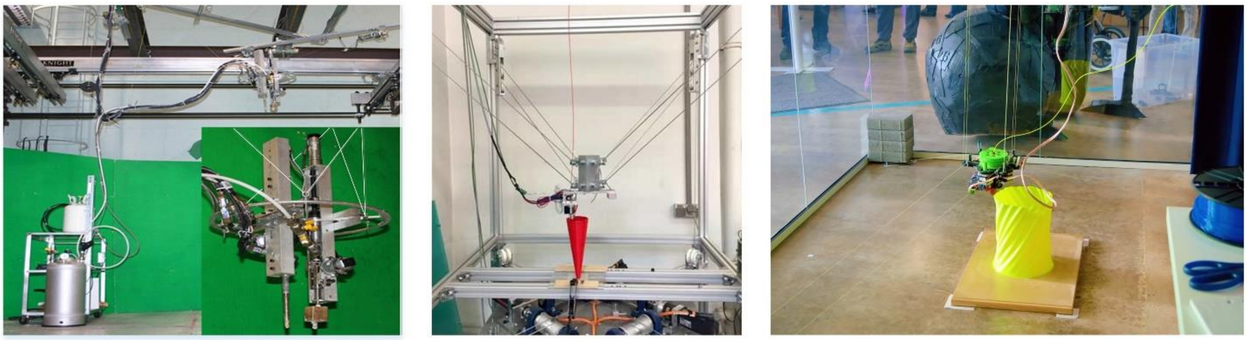
CDPRs have been successfully applied as large-space motion simulators, and they can be used to simulate acceleration in a large workspace. The CableRobot Simulator developed by Miermeister et al. [22], combined with virtual reality technology, can be used for flight training and entertainment (Fig. 4(a)). CDPRs have also been adopted in wind tunnel simulations owing to their advantages of low wind and water resistance. Bruckmann et al. [23] developed a cable-driven simulator for hydrodynamic experiments of hulls and submarines (Fig. 4(b)). ONERA in France designed the SACSO, a CDPR for wind tunnel tests [24] (Fig. 4(c)).



(a) CableRobot simulator [22] (b) CDPR used for submarine design [23] (c) SACSO [24]

Fig. 4 CDPRs used for motion simulation and wind tunnel tests

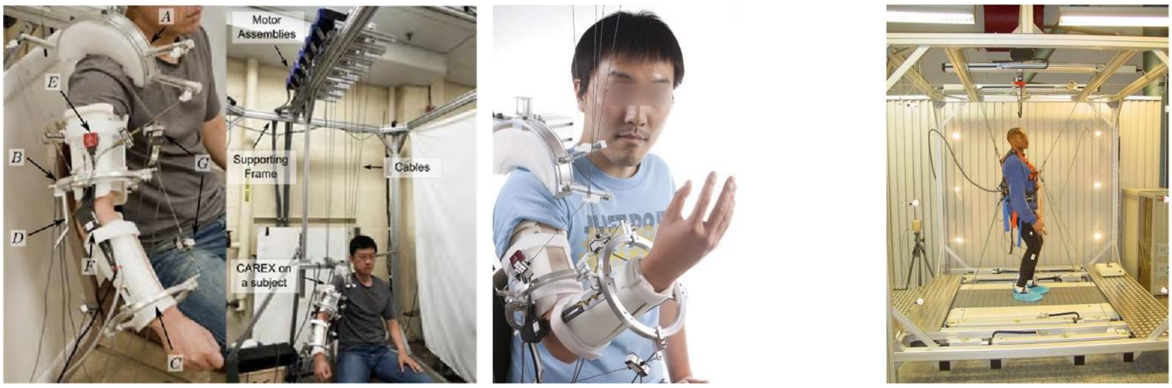
The low cost and large workspace of CDPRs make them good options for large-space three-dimensional (3D) printing. Barnett et al. [25] designed a suspended cable-driven 3D printer and constructed a 2.16-m-high statue of Sir Wilfrid Laurier (Fig. 5(a)). Zi et al. [26] designed a desktop 3D printer with parallel cable chains and achieved a 3-DOF translational motion. Pott et al. designed the CaRo printer [27] using four pairs of cables that formed parallelograms (Fig. 5(b)). Ludvigsen developed a fast-reconfigurable 3D printer called Hangprinter that cost approximately US$250 [28], adopting parallel cable chains (Fig. 5(c)).



(a) Foam printer [25] (b) CaRo printer [27] (c) Hangprinter

Fig. 5 CDPRs for 3D printing

A cable is an excellent transmission and traction medium, and cable chains are similar to biological muscles. CDPRs have been applied in bionics and medical rehabilitation. Researchers at Columbia University developed a cable-driven exoskeleton system called CAREX [29, 30] for upper limb rehabilitation (Fig. 6(a)). Surdilovic and Bernhardt at the Fraunhofer Institute developed the String-Man for gait rehabilitation [31] (Fig. 6(b)).



(a) CAREX rehabilitation robot [29, 30] (b) String-Man rehabilitation robot [31]

Fig. 6 CDPRs for rehabilitation

Each coin has two sides. The flexibility, unidirectional force, and continuum characteristics of the cable pose challenges to the research and application of CDPRs and facilitate new theories and methods. Considering the weight and elasticity of the cables, statics and kinematics analysis of CDPR couples and vibration are important challenges for dynamics and control. Theories on configuration design, kinematics and dynamics modeling, performance evaluation and optimization, and motion control of CDPRs have been established.

This paper reviews and analyzes theoretical research on CDPRs. Challenges and future research prospects for CDPRs are discussed. The remainder of this article is arranged as follows: Section 2 discusses the configuration design of CDPRs. Section 3 analyzes the kinematics and statics of CDPRs.

Section 4 presents the performance evaluation and optimization methods for CDPRs. Section 5 reviews the dynamics of CDPRs. Section 6 discusses the control challenges. Finally, an outlook is provided in Section 7.

2. Configuration Design

The CDPR is composed of a frame (base), cable chains, and an end effector (Fig. 7). Cable chains consist of actuators, guide pulleys, and cables. Cables are frequently wound on the winches (actuators) of the frame, guided by pulleys, and then connected to the end effector. The cable length between the cable outlet point A_i and cable connection point B_i changes with the rotation of the winches, thereby driving the motion of the end effector.

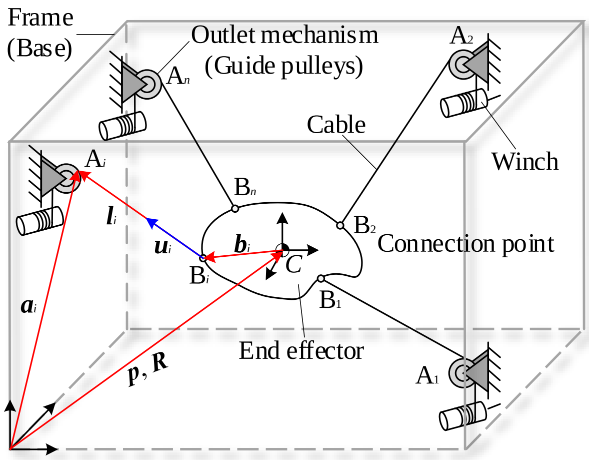


Fig. 7 Typical kinematic diagram of the CDPR

The configuration of a rigid robot refers to the arrangement of joints and links, which is the skeleton of a robot, determining its core kinematic performance and potential. The configuration design of CDPRs primarily focuses on the number and layout of the cables, and the key is whether the CDPR forms a tensegrity structure. The requirements of DOF are frequently the starting point of the configuration design. Owing to the unidirectional force characteristics of cables, the DOF analysis of CDPRs differs from that of rigid robots.

Ming et al. [32, 33] first studied the configuration of CDPRs using the vector closure principle. Subsequently, Verhoeven [34] proved that CDPRs can realize six types of DOFs: pure translational motion of 1, 2, or 3 DOFs (1T, 2T, 3T) with the point end effector, and the 2T1R, 3T2R, 3T3R (where T denotes translation and R denotes rotation) DOFs based on the nonpoint end effector (Fig. 8). Verhoeven [34] and Riechel et al. [35] established a configuration classification method for CDPRs considering the constraint capacity of cables to the end effector and defined the relationship between the number of cables (m) and the number of terminal DOFs (n). CDPRs are divided into four categories: under-constrained mechanism ($m < n$), incompletely constrained mechanism ($m = n$), fully constrained mechanism ($m = n+1$), and redundantly constrained mechanism ($m > n+1$). The under-constrained mechanism is seldom used because it cannot achieve a stable tensegrity structure, and the end effector has uncontrollable DOFs. For the CDPR to be in a fully constrained state, m must be greater than or equal to $n + 1$ [36, 37]. If gravity is considered a virtual cable, the incompletely constrained CDPR ($m = n$) can be considered a fully constrained CDPR ($m = n+1$) with limited acceleration.

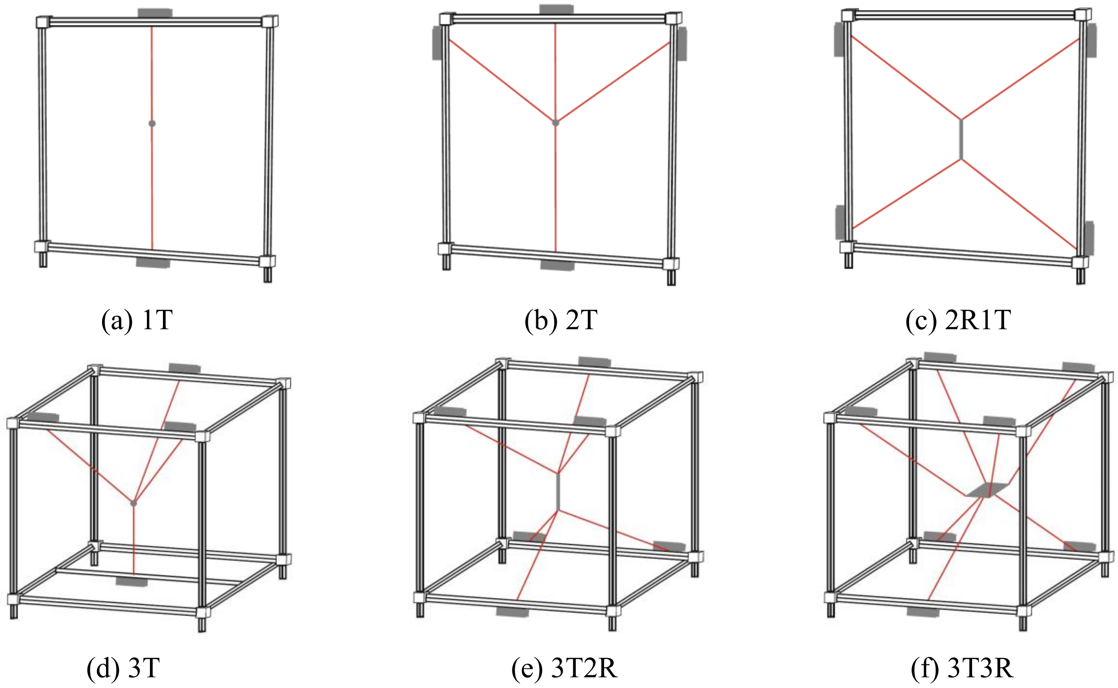
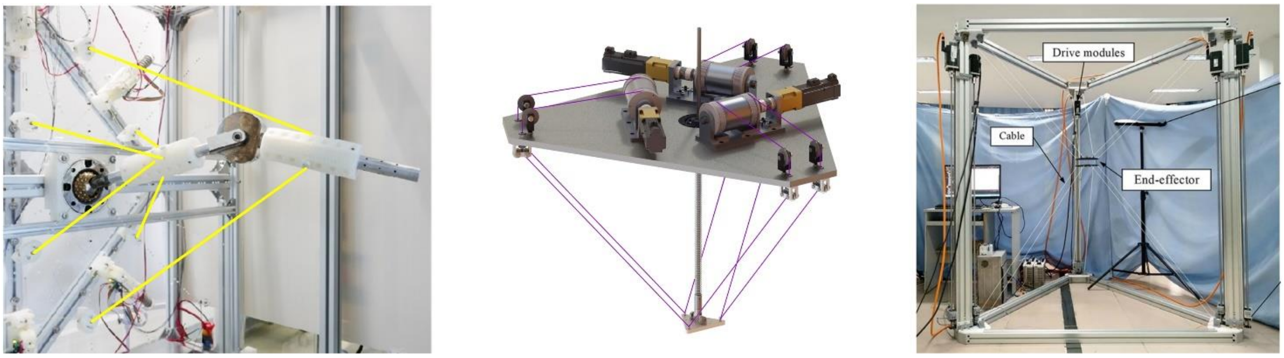


Fig. 8 Six types of DOFs for CDPRs [38]

Ensuring that the cables are in tension is a prerequisite for CDPRs, which must be considered during the configuration design. From this perspective, CDPRs can be intuitively divided into two categories [39]. Incompletely constrained CDPRs that utilize the gravity of the end effector and the load to maintain cables in tension are frequently called cable-suspended parallel robots (CSPRs). CSPRs achieve a fully constrained state through the gravity “cable” [40]. CSPRs are easy to build and control with a large workspace and heavy load capacity, which are generally used in spatial positioning and handling conditions. However, the terminal acceleration of the CSPR is limited. For fully constrained and redundantly constrained CSPRs, cable tension is ensured by arranging the cables on both sides of the end effector and pulling them against each other. A high stiffness and high-speed motion with significant acceleration can be achieved. Because m is greater than n, this results in actuation redundancy and an infinite cable-force distribution.

Recently, new types of CDPRs have emerged, which provide new approaches for innovative design. As shown in Fig. 9(a), a multilink cable-driven robot was proposed by combining the cable chain and serial rigid links [41, 42], which are commonly used in bionic and rehabilitation robots [43, 44]. Passive tensioning elements such as springs and cylinders were introduced into CDPRs to reduce the number of actuations and the control difficulty while ensuring complete constraints. The first CDPR with an auxiliary tensioning element was proposed by Landsberger [45], who used a central hydraulic cylinder in a 3-DOF CDPR to maintain cables in tension. Dekker and Behzadipour et al. designed DeltaBot [46] and BetaBot [47] robots by adding passive air cylinders in the center. Springs have gradually become a preferred option. The planar cable–spring mechanism [48], cable-driven humanoid neck robot [49], and TBot robot (Fig. 9b) [50] have been proposed. In addition to tensioning cables, springs aid in expanding CDPR workspaces [51, 52] and optimizing the energy consumption during operation (springs can be used as energy storage elements) [53].



(a) Multilink cable-driven robot [42] (b) TBot robot [50] (c) 3D CDPR printer [56]

Fig. 9 CDPRs combined with multilink, springs, and parallel-cable chains

To improve the constraint ability of cables on the end effector, parallel-cable chains were proposed and translational CDPRs with nonpoint end effectors were established. The parallel-cable chain is a group of cables (frequently two cables) that are always parallel to each other during motion and form a parallelogram structure to constraint the rotations of the end effector. Since parallel cables in the same group are wound and released simultaneously, they are generally driven by one winch. Bosscher et al. [54] first used parallel cables in a rescue robot. Alikhani et al. [55] designed a large-space translational CDPR with parallel cables. Zi [26] and Qian et al. [56] designed translational 3D CDPR printers (Fig. 9c). The parallel-cable chain effectively improve the constraint ability of the cables on the end effector and enriched the configuration and DOF form of the CDPRs. In addition, the modular and reconfigurable characteristics of CDPRs provide significant flexibility to change their configuration and performance [57], which satisfies the requirements of high flexibility and efficient reengineering in modern manufacturing.

3. Kinematics and Statics

3.1 *Notations and Kinematics*

The kinematic model establishes the relationship between the cable length and pose of the end effector. Based on the massless and inelastic assumptions of the cable, the cable outlet and connection points on the base and end effector are considered fixed points. The point-to-point straight-line model is widely adopted in the kinematic modeling of CDPRs. As shown in Fig. 7, given the pose of the end effector, the length of each cable can be obtained as

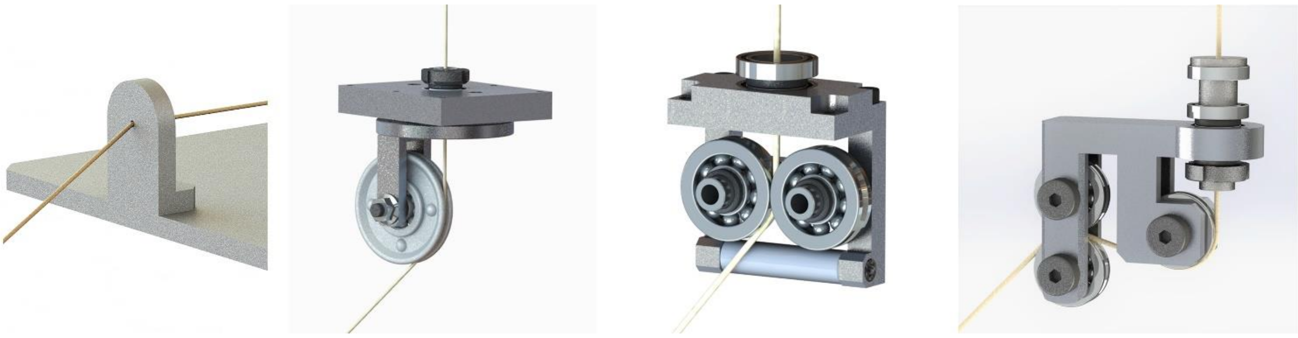
$$l_i = \left\| \boldsymbol{a}_i - \boldsymbol{p} - {}^{O}\boldsymbol{R}_p \boldsymbol{b}_i \right\|, \ \left(i = 1, 2, \cdots, m \right) \tag{1}$$

where l_i is the length of the i-th cable, $\boldsymbol{a}_i$ is the position of cable outlet point A_i on the base, $\boldsymbol{p}$ is the position of the end effector, ${}^{O}\boldsymbol{R}_p$ is the rotation matrix of the end effector with respect to the base, and $\boldsymbol{b}_i$ is the position of the cable connection point B_i in the local coordinate system $\{P\text{-}xyz\}$.

In practice, the cable outlet mechanism on the base has different structures and can be divided into four categories: the eyelet, single-pulley, double-pulley, and multiple-pulley types [58] (Fig. 10). The eyelet type is an ideal scenario in which the cable outlet point is fixed. However, the relative motion between the cable and the eyelet produces severe friction and causes wear or breakage of the cable, resulting in low reliability and poor practicability.

Pulleys are frequently adopted in the outlet mechanism. The position of the cable outlet point at which the cable leaves the pulley changes with the pose of the end effector. The pulley can be equivalent to an RRP kinematic pair under the spatial conditions [38] or RP kinematic pair under planar conditions (R and P represent the revolute and prismatic joints, respectively). When the span of the CDPR is large and the pulley radius is small, the kinematic model based on the point-to-point assumption has acceptable accuracy. Otherwise, the point-to-point model results in apparent errors.

Gonzalez-Rodriguez et al. [59] and Jin et al. [60] proposed a method of mounting compensation pulleys at the cable connection points of the end effector to counteract the errors; however, this method is primarily suitable for planar CDPRs in which the pulley does not swing or for low-speed spatial CDPRs.



(a) Eyelet type (b) Single-pulley type (c) Double-pulley type (d)Multi-pulley type

Fig. 10 Typical cable outlet mechanisms on the base

A more general approach is to establish a complete kinematic model considering pulley kinematics. A kinematic diagram of the CDPRs considering the pulley kinematics is shown in Fig. 11. When the pulleys are considered in the kinematic model, the tangent points and wrap angles of the cables on the exit pulleys should be calculated. Solutions for the kinematic modeling of the CDPR considering pulleys have been established [64]. The complete kinematics model with pulley kinematics significantly increases the positioning and trajectory accuracy of the CDPR. For example, the terminal accuracy of the IPAnema robot was increased by 21.6% [62, 63].

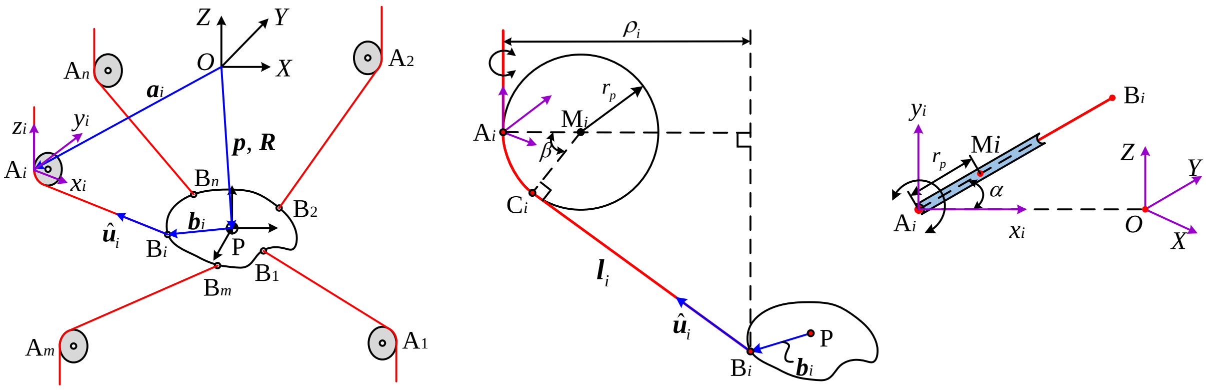
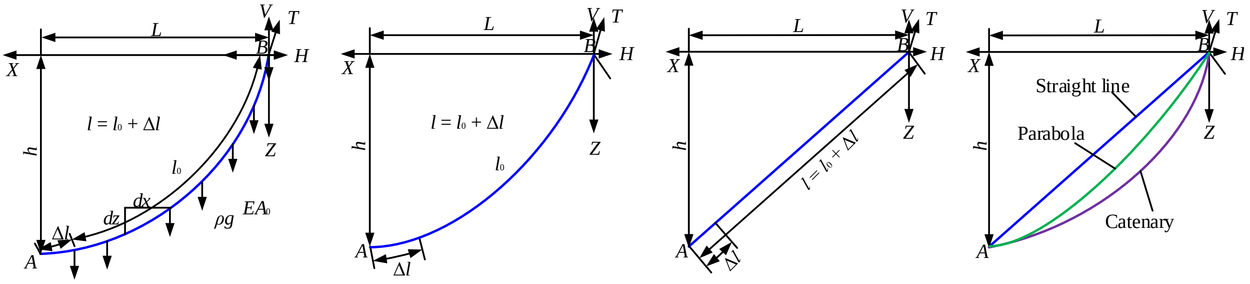


Fig. 11 Kinematic diagram of a CDPR considering the pulley kinematics

When the span of a CDPR is large and the weight of cables cannot be ignored, the cable's mass and elastic deformation will significantly decrease the accuracy of the point-to-point model. The kinematic modeling of a large-span CDPR requires consideration of the cable elasticity and mass.

Based on the straight-line model, refined cable models such as the catenary and parabolic models have been proposed [64, 65, 66] (Fig. 12). The catenary model has a high accuracy, but the equation is nonlinear and requires iterative calculations. The complex calculation and time consumption make it difficult to use for real-time control. The parabolic model is an approximation of the catenary model and is significantly easier to solve with lower accuracy.



(a) Catenary model (b) Parabolic model (c) Straight-line model (d) Comparison

Fig. 12 Catenary model, parabolic model, and straight-line model of cables

Compared with inverse kinematics, the forward kinematics of CDPRs are complicated without an explicit analytical solution. This is frequently solved by converting it into the optimization problem as

$$\boldsymbol{p} = \min\left(\boldsymbol{f}_{ik}\left(\boldsymbol{p}, \boldsymbol{a}\right) - \boldsymbol{L} \right) \tag{2}$$

where $\boldsymbol{f}_{ik}\left(\boldsymbol{p}, \boldsymbol{a}\right)$ is the inverse kinematics of the CDPR, and $\boldsymbol{L}$ is the given vector of cable lengths. Numerical methods can be used to increase the calculation efficiency, such as the integral formula [67], interval analysis [68], and the Levenberg–Marquardt algorithm [69]. Pulley kinematics can also be considered in the forward kinematics of CDPRs [70, 71].

Inverse kinematics are widely used because they are the basis of motion control and dimension design of CDPRs. Applications and research on forward kinematics that rely on numerical iteration are relatively few. The basic model of a cable is the point-to-point model. For refined kinematic modeling, it is necessary to consider the influence of cable sagging and the pulley mechanism.

3.2 *Statics and Cable Force Distribution*

The basis of the CDPRs is the balance of the cable forces. When all the cables are tensioned, the force acting on the end effector by the *i*-th cable is $t_i\boldsymbol{u}_i$, and the torque is $\boldsymbol{b}_i \times t_i\boldsymbol{u}_i$ (t_i represents the amplitude of the tension on the *i*-th cable). The external force and torque acting on the end effector are denoted as $\boldsymbol{F}$ and $\boldsymbol{M}$, respectively, and the static equilibrium equation of the CDPR can be expressed as

$$\begin{bmatrix} \boldsymbol{u}_1 & \boldsymbol{u}_2 & \cdots & \boldsymbol{u}_m \\ \boldsymbol{b}_1 \times \boldsymbol{u}_1 & \boldsymbol{b}_2 \times \boldsymbol{u}_2 & \cdots & \boldsymbol{b}_m \times \boldsymbol{u}_m \end{bmatrix} \begin{bmatrix} t_1 \\ t_2 \\ \vdots \\ t_m \end{bmatrix} + \begin{bmatrix} \boldsymbol{F} \\ \boldsymbol{M} \end{bmatrix} = \boldsymbol{JT} + \boldsymbol{W} = 0 \tag{3}$$

where $\boldsymbol{J} = \begin{bmatrix} \boldsymbol{u}_1 & \boldsymbol{u}_2 & \cdots & \boldsymbol{u}_m \\ \boldsymbol{b}_1 \times \boldsymbol{u}_1 & \boldsymbol{b}_2 \times \boldsymbol{u}_2 & \cdots & \boldsymbol{b}_m \times \boldsymbol{u}_m \end{bmatrix}$ is the structure matrix of the CDPR, $\boldsymbol{W}$ is the external force vector, and $\boldsymbol{T} = \begin{bmatrix} t_1 & t_2 & \cdots & t_m \end{bmatrix}^{\mathrm{T}}$ is the cable-force vector of the CDPR.

The cable-force distribution of a CDPR is a matrix solution problem. The objective is to determine a positive force vector $\boldsymbol{T}$ that satisfies the equation of $\boldsymbol{JT} + \boldsymbol{W} = 0$ with the given pose of the end effector and the external forces $\boldsymbol{W}$ applied to the end effector. This can be summarized as follows:

$$\begin{cases} \boldsymbol{JT} + \boldsymbol{W} = 0 \\ s.t.\ \ 0 < t_{\min} \le t_i \le t_{\max} \end{cases} \tag{4}$$

where $t_{\min}$ and $t_{\max}$ are the minimum and maximum limits of the cable-force range, respectively. When the CDPR is nonredundant, a unique solution can be obtained by solving Eq. (4). For redundant CDPRs, because m is greater than n, the structure matrix $\boldsymbol{J} \in \boldsymbol{R}^{n \times m}$ is a nonsquare matrix, and there are infinite groups of solutions for the cable forces. The generic cable-force solution in Eq. (4) is

$$\boldsymbol{T} = \boldsymbol{J}^{+}\boldsymbol{W} + \left(\boldsymbol{I} - \boldsymbol{J}^{+}\boldsymbol{J}\right)\lambda \tag{5}$$

where $\boldsymbol{J}^{+} = \boldsymbol{J}^{\mathrm{T}}\left(\boldsymbol{J}\boldsymbol{J}^{\mathrm{T}}\right)^{-1}$ is the Moore–Penrose inverse of matrix $\boldsymbol{J}$, $\boldsymbol{I} \in \boldsymbol{R}^{m \times m}$ is the m-dimensional unit vector, $\left(\boldsymbol{I} - \boldsymbol{J}^{+}\boldsymbol{J}\right)\lambda$ is the homogeneous solution of the equation $\boldsymbol{JT} = \boldsymbol{W}$, $\lambda \in \boldsymbol{R}^{n}$ is an arbitrary vector, and $\left(\boldsymbol{I} - \boldsymbol{J}^{+}\boldsymbol{J}\right)\lambda$ forms the zero-space vector of the structure matrix $\boldsymbol{J}$.

For redundant CDPRs, it is difficult to directly solve the cable force using the above equation. Therefore, the solution is converted into an optimization problem as follows:

$$\begin{aligned} &\text{objective function: optimize } \boldsymbol{H}(\boldsymbol{T}) \\ &\text{subjected to: } \begin{cases} \boldsymbol{JT} + \boldsymbol{W} = 0 \\ 0 < t_{\min} \le t_i \le t_{\max} \end{cases} \end{aligned} \tag{6}$$

where $\boldsymbol{H}(\boldsymbol{T})$ is the target function. The optimization objective $\boldsymbol{H}(\boldsymbol{T})$ can be determined according to the requirements. The common optimization objectives are the minimum 1-norm or 2-norm of the cable-force vector $\boldsymbol{T}$. The minimum 1-norm optimization can be effectively solved using a linear programming method [72, 73]. However, the obtained cable forces with the minimum 1-norm may have discontinuities when the end effector follows a continuous path. The minimum 2-norm optimization is frequently adopted with the bounded quadratic programming method [74, 75]. Gosselin and Grenier [76] discussed the problems of p-norm optimization thoroughly and explained the differences. If the order of the norm p is large, it will cause a dramatic change in the cable forces under a continuous trajectory. The 2-norm and 4-norm optimizations are preferred.

The cable force value obtained minimum p-norm optimization tends to be the minimum limit of the available range. If the cable force is small, the cable is prone to sagging. Relative p-norm optimization [76] was proposed to avoid this scenario. The mathematical expression of the relative p-norm optimization can be expressed as

$$\begin{aligned}&\text{objective function: optimize } \eta(\boldsymbol{t}) = \left\|\boldsymbol{t} - \boldsymbol{t}_{\text{ref}}\right\|_p = \sqrt[p]{\sum_{i=1}^{m}\left|t_i - t_{\text{ref},i}\right|^p} \\ &\text{subjected to: } \begin{cases} \boldsymbol{JT} + \boldsymbol{W} = 0 \\ 0 < t_{\min} \le t_i \le t_{\max} \end{cases}\end{aligned} \tag{7}$$

where $t_{\text{ref},i}$ is the target cable force. $t_{\text{ref},i} = (t_{min} + t_{max})/2$ is often adopted [77]. In addition to the relative p-norm optimization, Lim et al. [78] used a tension index to adjust the cable forces to keep them away from the limits. Mikelsons et al. [79] proposed the gravity center of the plane of effective cable forces as the optimal solution.

When calculating the cable forces numerically, an important problem is time consumption considering the real-time control of the CDPR. Numerical iterative search methods based on the Karush–Kuhn–Tucker (KKT) theory [80, 81], improved gradient projection method [82], and interval analysis [83] have been proposed to increase the computational efficiency. Gradient-based optimization methods can frequently guarantee results within a particular period, but unpredictable nonconvergence may occur [83].

In addition to numerical calculation methods, geometric methods have been proposed for the cable-force distribution problems of redundant CDPRs. Geometric methods primarily include the cable-force polygon method [84, 85] and the gravity center method [79]. Combined with the gravity center method, several geometric cable-force optimization methods have been proposed based on the feasible region of the cable force. The feasible region of cable forces (which is frequently a cable-force polygon) should first be determined using the polygon method. Cui et al. [86] proposed a polygonal calculation algorithm that can effectively obtain the feasible region of cable forces based on the Graham scanning method.

In summary, the methods of solving cable forces for redundant CDPRs are divided into geometric and numerical methods. The p-norm numerical optimization method is the most commonly used. The relative p-norm optimization can adjust the target value of the cable forces to make them far away from the force limits. The geometric method has some advantages such as simple calculation and avoiding iterations; however, it is currently only used for CDPRs with specific configurations and simple optimization objectives.

3.3 *Workspace*

The workspace is an important challenge in robot kinematics and applications. The workspace of a rigid robot is determined by analyzing the joint motion range and chain size. The workspace boundary is clear and can be usually expressed algebraically; the workspace of CDPRs is highly coupled with the cable forces. Various workspaces have been presented for CDPRs considering the constraints on the cable tension and external forces.

The static workspace is the most basic one, and it is defined as the set of poses that the end effector can attain and remain still with positive cable forces, with gravity as the only external force [87]. Subsequently, the wrench closure workspace (WCW) [88] and the force closure workspace (FCW) for the point end effector [89] were proposed. The WCW is the pose set in which the CDPR can be balanced by a set of positive cable forces under an external wrench of any amplitude and direction. In the definition of the WCW or FCW, the external and cable forces are not bounded. Considering the boundaries of cables and external forces, Ebert-Uphoff proposed the concept of the wrench feasible workspace (WFW) [90, 91], which is defined as the set of poses in which the end effector can generate a particular range of wrenches or resist a particular range of external wrenches with limited cable forces. For the CDPR with the point end effector, the WFW degenerates to the force feasible workspace (FFW) [92]. In addition, Verhoeven et al. [93] proposed a controllable workspace, and the physical meaning was equivalent to the WFW. Alikhani et al. defined the tensionable workspace of CDPRs [94] that is equivalent to the FCW. Barrette and Gosselin [95] proposed the concept of a dynamic workspace. The set of poses in which the end effector achieves dynamic balance under bounded acceleration and cable forces without external force is called the dynamic feasible workspace (DFW). Gagliardini [96] further proposed an extended version of the DFW by considering the external wrench, centrifugal force, and Coriolis force. Shao et al. [97] realized the unification of dynamic and static workspaces based on the weak equivalence principle by combining the gravity and inertial force into a new equivalent gravity.

Based on these definitions, the calculation methods for workspaces were established. Because the static workspace is simple, WCW and WFW are the primary focus. The null space method by solving the pseudo-inverse matrix [99] and the recursive method of matrix dimensionality reduction [89] have been proposed from an algebraic perspective. Zlatanov [99] and Dong et al. [100] established a feasible solution method for WCW and WFW based on the convex set theory. Gouttefarde et al. [101] established a solution method for WFW based on interval analysis. Abbasnejad et al. [102] proposed a ray-based method for solving the WCW. The interval analysis and ray-based methods are essentially global search methods, which define the boundary of the workspace through interval dichotomy or rays. For CDPRs with a simple structure, the geometric and force vector closure methods are feasible and intuitive.

The analysis and solution of the dynamic workspace are coupled with the terminal acceleration of the CDPR, which converts the analysis and solution of the dynamic workspace into a trajectory-planning problem, and the research on dynamic workspace primarily focuses on CSPRs. Research on dynamic trajectory planning of CDPRs can be divided into three types: periodic, point-to-point motion, and transition trajectory planning [103, 104, 105]. The planning of the dynamic trajectory primarily focuses on the feasibility of the trajectory. The commonly used trajectory forms are the polynomial and trigonometric function approximations of the pendulum trajectory [106, 107]. The performance of the dynamic trajectory can be gradually considered, such as the stability of the trajectory and the time–energy optimal principle.

Generally, the workspace of CDPRs is more challenging than that of rigid mechanisms, which are highly coupled with the cable forces and fundamentally determined by the configuration. The WCW is an ideal workspace that does not consider the boundary constraints of cable and external forces. The WFW is more practical, and its calculation methods are the primary focus. The cable-force distribution is dependent on the selection of the solution method such that the workspace obtained with different cable-force solution methods can change. The establishment of the dynamic workspace further expands the motion range of the end effector and transforms the analysis of the workspace into the solution of the trajectory.

3.4 *Stiffness*

The stiffness of the CDPRs is determined based on the cable forces. The cable-force distribution affects the stiffness matrix [108]. In early research, the spring model of the cable was used to establish the stiffness model of the CDPRs [109]. More accurately, the stiffness of a CDPR should be defined by the motion vector of the end effector caused by the wrench acting on it. When there is a slight change on the wrench ($d\boldsymbol{W}$), it will inevitably cause the corresponding small motion of the end effector ($d\boldsymbol{X}$), and the stiffness of the CDPR is defined as

$$\boldsymbol{K} = \frac{d\boldsymbol{W}}{d\boldsymbol{X}} = -\frac{d\boldsymbol{J}}{d\boldsymbol{X}}\boldsymbol{T} - \boldsymbol{J}\frac{d\boldsymbol{T}}{d\boldsymbol{X}} = \boldsymbol{K}_1 + \boldsymbol{K}_2 \tag{8}$$

The stiffness of the CDPR consists of two parts. $\boldsymbol{K}_1 = -\frac{d\boldsymbol{J}}{d\boldsymbol{X}}\boldsymbol{T} = \boldsymbol{H}\boldsymbol{T}$ is the static stiffness determined by the configuration, pose of the end effector, and cable forces. $\boldsymbol{K}_1$ is called the geometric stiffness matrix [110] or the active stiffness [111], which is related to the cable forces. The key to obtaining $\boldsymbol{K}_1$ is to calculate the Hessian matrix $\boldsymbol{H}$. Cui et al. [112] introduced an analytical method of deducing the Hessian matrix based on line geometry and directional cosines. Surdilovic [110] and Yeo et al. [113] proposed the calculation results of $\boldsymbol{H}$ based on Kronecker's product or tensor product.

$\boldsymbol{K}_2 = -\boldsymbol{J}\frac{d\boldsymbol{T}}{d\boldsymbol{X}}$ represents the stiffness generated by the change in the pose of the cables, which is called the cable stiffness matrix, also known as the passive stiffness. $\boldsymbol{K}_2$ depends on the configuration, pose of the end effector, and material properties of the cable. Compared with $\boldsymbol{K}_1$, the solution of $\boldsymbol{K}_2$ is much simpler, and is expressed as follows:

$$\boldsymbol{K}_2 = -\boldsymbol{J}\frac{d\boldsymbol{T}}{d\boldsymbol{X}} = -\boldsymbol{J}\frac{d\boldsymbol{T}}{d\boldsymbol{L}}\frac{d\boldsymbol{L}}{d\boldsymbol{X}} = \boldsymbol{J}diag\begin{pmatrix}\frac{E_1A_1}{l_1} & \cdots & \frac{E_mA_m}{l_m}\end{pmatrix}\boldsymbol{J}^{\mathrm{T}} \tag{9}$$

where E_i and A_i are the elastic modulus and cross-sectional area of the i-th cable, respectively, and l_i is the length of the i-th cable.

In redundant CDPRs, there are infinite solutions for the cable forces, which enables the adjustment of the stiffness of the CDPR through the cable-force distribution [114, 115]. Cui et al. [112, 116] studied the controllable stiffness of a CDPR based on static stiffness analysis and cable tension distribution to increase the stiffness consistency in the workspace. The variable stiffness device (VSD) has been designed to fine-tune and reduce the stiffness of the CDPR [113, 117, 118]. The VSD is generally composed of spring and rigid components embedded in the cable chain. In large-span CDPRs, the cable kinematics and force differ from those of small-span CDPRs because of the influence of the weight and flexibility of cables, and the stiffness changes. Du [119], Yuan [120], and Arsenault [121] explored the significant influence of cable mass and deformation on the stiffness of large-span CDPRs.

In summary, the basis of the design and analysis of CDPRs is the balance of the cable-force system, which is completely different from the kinematic analysis of rigid robots. The workspace, kinematics, and stiffness of the CDPRs are all related to the distribution of the cable forces. Currently, the cable-force distribution methods primarily solve the problems of feasibility and continuity of cable forces; however, research on the impact of the cable-force distribution on the performance (such as the ability to resist external forces, cable deformation, and terminal errors) is still lacking.

4. Performance Evaluation and Optimization

Dimensional optimization is an important method for a robot to obtain a good kinematic performance. The performance evaluation index is the standard for optimization, which makes the designs quantitatively comparable. Based on this, an optimization design method can be established using suitable mathematical tools, and the objective function is constructed with different performance indices.

The volume or area of the workspace is the most basic and commonly used performance index for the optimization of CDPRs [122, 123, 124]. However, it is often insufficient if only the size of the workspace is measured because there could be locus with poor performance inside the workspace. Indices used to measure the quality of the workspace have been proposed. The most common method is to adopt the conditioning number and dexterity indices of the parallel robots [125, 126, 127] to determine the global conditioning number and dexterity in the workspace based on the workspace size.

Cable-force distribution and stiffness indices have also been proposed for CDPR optimization. Yang and Pham [128] defined the index of the tension factor, which equals the ratio of the minimum cable force to the maximum cable force in the workspace. The tension factor was used to evaluate the quality of the FCW of a fully constrained CDPR. Duan et al. [48] proposed a standard deviation of cable forces in the workspace. Tang et al. [129] proposed an index as the variance of the cable forces over the minimum tension. The uniformity of the cable forces [130, 131] is often adopted as an optimization objective. In cable-driven rehabilitation robots, minimizing the maximum cable force is important because cable forces that act on the human body affect comfort and safety [132, 133, 134]. Shao et al. [135] evaluated the force exerted by a cable-driven exoskeleton on an arm by defining the maximum force index (MFI) and average force index (AFI). The dimensional parameters of the cable-driven exoskeleton were optimized using the MFI and AFI indices with the atlas method.

The stiffness of CDPRs is relatively low, and optimization is often performed to increase the stiffness [136, 137, 138]. To evaluate the stiffness performance, Li et al. [139] proposed an overall stiffness index (OSI). Cui et al. [140] proposed the concept of constant stiffness space (CSS) and used the maximum CSS as a performance index to optimize the parameters of the CDPR through the response surface model.

Specific and effective indices have been proposed for special types of CDPRs. Gouttefarde et al. [141] defined an index for heavy-duty CSPRs considering the maximum acceptable distance between the mobile platform geometric center and the payload mass center. Zhang et al. [142] defined the orthogonality-based local actuation index (OLAI) and the orthogonality-based local constraint index (OLCI) based on the orthogonality of the terminal actuation and constraint forces. The kinematic parameters of the high-speed TBot robot were optimized using the atlas method. Currently, orthogonality-based indices are only applicable to nonredundant CDPRs.

The optimal design of a CDPR is often a multiobjective optimization problem. Genetic and particle swarm algorithms have been widely adopted [132, 133, 134]. Jamwal et al. [143] proposed an evolutionary algorithm-based nondominated sorting algorithm (NSGA II) for multiobjective optimization problems. Scholars from Tsinghua University often use the atlas method to optimize designs [142, 144]. The atlas method visually displays the value variations of indices with the design variables to superimpose and select the optimal design parameters. However, the atlas method is only applicable when the number of parameters does not exceed three.

In summary, the existing performance evaluation indices for CDPRs primarily involve the workspace, dexterity, cable-force distribution, and stiffness. In fully and redundantly constrained CDPRs, the indices of stiffness and workspace are determined based on cable forces. It is necessary to determine the cable-force distribution method before performing the analysis and optimization, and the workspace and stiffness indices cannot be decoupled from the cable force. The aim of the performance evaluation is to rapidly determine the advantages and disadvantages of the configuration. The performance index should have a clear and unique value for a certain configuration. The Jacobian matrix and orthogonality-based indices can achieve this objective, but they are primarily used for nonredundant CDPRs. Performance indices and optimization design methods that are decoupled from cable forces should be studied in the future.

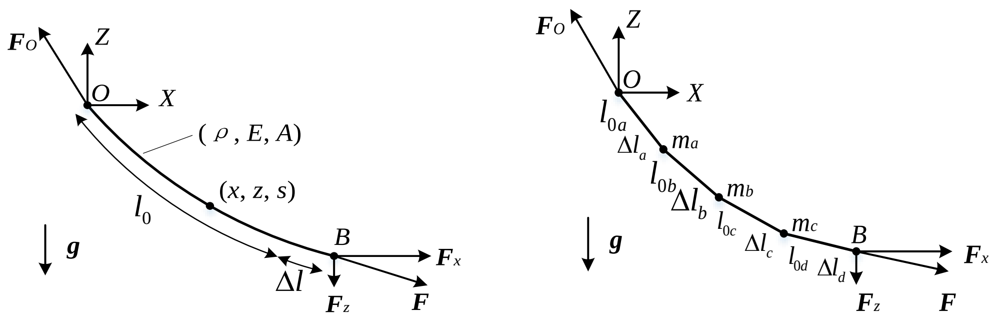
5. Dynamics

The key to CDPR dynamics is the modeling of cables. Depending on the cable's span and mass and CDPR configurations, there are four main types of cable dynamic models: the massless inelastic, massless elastic, continuous mass elastic, and distributed mass (or concentrated mass) elastic cable models.

In early research on the dynamic modeling of CDPRs, the massless inelastic cable model was used, and the cable mass and elasticity were ignored. The dynamic model of the CDPR is simplified to the dynamics of the end effector under cable and external forces. The Newton–Euler method [145], virtual work principle [146], Lagrangian method [147], and Kane's method [148] are used to build the dynamic model.

Furthermore, axial linear or nonlinear springs have been used for the elastic deformation modeling of cables under tension [149]. The massless elastic cable model is often used to model fully or redundantly constrained CDPRs with small spans [150], such as the BetaBot [108] and IPAnema [151]. Damping can be included, and the spring–damping model has been widely used in CDPRs [152, 153, 154]. In addition, the hysteresis and creep behaviors [155] can also be included in the spring–damping model. Choi [156] proposed an integrated nonlinear dynamic model of a polymer cable, and dynamic behaviors, such as the nonlinear elongation, hysteresis, creep, and short-term and long-term recovery, were described with the integrated nonlinear dynamic model based on the viscoelastic model.

For large-span CSPRs, the mass of the cable causes significant differences in the magnitude and direction of the cable force and results in significant modeling differences. A continuous-mass elastic cable model and a distributed mass (or concentrated mass) elastic cable model were proposed for large-span CSPRs to describe the dynamic characteristics caused by the self-weight and sagging effects of long cables [157] (Fig. 8).



(a) Continuous-mass elastic cable model (b) Distributed-mass elastic cable model

Fig. 13 Continuous-mass and distributed-mass elastic cable models

The continuous-mass elastic cable model corresponds more with actual CSPRs. The catenary or parabola [158, 159] is generally used to describe the shape of a cable. The finite element method (FEM) and the integral method are used for the dynamic modeling of continuous-mass or distributed-mass cables. The FEM is more popular because it is mature and intuitive [160, 161, 162, 163]. Tempel et al. [164] proposed a modified rigid-body FEM based on a rigid body and spring–damping elements and established a multibody dynamics model of a planar 3-DOF CDPR.

Ottaviano et al. [157] studied and compared four types of cable models and indicated that the key to selecting a suitable cable model is to solve the ratio of the end-effector mass to the cable mass or the ratio of the wrench on the end effector to the cable forces. The core is the balance between accuracy and model complexity. In addition, as mentioned in Section 2, rigid–flexible coupling or hybrid CDPRs were gradually designed and used. In the modeling of these new types of CDPRs, rigid–flexible coupling problems are encountered. The efficient modeling method of the rigid–flexible coupling model will be an important research direction in the future.

The vibration of the CDPR occurs owing to the elasticity of cables. Based on the elastic dynamic model, time-domain and frequency-domain vibration analyses can be performed. Three methods are commonly used in the vibration or stiffness analysis of CDPRs: (1) analytical analysis based on the simplified elastic model of CDPRs, (2) FEM, and (3) dynamic stiffness method. Diao et al. [149] analyzed the vibration of a fully constrained CDPR based on the spring string vibration model and indicated that the transverse vibration of cables can be ignored compared with the axial flexibility of cables for CDPRs. This conclusion confirms the reliability of the cable model as a longitudinal spring. Shao [157] and Liu et al. [165] analyzed the dynamic characteristics of the low-order natural frequency and mode shape of the feed support system of the FAST, based on the spring–damping concentrated mass model. The FEM is primarily used to analyze the vibration and mode of CDPRs under the conditions of distributed and continuous mass cable models [166, 167]. The accuracy of FEM depends on the number of elements; therefore, a strong trade-off exists between accuracy and computational complexity. Yuan et al. [168] proposed a vibration analysis method based on a dynamic stiffness matrix. The dynamic stiffness matrix method provides better accuracy than the FEM because it relies on frequency-dependent shape functions that are exact solutions of the governing differential equations.

For nonredundant CDPRs (primarily CSPRs), the FEM, continuous-mass-based catenary model, or parabolic model can solve the dynamics modeling problems well. However, for fully or redundantly constrained CDPRs, dynamic modeling and vibration analysis are more difficult because they involve cable-force distribution and deformation coordination conditions. In addition, there are also differences in the vibration characteristics of the two types of CDPRs. The vibration of the large-span CSPRs is primarily reflected in the low frequency and large amplitude, while the small-span redundant CDPRs are more manifested in the higher-frequency vibration. This results in differences in the vibration suppression control methods, which will be discussed in the following section.

6. Control

6.1 *Motion control*

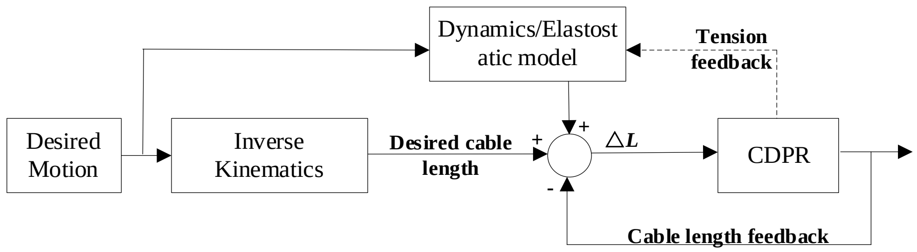
Control is the guarantee that the robot can achieve the required function. The most common method is kinematics-based cable length control [169], such as proportional–integral–derivative (PID) control based on the feedback of the motor encoder. Ensuring sufficient positive cable forces and the effectiveness of the kinematics control model are the primary challenges in the control of CDPRs [170].

However, owing to the self-weight and flexibility of cables, nonlinear and time-varying characteristics exist in the mapping of the encoder feedback and cable length. Closed-loop position feedback has been used in large-span CDPRs to increase the accuracy of kinematic control [171, 172]. In addition, Shang et al. [173] studied the synchronization error of CDPRs in the cable space and designed a synchronization controller to realize the coordinated movement between the cables and ultimately increase the tracking accuracy of the end effector.

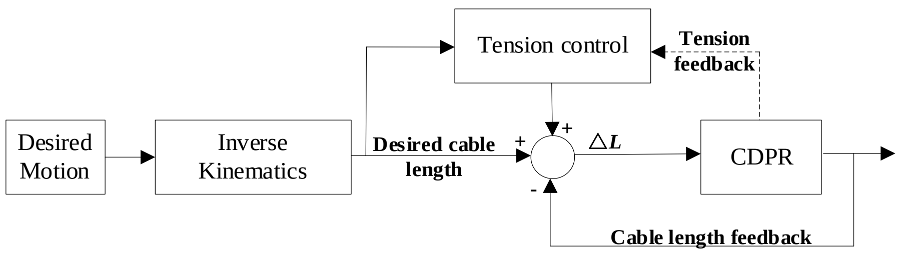
The elasticity of the cable interconnects the length deformation and cable force, which means that the cable force can be adjusted through cable length control in kinematics. Based on kinematic control, a dynamic or an electrostatic model can be adopted to establish the feedforward controls (Fig. 14(a)). The dynamic model can be adopted to predict the cable force based on the motion status and adjust the cable length accordingly [174]. In addition, the cable force can be measured using sensors, and the cable lengths are adjusted according to the cable force deviation [166], avoiding cable sagging [175]. Baklouti et al. [176] studied a feedforward control scheme based on an elasto-dynamic model that could reduce the vibration caused by the elasticity of the cables. When the length and force of the cables are measured, cascade control can be established (Fig. 14(b)). The dynamic or cable-force control logic can be rearranged as a secondary controller to receive the output of the kinematic model and control the cable length. Abdelaziz et al. [177] discussed a cascade position control strategy for CDPRs with an internal cable-force control loop.

Model-based controls require accurate parameters. However, owing to the existence of uncertainty and error, some parameters in the models cannot be accurately determined or obtained. In such scenarios, nonlinear and intelligent control methods that do not rely on accurate models have been adopted, such as fuzzy and adaptive control. For an improvement in the traditional PID control, fuzzy PID controllers have been developed and used [178, 179] to adjust the gain parameters more robustly when encountering disturbances and parameter uncertainties. Fuzzy sliding-mode controllers have also been used. For example, Zi et al. [180] established an adaptive fuzzy sliding mode controller for a hybrid CDPR. Babaghasabha et al. [181, 182] designed an adaptive robust sliding mode controller based on the upper limit of uncertainty and a composite robust controller based on singular perturbation theory to counteract the unstructured and parameter uncertainties of CDPRs. Tajdari et al. [183]

proposed the robust control of a 3-DOF CDPR with an adaptive neuro-fuzzy inference system. The developed PID controller was used to provide a learning dataset for training a neural network. The well-trained network was used to control the CDPR. Asl et al. [184] developed a new nonlinear controller with a learning ability to compensate for modeling uncertainty that adopted an adaptive multilayer neural network to solve time-varying external interference.



(a) Feedforward control based on kinematics



(b) Cascade control based on kinematics

Fig. 14 Control block diagram

In addition to the above-mentioned controllers, performance-enhanced controllers based on specific CDPRs have also been developed. Yu et al. [185] studied an enhanced trajectory-tracking control with active stiffness control. The controller implements stiffness adjustment in the workspace by optimizing the cable-force distribution. Zarei et al. [186] proposed the concept of phase trajectory length and oscillation index and used new concepts to optimize the controller gain parameters to reduce the oscillation of a system. Jamshidifar et al. [187] studied the vibration decoupling modeling and robust control of redundant CDPRs and used linear parameter-varying (LPV)-H_∞ control to suppress the adverse effects of external interference on the trajectory tracking performance of the end effector.

6.2 *Vibration suppression control*

Vibration suppression is a key and challenging problem in both the theory and application of CDPRs. These methods can be divided into two categories: passive and active vibration suppression.

Passive vibration suppression uses the damping and friction of the robot itself to dissipate the vibration energy. Because the efficiency is low, the robot must pause and cannot guarantee a continuous movement of the end effector. Extra dampers can be added to accelerate the dissipation of vibration energy [188, 189, 190], but they are only efficient for the vibration of a pre-designed target frequency and are difficult to apply to CDPRs whose vibration characteristics vary with terminal poses.

Active vibration suppression restricts the vibration amplitude within a limited range by implementing active continuous control, which does not interrupt the continuous movement of the CDPR and is the main method used. Active vibration suppression primarily uses three methods: pose compensation, internal force, and input filtering. Pose compensation is achieved by directly or indirectly measuring the end-effector error in real time and transforming the error into the cable space of the robot to perform kinematic compensation [191, 192] or adopting an additional small robot [193]. Internal force vibration suppression eliminates or reduces the vibration of the end effector by controlling the cable forces or the reaction force of an additional mechanism. Rushton et al. [194] proposed a control strategy to eliminate out-of-plane vibrations in a planar CDPR by controlling the cable forces. Rijk [195] and Rushton et al. [196] proposed a vibration control method that adds a multiaxis response system (MARS) to a planar CDPR. When the rigid pendulum swings, it generates a reaction force and torque on the end effector to achieve vibration suppression. Input filtering, also known as input shaping, is an open-loop control technique that eliminates self-excited vibrations at a certain frequency. Korayem et al. [197] used a robust input shaper to prevent the excitation of natural modes. Montgomery et al. [198] used a dual-mode zero-vibration–extra-insensitive (ZV-EI) shaper to reduce the vibration of suspended SkyCam robots.

Large-span CDPRs usually have lower frequencies and narrower control bandwidths, which are more prone to low-frequency and large-amplitude vibrations. Therefore, an additional mechanism is frequently required to perform pose compensation or internal force vibration suppression. For small-span CDPRs, while most of them are redundant CDPRs, they have higher vibration frequencies and a wider control bandwidth. Vibration suppression methods that control cable lengths or forces are applicable.

Control is the main method used to determine the function and performance of CDPR and has become the focus of research in the field of CDPRs. Model-based feedforward control, feedback linearization, cascade control, and adaptive robust control appear one after another. It is foreseeable that fuzzy control, adaptive control, and even intelligent control will become the mainstream of future research with increased accuracy requirements and an in-depth analysis of the system uncertainty and nonlinear factors. Vibration is an eternal topic of CDPRs and is a main factor that limits the application of CDPRs. The efficient vibration control of CDPRs is an important breakthrough in its applications.

7. Outlook

As a novel type of parallel robot, CDPRs use cables instead of rigid chains to drive the end effector, which embodies the high-performance development trend of robots, reflects the advanced lightweight concept, and has inherent advantages in rigid–flexible fusion and serial–parallel hybrid configurations. CDPRs have significant advantages such as large workspace, low inertia, high dynamic characteristics, low cost, simple structure, and easy reconstruction, with successful applications in various fields. Additionally, the unidirectional force characteristics of the cable result in tension constraints and uniqueness in the configuration design, while cable flexibility challenges the modeling and control of CDPRs. The future research and application prospects of the CDPRs are shown in Fig. 15.

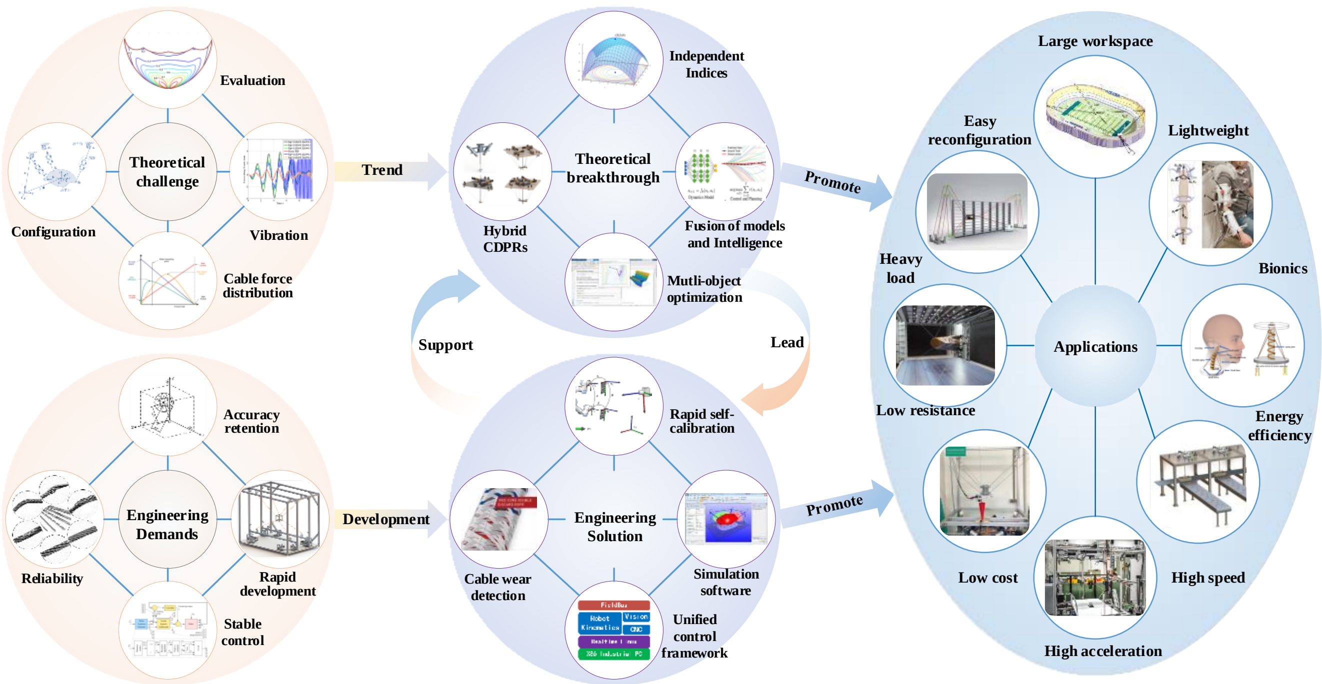


Fig. 15 Research and application prospects of CDPRs

Generally, cables are good at transmission and weak at constraints. The configuration composed of only cable chains is limited. The configuration and DOFs are enriched by adopting new structures. The combination of rigid chains, parallel cables, and passive tensioning elements improves the performance and practicability of CDPRs and has become an emerging trend in configuration design. Parallel cables and rigid chains can improve the constraint capability, while passive tensioning elements can prevent driving redundancy. In the future, hybrid CDPRs will become popular, and they can be closely integrated with bionics. Moreover, inspired by animals, high-redundancy CDPRs can be a potential solution for more efficient and compact structures. Reconfigurable and modular CDPRs will also be a direction for future research and application of CDPRs.

Effective static analysis and cable-force distribution methods have been proposed to ensure positive and bounded cable forces. Because the cable forces directly affect the performance, vibration, and control of the CDPRs, more factors should be considered in the cable-force distribution based on real-time requirements. The solution of cable forces with more reasonable constraints should be explored, such as the energy efficiency, uniformity of cable forces, and stiffness. The polygon methods focus on a rapid determination of the vertices of the feasible region of the cable-force polygon according to the configuration of the CDPR. A method to perform multiple-object optimization would also be meaningful.

The workspace of CDPRs is more challenging than that of rigid mechanisms, which are highly coupled with cable forces. Performance indices that are decoupled from the cable force and directly based on configuration require further in-depth research, which will create the foundation for optimized designs. Coupling with the cable force provides an approach for the stiffness adjustment. The stiffness modeling of cable-driven multibody robots and hybrid CDPRs requires further research. Stiffness adjustment based on the cable-force distribution still lacks precise quantitative research and is worth investigating in the future.

As the performance requirements of the robot increase, the accuracy of the kinematic and dynamic models of CDPRs continues to improve with the pulley kinematics and the continuous-mass elastic cable model. Considering the configuration innovation, the modeling of rigid–flexible coupling hybrid CDPRs will be an important research direction in the future. The balance of accuracy and model complexity should be considered when adopted in the control. Because terminal accuracy is frequently the most important parameter of a robot, kinematics-based control is widely used in CDPRs. Elastostatic and dynamic models are adopted to improve performance. Comprehensive optimization of the configuration design and control, as well as the fusion of models and intelligent algorithms, will be expected to further improve the comprehensive performance of the control system.

In terms of application, CDPRs have been successfully used in the fields of astronomical telescopes, lifting and handling, motion simulators, rehabilitation, and bionics. CDPRs will be promoted in more fields in the future with a solid industrial foundation, and the following challenges require consideration.

1) The reliability and service life of CDPRs. The CDPR cables easily wear and break during operation, and it is difficult to guarantee the sustainable and reliable operating time of the CDPRs. There is a lack of relevant research and specifications for the durability of CDPRs, such as cable wear detection and replacement specifications. The Liebherr corporation has conducted related research and proposed vision-based cable wear detection [199].

2) The accuracy retention of CDPRs. Owing to factors such as the reconfiguration, nonlinear deformation of cables, and creep of cables under long-term tension, it is difficult to guarantee the accuracy retention of CDPRs. Accuracy degradation has an important impact on their application, particularly in industrial applications. Rapid self-calibration is a feasible approach.

3) The vibrations control of CDPRs. CDPRs are prone to vibration owing to cable flexibility and low rigidity. Although various vibration suppression methods have been proposed for CDPRs, they are often specific and lack versatility for different types of CDPRs. In actual implementations of vibration suppression controls, the requirements for the controller are relatively high, and the cost is high. A unified framework for the control hardware and software should be proposed.

4) The rapid development cycle of CDPRs. On one hand, the industrial infrastructure of CDPRs is still insufficient, such as high-performance ropes, drive modules, and control systems. On the other hand, there is a lack of mature software that supports the efficient analysis and development of CDPRs. The software CASPR [200] developed by Lau et al. and WireX [201] developed by Pott et al. have been good attempts, but continuous improvement is still required.

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