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Applications and Control of Cable-Driven Parallel Robot: A Review

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HIGHLIGHTS

- This paper gives a review of cable driven parallel robot, its types, applications, modelling and control.

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ABSTRACT

A cable driven parallel robot (CDPR) is a specific kind of parallel robot that utilizes cables as opposed to traditional rigid links to perform their functions. This gives it the advantages of being lightweight, having a wide operational workspace, and being easier and less expensive to implement than alternatives since it only requires cables operated by motors and fixed to a structure suitable for a certain application, allowing them to move and rotate an end-effector. The concept of this robot is not new though using a fully automated version of it was only started in the mid-1980s and witnessed extensive research in the past two decades. This paper gives a review of this robot, its types, applications, modelling and control which is helpful in shortening the time for researchers in this area. CDPRs are still a fruitful area for research like exploiting it in new applications or improving and designing new control strategies.

I. INTRODUCTION

Robots significantly contribute to daily life in the modern era by improving several areas of industry, military, and services in general. Regarding their configurations of connections, robots can be divided roughly into two major categories of serial robots and parallel robots. Serial robots with arm-like shapes share the open-loop architecture of having a single kinematic chain that consists of a sequence of links and actuated joints from the base to the end-effector. Alternatively, parallel robots, introduced in the 1960s, consist of several kinematic chains in a closed-loop structure, with the links being attached to actuators mounted on the base. Parallel robots can be thought of as multi-serial robots with a common end effector. They are similar to some of the multi-degree joints in the human body, like the neck [1].

It is important to note that the key difference between these two classes is in topology, not geometry. Both types have their own advantages and disadvantages; however, an important limitation

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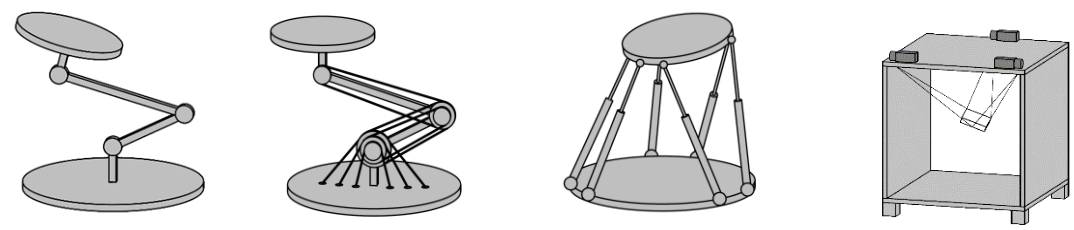
in both of these categories is the payload-to-weight ratio. That is, to either expand the workspace extent or the end effector weight, the robot structure has to be considerably heavier. Parallel robots are better than serial robots in this respect because in parallel robots the actuators are mounted at the base instead of the joints, and most of the bending effects due to added weight are converted to buckling effects. That said, their stiff structure creates a limit on the allowable weight of the payload.

One of the promising solutions to this problem is the use of cables instead of rigid links in parallel robots. Since Landsberger presented the first cable-driven parallel robot (CDPR) in the 1980s, CDPRs have gained significant popularity because of their optimal payload-to-weight ratio, ability to move over large distances, and simplicity of reconfiguration. The actuating cables of CDPRs can only generate tension forces, which requires the use of actuation redundancy to ensure full motion in all degrees of freedom without the need for external forces. These features impose serious difficulties in CDPR modeling, design, analysis, and control [1]-[3]. *Fig. 1*. illustrates a sketch of the main types of robots [4].



(a) (b) (c) (d)

FIG. 1. (A) SERIAL ROBOT (B) CABLE DRIVEN SERIAL ROBOT (C) PARALLEL ROBOT (D) CABLE DRIVEN PARALLEL ROBOT.

II. CDPR CLASSIFICATION

CDPRs operate by having several cables that join the end effector to the base. They control the motion of the end effector by altering the length of the cables or the attachment points of the cables. Verhoeven (2004) came up with a complete classification approach that considers the constraint capacity of cables, in addition to establishing the relation between the number of cables, c, and the end-effector degrees of freedom d. When ($c < d$), this is the under-constrained mechanisms, where CDPRs require particular forces for operation and balance, and cannot accept arbitrary external forces. They are comparatively rare due to problems of instability and uncontrollable degrees of freedom. When ($c = d$), this is the incompletely constrained mechanisms, where CDPRs, though kinematically fully constrained, nonetheless require supplementary forces to come to equilibrium. When ($c = d + 1$), this is the fully constrained mechanisms, where CDPRs can determine end-effector poses using only the cables. Both motion and force constraints are controlled using cable tension.Finally, when ($c > d + 1$), this is the redundantly constrained mechanisms. CDPRs contain redundant constraints that allow multiple static equilibrium solutions since there are more kinematic constraints than degrees of freedom [4][5].

CDPRs can be categorized according to their workspace into two classes: planar and spatial. Planar CDPRs move in a planar or two-dimensional workspace that is mainly vertical in orientation. Spatial CDPRs move in a three-dimensional space with the end-effector having the facility to displace in translation, rotate, or both.

Furthermore, Verhoeven [4] introduced a classification of CDPR based on the number of degrees of freedom being controlled and is shown in and *Fig. 2*. Possible degrees of freedom classes (R stands for rotational, T for translational degrees of freedom).

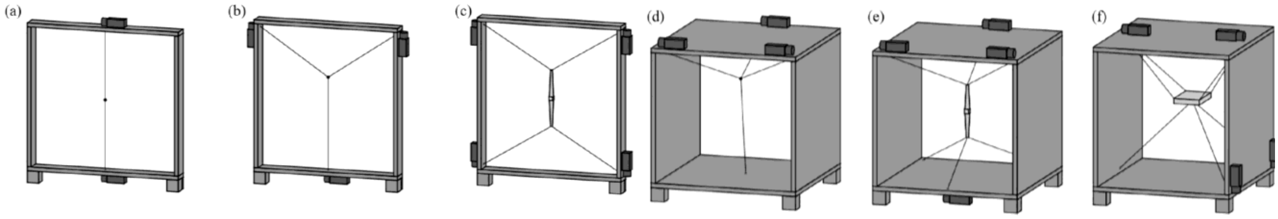


FIG. 2. CLASSIFICATION OF CDPRS BASED ON THE NUMBER OF CONTROLLED DEGREES OF FREEDOM [4] (A) LINEAR MOTION OF A BODY, 1T (B) PLANAR MOTION OF A POINT, 2T (C) PLANAR MOTION OF A BODY, 1R2T (D) SPATIAL MOTION OF A POINT, 3T (E) SPATIAL MOTION OF A BEAM, 2R3T (F) SPATIAL MOTION OF A BODY, 3R3T.

Based on cable arrangement, CDPRs are categorized as Suspended and Non-suspended CDPRs. A CDPR is considered suspended when all its driving cables are in the position above the end-effector plane, with gravity functioning as an additional stabilizing force. Their workspace is mostly below the fixed cable anchor points, and the design heavily considers payload capacity. It can be said that for suspended CDPRs, they use an extra hidden cable, which is gravity, to ensure the required tension. Non-suspended CDPRs are more robust and fit better for precise and fast applications but they cannot be employed in a large workspace because the cables interfere with other objects. Therefore, suspended CDPRs have more applications and research interest despite the challenges in stability and acceleration [6].

These classifications and characteristics guide the design, modeling, analysis, and control of CDPRs, making them versatile for various applications.

III. APPLICATIONS OF CDPR

CDPRs are gradually taking their place in a wide range of applications with the motivations behind their increasing popularity is clear. Their lightweight design, convenience of installation, and astounding flexibility mean that these systems become a tempting supplement to traditional industrial robots. Unlike heavier robots, CDPRs can be rapidly installed and readily moved, and so are ideally suited to challenging environments. They are perfect for use when space is limited, payload capacity or cycle times are critical. As explored in detail in [1], CDPRs are opening up new applications in areas where traditional robotics faces physical confinements or operational constraints.

A. Cable Camera System

A suspended cable camera system is a type of CDPR that is designed to stay out of the camera's view. Its suspended nature relies on the force of gravity, which translates to a reduced degree of stability and greater vulnerability to external vibrations in comparison to ground-anchored systems. When the camera platform is purely passive, meaning all motion is controlled solely by the cables, it is necessary for the number of cables or actuators (c) to be equal to the number of degrees of freedom (n). Failure to achieve this balance creates an under-constrained system, which, in turn, leads to additional control issues related to reduced stability [1].

To work on these difficulties, professional cameras often have specialized rotational degrees of freedom that allow independent control of pan (rotation about the horizontal axis), tilt (rotation about the vertical axis), and roll (rotation about the camera axis). This separate segregation makes the cable control system more efficient, as it can focus entirely on translational motion [7].

Depending on the purpose of use, cable cam systems are grouped into 1T, 2T, and 3T according to their translation movement capabilities. A 1T system provides one-dimensional point-to-point motion at high speed, making it especially useful in fast sports like racing. Robyline by Movicom [8] is a typical example of such a type, and it is shown in *Fig. 3a*. The 2T setup provides two-dimensional motion in the vertical direction, which is useful in locations where horizontal mobility is constrained or dangerous; CamCat 2D [9] in *Fig. 3b* is a good example. For complete three-dimensional mobility, 3T systems use three or more cables to move the camera in space with complete freedom. These systems are highly praised in sports coverage and event production because of their ability to offer sweeping and cinema-like images. An example of such a device is RobyCam 3D, as shown in *Fig. 3c*, where it is suspended over a football stadium by four cables [10].

(a) (b) (c)

FIG. 3. (A) 1T CABLE CAMERA SYSTEM (B) 2T CABLE CAMERA SYSTEM (C) 3T CABLE CAMERA SYSTEM.

B. Cable Robot Crane

CDPRs are widely used in many industries and often grouped in the broad umbrella of cable robot cranes. These flexible systems have been applied in a wide range of applications that include pick-and-place tasks, construction, welding, painting, cleaning, and assembly [1][2].

One of the early applications of CDPRs was cable crane. The NIST RoboCrane [11] was CDPR prototypes have been carefully designed with the aim of enabling pick-and-place tasks and warehouse automation. In addition to that, robust CDPR architectures with optimal performance in thus field have been developed, as discussed in research by Picard [12] and Zhang et al. [13]. A novel under-constrained design of CDPR put forth by Kumar [5] takes the state of the art to the next level by placing actuators and control units in the end-effector and thus improving efficient handling on production lines.

A significant area of use is automated warehouse management in which CDPRs were successfully employed to handle materials and streamline logistic functions, studied in research by Alias et al. [14]. Practical application of CDPRs in crane systems was investigated with the objective of improving the efficiency of conventional cranes by increasing dexterity and improving the working space. Lessanibahri et al. [15] discussed a framework for determining the suitability of CDPR structures for lifting operations based on considerations such as wrench closure and deployment time. These are considered critical for dynamic and versatile crane systems. Cardou et al. [16] took this discussion further by focusing on the time-optimal motion planning of CDPRs for crane operations, illustrating how dynamic constraints and collision avoidance are managed through a convex optimization-based method. Since then there are several advances in developing crane CDPRs. Han et al. [17] developed a reconfigurable CDPR that is aimed to maintain stability and prevent tipping in lifting operations, an important consideration for the use of cranes. This approach enables the robotic crane to handle higher cable tensions in a secure way while considerably increasing its working space to enhance its productivity and versatility for operations requiring dynamic load handling and precise end-effector placement. The varying load weight could be a challenge that need more research to handle efficiently. *Fig. 4.* illustrates two examples of using CDPRs in logistic operations [18][19].

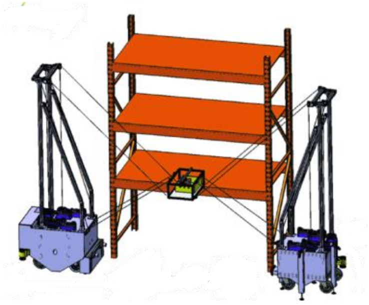


FIG. 4. (LEFT) A COOPERATIVE CRANE SYSTEM BEING USED TO MOVE AN HEAVY OBJECT [18]. (RIGHT) A CDPR MOUNTED ON TWO MOBILE PLATFORMS [19].

C. Rehabilitation

Robots in rehabilitation and physical therapy have proven its effectiveness and reduced the need for extra healthcare givers. CDPRs have been used in this field as alternative handy robots with some advantages over classical exoskeleton robots such as flexibility and extra workspace [20].

Cable-based robots that can be used in rehabilitation purposes can be categorized into two main groups: exoskeleton-based robots and end-effector-based robots. Exoskeleton-based robots mimic the skeletal limb of the human and use robot joints that mimic the motion of the joints of humans. On the other hand, end-effector-based robots use their end-effectors to act on a single body part without imposing motion and force on other parts of the body [21].

Moreover, these robots are classified as serial and parallel robots based on their linkage arrangements. They can be summarized as follows [22]:

- *Serial exoskeleton-based cable-driven robots* have robotic joints with a single degree of freedom revolute axes arranged in series, thus providing several degrees of freedom to achieve higher flexibility.
- *Serial end-effector-based robots* employ cable-driven revolute axes and series-interconnected link arrangements.
- *Parallel exoskeleton-based Robots* use cable-driven parallel mechanisms to offer multiple degrees of freedom simultaneously.
- *Parallel end-effector-based robots* have an end-effector driven by cables in parallel.

The last two resemble CDPRs.

Exoskeleton-based rehabilitation CDPRs were proposed to rehabilitate different parts of the body such as the hand [23], arm [24], shoulder [25], hip [20], and ankle [26].

End-effector rehabilitation CDPRs are more flexible than the previous one because the robots' actuators are not directly attached to the patient's body. Additionally, the same CDPR can be modified for rehabilitation of different body parts with some adjustments. A major drawback of this technology is its large and non-portable structure, along with the fact that it cannot rehabilitate more than one body part at a time [22]. Similar to exoskeleton-based rehabilitation CDPRs, They have been used to provide rehabilitation to different areas of the body. Some prominent examples include rehabilitation of the head-neck joint [27], upper limbs [28][29], and lower limbs [30]. *Fig. 5*. illustrates two examples of using CDPRs for upper limps rehabilitation [31][32].

FIG. 5. (LEFT) EXSKELITON CDPR FOR HAND REHABILITATION [31]. (RIGHT) END-EFFECTOR CDPR FOR ARM REHABILITATION [32].

D. Other Applications

Using One of the major scientific projects conducted in China’s “Eleventh Five-Year Plan” is the Five-hundred-meter Aperture Spherical radio Telescope (FAST), an innovative project that utilizes a six-cable, six-degree-of-freedom suspended CDPR to precisely track celestial radio sources [33]. Its sketch is shown in *Fig. 6.(a).*

In the field of amusement rides, the suggested a CDPR amusement ride (*Fig. 6.(b)*), as explained by Verl et al. [34], is a novel design where a end-effector is attached to a support frame by articulated elements and variable-length cables. The cables are driven by winches to allow dynamic motion and adjustment.

CDPRs have proven useful in farm practice with regard to optimizing the efficient use of available resources in current farming systems [35].

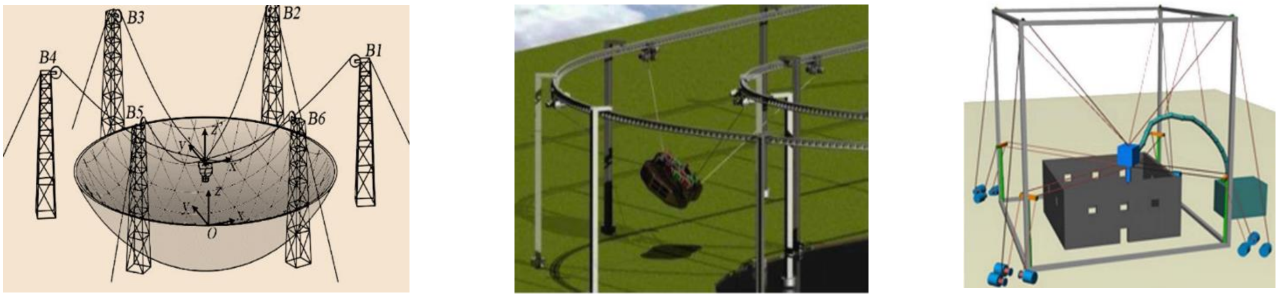
In the heavy industry field, Zheng et al. [36] presented a novel cable-driven parallel robot dubbed the “flying carpet” for the maintenance of huge 10,000-ton steel ships.

Additionally, CDPRs are being integrated into automated construction applications. Construction 3D printing is considered an Innovative technology because of the design flexibility and low cost [37]-[40]. *Fig 6.(c)* shows a 3D printing of ahouse. Barnett and Gosselin [41] presented a prototype CDPR as a 3D printer employing polyurethane foam as the structure material. Contour crafting Cartesian CDPR was presented by Bosscher et al. [42]. Automated masonry CDPR presented by Bruckmann and Boumann [43] as a cost-effective CDPRs for all levels of constructions.

CDPRs were used to hold objects in wind tunnel testing machines. Because of using cables, they minimally interfere with air stream flow used in the test [44]-[46].

Shao et al. [47] presented a planar CDPR to perform the external cleaning of buildings. This work was an extension of previous work in the same field [48][49]. Cleaning CDPRs are not exclusive to us on building. Underwater liter removal CDPR is presented by Gouttefarde et al. [50]. Equipped with sensors and grippers, it was used to detect and handle marine litter. Also, a primary lamella sedimentation tank cleaning CDPR was proposed by Leung et al. [51]which replaces the need for labor in dangerous tasks.

Other applications of crane-like large-scale CDPRs include collections of concentrated solar power plants [52], maintenance of large ground-deployed solar panels [53] and many other tasks necessitate positioning specialized equipment around large workpieces, such as ships, airplanes, windmill blades, and steel structures.



(a) (b) (c)

FIG. 6. (A) FAST [33] (B) CDPR AMUSEMENT RIDE [34] (C) CONTOUR CRAFTING OVERCONSTRAINED CDPR [37].

IV. KINEMATICS AND DYNAMICS OF CDPR

This section focuses on the systematic derivation of a complete task-space kinematic and dynamic model for a general spacial CDPR of 3T3R. The other structures are a simplified structure of this one. Furtheremore, the model forms the basis for adaptive control strategies that make use of the linearity-in-parameters nature that exists both in the kinematics and the dynamics. By careful mapping of the interrelations between different coordinate spaces, the aim is to obtain a formulation that is computationally efficient and well-suited for real-time control implementations.

The CDPR is assumed to have a fixed base and an end-effector that are connected by m cables as shown in *Fig. 7*. A_i is the base attachment point of the i^{th}cable and, B_i is the end-effector attachment point of i^{th} cable. A global coordinate frame O-xyz is fixed at the base. A local coordinate frame P-xyz is attached to the end-effector center of mass. The pose of the end-effector, $X = [p^T\ \phi^T]^T$, consists of a position vector, $p = [x\ y\ z]^T$, and an orientation vector, $\phi = [\alpha\ \beta\ \gamma]^T$.

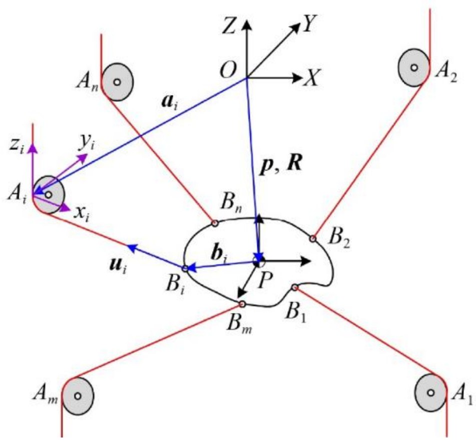


FIG. 7. KINEMATIC DIAGRAM OF A CDPR [2].

The length of the i^{th}cable l_i is determined by the vector loop equation [54]:

$$l_i \cdot u_i = Rb_i + p - a_i, (i = 1, \dots, m) \tag{1}$$

where a_i is the position of A_i in global frame, b_i is the position of B_i in end-effector frame and u_i is the unit vector along the i^{th}cable direction given by:

$$u_i = \frac{Rb_i + p - a_i}{l_i} \tag{2}$$

The rotation matrix R, which transforms coordinates from the end-effector frame to the base frame, is expressed as:

$$R = \begin{bmatrix} c_\beta c_\gamma & c_\gamma s_\alpha s_\beta - c_\alpha s_\gamma & s_\alpha s_\gamma + c_\alpha c_\gamma s_\beta \\ c_\beta s_\gamma & c_\alpha c_\gamma + s_\alpha s_\beta s_\gamma & c_\alpha s_\beta s_\gamma - c_\gamma s_\alpha \\ -s_\beta & c_\beta s_\alpha & c_\alpha c_\beta \end{bmatrix} \quad (3)$$

where $c(\cdot) = \cos(\cdot)$ and $s(\cdot) = \sin(\cdot)$.
If q is set to be the vector of cable lengths (joint space) then its time derivative relates to the end-effector velocity via the Jacobian matrix $J(X)$:

$$\dot{q} = J(X) \cdot \dot{X} \quad (4)$$

where $J(X) \in \mathbb{R}^{m\times n}$ is structured as:

$$J(X) = \begin{bmatrix} u_1^T \times (Rb_1) \\ \vdots \quad \vdots \\ u_m^T \times (Rb_m) \end{bmatrix} \quad (5)$$

This kinematic relationship is linear in a set of parameters θ_k, enabling the representation:

$$J(X) \cdot \xi = Y_k(X,\xi) \cdot \theta_k \quad (6)$$

where $\xi \in \mathbb{R}^n$ is an arbitrary vector, $Y_k$is a kinematic regressor matrix and $\theta_k$is a vector of kinematic parameters

The task-space dynamics of the end-effector are governed by the general equation of motion:

$$M(X)\ddot{X} + C\big(X,\dot{X}\big)\dot{X} + G = J^T T \quad (7)$$

where $M(X)$ is the inertia matrix, $C\big(X,\dot{X}\big)$is the oriolis and centrifugal effects, G is the gravity force and T is the cable tension vector. The joint-space dynamics (actuators dynamics) are governed by the general equation of electrical motors:

$$I_m\ddot{q} + F_v\dot{q} + F_c \cdot \text{sign}(\dot{q}) + NT = \tau \quad (8)$$

where $I_m$is the actuator inertia, $F_v$is the viscous friction, $F_c$is the coulomb friction, N is the transmission matrix, and τ is the actuator torque. Solving for tension T yeilds:

$$T = N^{-1}(\tau - I_m\ddot{q} - F_v\dot{q} - F_c \cdot \text{sign}(\dot{q})) \quad (9)$$

Substituting into the task-space dynamics yields the full coupled dynamic model:

$$M(X)\ddot{X} + C\big(X,\dot{X}\big)\dot{X} + G + J^T N^{-1}\big(I_m\ddot{q} + F_v\dot{q} + F_c \cdot \text{sign}(\dot{q})\big) = J^T N^{-1}\tau \quad (10)$$

Applying the kinematic relationships $\dot{q} = J\dot{X}$ and $\ddot{q} = \dot{J}\dot{X} + J\ddot{X}$, we obtain the extended task-space model:

$$M_e\ddot{X} + C_e\dot{X} + G_e + F_e = \tau_e \quad (11)$$

where: $M_e = M + J^T N^{-1} I_m J$is the extended inertia matrix, $C_e = C + J^T N^{-1} I_m \dot{J}$ is the extended Coriolis matrix, $G_e = G$, $F_e = J^T N^{-1}\left(F_v J\dot{X} + F_c \cdot \text{sign}\big(J\dot{X}\big)\right)$, and $\tau_e = J^T N^{-1}\tau$.

The derived model preserves some key characteristics that are important for controller synthesis:

- Positive Definite Inertia Matrix: M_e is a symmetric and positive definite.
- Skew-Symmetry: $\dot{M}_e - 2C_e$ is a skew-symmetric.
- Linearity in dynamic parameters: The dynamics can be expressed as a regression relationship:

$$M_e\ddot{X} + C_e\dot{X} + G_e + F_e = Y_d\big(X,\dot{X},\ddot{X}\big)\theta_d \quad (12)$$

where $Y_d$is the dynamic regressor matrix and θ_d is the vector of dynamic parameters (inertia, friction, gravity terms, etc.). The regressor Y_d depends on estimated kinematic parameters $\hat{\theta}_k$. It can be updated online, enabling adaptive parameter estimation $\hat{\theta}_d$ during control execution [55].

V. CONTROL OF CDPR

In the early stages of CDPRs development in the 1980s, the focus was mainly on basic design, kinematic modeling, and workspace analysis, thus laying groundwork for subsequent control strategies and applications. Investigating all the strategies is not a feasible task because every case is unique in dealing with a specific structure and application demands. This section aims to skim the main controllers used in this subject in general.

The control of CDPRs is more challenging in comparison to conventional parallel robots with rigid links because of the unique nature of cables. The low inherent stiffness of these systems also hinders the exact control of both position and orientation of end-effector. Additionally, the need to have all cables in positive tension to obtain control requirements places extra constraints on control system design [56]. Kinematics and Dynamic control methodologies are generally the most used by CDPRs. Kinematic control methods rely on inverse kinematics transformations to convert desired manipulator end-effector trajectories to appropriate cable length commands. On the other hand, dynamic controllers take into account the nonlinear nature of the dynamics to provide faster and more precise control [57].

Choosing the right controllers depends on some other conditions such as [12]:

- *Linear / Nonlinear CDPRs*: In some structures of CDPRs, they ca work as MIMO linear system.
- Under-actuated / Over-actuated CDPRs: This concept has been explained earlier here and they relate to the concept of under-constrained/over-constrained CDPRs. Over-actuated CDPRs are hard to apply forward kinematics control methods on them. Underactuated CDPRs are more challenging and there are much recent research to handle their stability [5][58][59]. It is possible for CDPRs to be over-actuated but under-concentrated. It is called “flat system” [60].
- *Certain / Uncertain CDPRs*: CDPRs are uncertain systems by nature but can be considered certain in some cases for simplicity. The uncertainty comes from different factors such as cable sagging, cables elasticity, cables weight, variable end-effector weight, unmodeled parameters in the CDPRs and actuators dynamics, and sensors noise.
- *Joint / Task space*: Joint space in CDPRs is when cable lengths and actuator angles are considered in the design of the controller. Task space is when the Cartesian position of the end-effector is the observed parameters. Some control designs work on both spaces [61].
- *Position / Force control*: Position control is achieved through re-arranging motor positions to change the cable lengths and thus controlling the end-effector position. On the other hand, force control enables end-effector positioning through control of cable forces at their point of attachment to form a combined wrench composed of force and torque exerted on the end-effector.
- *Centralized / decentralized control*: Decentralized control approaches take center stage in literature. In this design framework, a controller is assigned to each cable separately, thus enabling individual control. In CDPRs, this is achieved by using individual Single Input Single Output (SISO) controllers for each motor, where each controller is responsible for its own respective path. As a result, coordinated motion of the end-effector is achieved through the combined efforts of the individual motors in synchronism. Centralized methodologies are rarely used because they are complex in nature, and they need to have a complete grasp of the CDPR model.

Adequate control is important in making sure that a robot can effectively perform its prescribed operations. One of the earliest specialized control strategies for CDPRs was the technique presented in [62]. The strategy adopted in this work used a nonlinear decoupling control law based on the dynamic model of the robot. A proportional controller was used to counter the difference between desired and sensed cable lengths, and desired cable lengths were generated through a trajectory generation process. One common form of control of CDPRs was in the control of cable lengths according to kinematic theory. Through the past two decades there have been many advances in using different controllers for CDPRs. Categorizing the controllers is not an easy job because many of them are hybrids of different techniques. That said, a rough categorization is presented here.

A. Proportional-Derivative/Proportional-Integral-Derivative Controllers

Proportional–Integral–Derivative (PID) controllers and their simplified counterpart, Proportional–Derivative (PD), form the building blocks of control systems in industry. Their enduring popularity is due to the balanced mix of simplicity, ease of tuning, dependability, and versatility, which make them integral to almost all types of applications [63]. PID controllers have been used for CDPRs all the time since their emergence. Even recent research has picked the PID controller as the first choice when a new idea is explored or applied. A notable early example includes Kawamura et al. [64], who employed a PD controller in joint space to control the FALCON-7 robots incorporating end-effector weighting to maintain stability under gravitational effects. Similarly, Aflakiyan et al. [65] combined the PD controller with the computed torque method for enhanced optimization. Wei et al. [66] refined the PD controller to achieve better stability and tracking in a high-speed camera system. Further applications include gyroscope and inertial measurement unit to evaluate position errors of feedback control by Zou et al. [30]. Inel et al. [67] concluded that PID controllers yielded faster responses than PD controllers when they compare between them for controlling a planar CDPR.

Moreover, a PID force servo controller tailored for a reconfigurable rehabilitation CDPR was developed in [68]. In the realm of construction, Tho and Thinh [38] integrated PID control with kinematic optimization and cable sag compensation to support stable 3D concrete printing. Jomaratove et al. [69] applied localized PID control per cable, while Guagliumi et al. [70] introduced a hybrid PID position–force scheme in Cartesian coordinates to maintain cable tensions without force sensors. Li and Li [71] took it a step further by implementing PID control in a novel rod–cable hybrid CDPR, achieving precise positioning and trajectory tracking.

Various improvements to the classical PID control methods were proposed to enhance their efficiency. Khosravi et al. [72] and Di Paola [73] introduced robust modifications of these techniques. The latter used sliding-mode adaptation to provide safety to the load in case of cable failure. Fuzzy PID controllers [74]-[78] enabled better tuning of gains in the presence of parameter uncertainties. *Fig. 8* illustrates the controller proposed in [78].

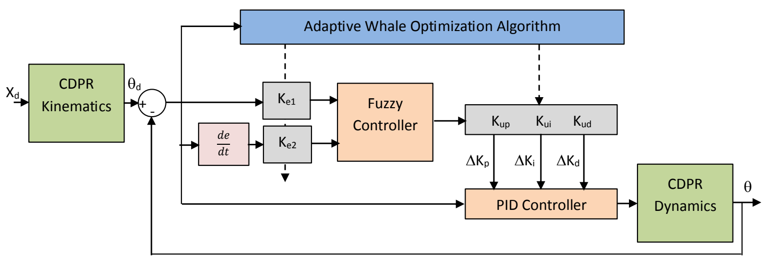


FIG. 8. THE CONTROL DIAGRAM OF FUZZY PID CONTROL STRATEGY BASED ON AN ADAPTIVE WHALE OPTIMIZATION ALGORITHM [78].

These Fuzzy PID controllers had many structures [79]. Aboud et al. [80] utilized fractional-order PID control technique using the particle swarm-optimized fractional-order approach, yielding improved smoothness and accuracy of tracking. Finally, combining PID with deep reinforcement learning by Joyo et al. [81] enhanced significantly the intelligence and flexibility of the CDPR control system. Table I summarizes this section.

TABLE I. SUMMARY OF SECTION A (PD/PID CONTROLLERS)

Authors	Ref.	Control Strategy Applied	Discription
Kawamura et al., 1997	[64]	PD Controller with End-Effector Weighting	Implemented PD control in joint space for FALCON-7 robots, incorporating end-effector weighting to maintain stability under gravitational effects.
Aflakiyan et al., 2015	[65]	PD Controller with Computed Torque Method	Combined PD control with computed torque method for enhanced optimization in CDPRs.
Wei et al., 2016	[66]	Modified PD Controller	Refined PD controller to achieve better stability and tracking in a high-speed camera system.
Zou et al., 2018	[30]	PD Controller with Gyroscope and IMU Feedback	Utilized gyroscope and inertial measurement unit to evaluate position errors of feedback control.
Inel et al., 2015	[67]	Comparison of PID and PD Controllers	Found that PID controllers yield faster responses than PD controllers for planar CDPR control.
Aflakian CDPR, 2018	[68]	PID Force Servo Controller	Developed a PID force servo controller tailored for a reconfigurable rehabilitation CDPR.
Tho & Thinh, 2021	[38]	PID Control with Kinematic Optimization and Cable Sag Compensation	Integrated PID control with kinematic optimization and cable sag compensation for stable 3D concrete printing.
Jomaratove et al., 2023	[69]	Localized PID Control per Cable	Applied localized PID control per cable in CDPRs.
Guagliumi et al., 2024	[70]	Hybrid PID Position–Force Control in Cartesian Coordinates	Introduced a hybrid PID position–force scheme to maintain cable tensions without force sensors.
Li & Li, 2025	[71]	PID Control in Rod–Cable Hybrid CDPR	Implemented PID control in a novel rod–cable hybrid CDPR, achieving precise positioning and trajectory tracking.
Khosravi et al., 2014	[72]	Robust PID Control	Proposed robust PID control methods for CDPRs to enhance efficiency.
Di Paola, 2024	[73]	Sliding-Mode Adaptive PID Control	Introduced sliding-mode adaptation to provide safety to the load in case of cable failure.
Zi et al., 2008	[74]	Fuzzy PID Controllers	Enabled better tuning of gains in the presence of parameter uncertainties using fuzzy logic.
Najafi & Bakhshizadeh, 2016	[75]	Fuzzy PID Controllers	Focused on handling the complexity introduced by flexible cables.
Tajmadari et al., 2017	[76]	Fuzzy PID Controllers	Developed a PID controller to provide a learning dataset for training a neuro-fuzzy network.
Carpio et al., 2021	[77]	Fuzzy PID Controllers	Developed a simple and practical decoupled control structure for the position control of a planar CDPR using fuzzy PID
Zhou et al., 2023	[78]	Fuzzy PID Controllers	Developed a fuzzy gain scheduling for PID controller and the process is optimized by an adaptive whale optimization algorithm.
Aboud et al., 2024	[80]	Fractional-Order PID Control with Particle Swarm Optimization	Utilized fractional-order PID control technique using the particle swarm-optimized approach, yielding improved smoothness and accuracy of tracking.
Joyo et al., 2025	[81]	PID Combined with Deep Reinforcement Learning	Combined PID with deep reinforcement learning to enhance the intelligence and flexibility of the CDPR control system.

B. Feedback Linearization

Transitioning from classical control, feedback linearization offers a powerful approach for handling nonlinear dynamics. By transforming nonlinear systems into equivalent linear ones via input redefinition, control design becomes significantly more manageable [82]. Oh and Agrawal [83] were early adopters of feedback linearization in CDPRs, integrating linear and quadratic programming to ensure positive cable tensions and predictive control. Zarei et al. [84] advanced this technique by designing a controller that reduced oscillations and minimized phase trajectory. Others, like Korayem

[85] and Begey [86] (*Fig. 9*), further applied it to accommodate structural uncertainties and cable elasticity.

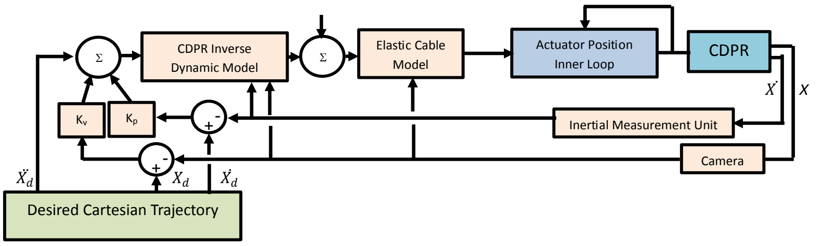


FIG. 9. CARTESIAN MODEL-BASED CONTROL OF ELASTIC CABLE CDPRS, WITH AN ACTUATOR POSITION INNER CONTROL LOOP [86].

C. Robust and Adaptive Control

With the models created by CDPR often being subject to the influence of parametric uncertainties as well as dynamic disturbances from payload variations and friction fluctuations, adaptive and robust control techniques have become the favored alternative. These are often integrated to counter both the dynamic and kinematic errors [55].

Zarebidoki et al. [87] were one of the first to utilize adaptive inverse dynamic control. In [88], an adaptation mechanism using fuzzy radial basis functions specifically was designed to handle significant loads. Lamauri et al. [61] employed a double-space adaptation approach and El-Ghazaly et al.[89] used an adaptive terminal sliding mode controller to regulate cable tension within safe ranges. Other contributions included some adaptive robust techniques such as singular perturbation [90], fuzzy tuners [91], and adaptive neural networks handling actuator saturations [92]. Adaptive nonsingular fast terminal sliding mode controllers were used in [93][94] with the distinction of being insensitive to the precision of system models. Ji et al.[55] considered synchronization control under dynamic uncertainties, while the developed adaptive controller by Harandi et al. [95] addresses the intricate problems related to the Jacobian in the kinematics of parallel robots. Liu et al. [96] extended the work of Zi [88] by developing an adaptive fuzzy-controller that could provide safe disturbance resistance as well as stable pick-and-place maneuvers. Furthermore, a sliding-mode adaptive PID controller [73] and a convergence-guaranteed adaptive control [97] underscored the significance of adaptive methodologies to enhance safety and performance results. Asl and Janabi-Sharifi [92] used Artificial Neural Networks to combat input saturation, while Piao et al. [98] used these networks to estimate cable tension, both being considered key components in adaptive control systems, as shown in *Fig. 10*.

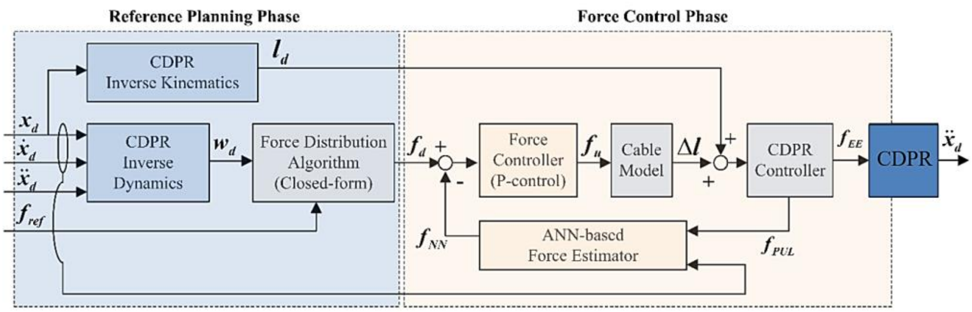


FIG. 10. BLOCK DIAGRAM OF THE PROPOSED FORCE CONTROL ALGORITHM USING THE ARTIFICIAL NEURAL NETWORKS FORCE ESTIMATOR [98].

Together with adaptive techniques, sliding mode control is widely employed because of its fault-tolerant capability against uncertainties and external disturbances. Lv et al. [99] developed a real-time feedback-based sliding mode control strategy to achieve accurate six degrees of freedom control. Zi et al. [100] proposed an adaptive fuzzy sliding mode control system for a winding CDPR that outperformed traditional PID controls in terms of accuracy and resilience. Other robust controllers include a cascade sliding mode control design [101] and non-iterative super-twisting sliding mode control approach [102], which maintained tension integrity without computational loads. Alternative to sliding mode control, synergetic adaptive controller was utilized in [103] with dragonfly algorithm optimization technique to achieve robust and high performance tracking response.

Classical control methods were also made robust and applied in CDPRs. Jamshidifar et al. [104] used used a linear parameter-varying H∞ robust vibration compensator, while Chellal et al. [105] utilized a vision-based H∞ robust position controller. Table II summarizes this section.

TABLE II. SUMMARY OF SECTION C (ROBUST AND ADAPTIVE CONTROL)

Authors	**Ref.**	**Control Strategy Applied**	**Discription**
Zarebidoki et al., 2011	[87]	Adaptive Inverse Dynamics	Early application of adaptive inverse dynamic control in CDPRs.
Zi et al., 2014	[88]	Adaptive Fuzzy (Radial Basis Functions)	Designed a fuzzy adaptation scheme to handle large load variations.
Lamauri et al., 2013	[61]	Double-Space Adaptation	Employed adaptation in both task and joint spaces.
El-Ghazaly et al., 2015	[89]	Adaptive Terminal Sliding Mode	Controlled cable tension within safe ranges under disturbances.
Babaghasabha et al., 2016	[90]	Adaptive Robust via Singular Perturbation	Applied singular perturbation method for robustness.
Yang et al., 2016	[91]	Adaptive with Fuzzy Tuners	Used fuzzy tuning for handling uncertainties in system dynamics.
Asl & Janabi-Sharifi, 2017	[92]	Adaptive Neural Network	Handled actuator saturation using neural networks.
Wang et al., 2018	[93]	Nonsingular Fast Terminal Sliding Mode	Developed a controller insensitive to model accuracy.
Hosseini et al., 2019	[94]	Adaptive Fast Terminal Sliding Mode	Developed an adaptive F-SMC ensuring roubustness and performance.
Ji et al., 2021	[55]	Adaptive Synchronization Control	Addressed dynamic uncertainty with synchronization.
Harandi et al., 2021	[95]	Adaptive Kinematic Control	Solved Jacobian-related issues in parallel robot kinematics.
Liu et al., 2022	[96]	Adaptive Fuzzy	Improved stability and disturbance resistance in pick-and-place tasks.
Di Paola, 2024	[73]	Sliding Mode Adaptive PID	Provided safety in case of failure using sliding-mode PID.
Zhang et al., 2024	[97]	Convergence-Guaranteed Adaptive Control	Developed control with theoretical performance guarantees.
Piao et al., 2019	[98]	Neural Network Estimator	Estimated cable tension using neural networks.
Lv et al., 2017	[99]	Real-Time Sliding Mode	Accurate 6-DOF control with real-time feedback-based sliding mode.
Zi et al., 2017	[100]	Adaptive Fuzzy Sliding Mode	Outperformed PID in tracking accuracy and robustness.
Khalilpour et al., 2019	[101]	Cascade Sliding Mode	Designed multi-layer control architecture for improved robustness.
Ameri et al., 2024	[102]	Super-Twisting Sliding Mode	Maintained tension integrity with low computational cost.

Alwan et al., 2025	[103]	Synergetic Adaptive + Dragonfly Optimization	Achieved high-performance tracking with robust adaptive synergetic control.
Jamshidifar et al., 2018	[104]	LPV H∞ Robust Vibration Control	Used a linear parameter-varying robust controller for vibration compensation.
Chellal et al., 2016	[105]	Vision-Based H∞ Robust Control	Applied vision-based robust position controller in CDPRs.

D. Other Control Techniques

Cuvillon et al. [106] introduced gain scheduling strategies to dampen vibrations, adapting control gains to dynamic changes. Model Predictive Control and its nonlinear extension have been attracting significant attention in current research. Nonlinear model predictive control is used in the Santos et al. [107] research, while [108][109] used model predictive control schemes that explicitly handle cable tension limits and redundancy resolution. Non classical controllers is developed in [110] where an algebraic feedforward motion planning system was used rather than a traditional feedback controller. Moreover, some of the classical approaches have been utilized for CDPR control recently. Linear quadratic Gaussian control framework is applied in [111] to enable the CDPR to precisely track optimized trajectories, addressing challenges such as partial observability and external vibrations. Adaptive controller based on extended Kalman filter is utilized in [112] to estimate crucial system states, including uncertain actuator positions and the end-effector's pose. These estimates are then directly integrated into the feedback controller to compensate for the uncertain parameters.

VI. CONCLUSIONS

This work provides an overview of CDPRs, including a variety of applications such as cable camera systems, robot crane, rehabilitation, construction, amusement, and agriculture. In addition to this, the work assesses relevant control methods with the focus on recent research. The review started with typical PID controllers, and ended with more advanced techniques such as adaptive control, robust schemes, and model predictive approaches. Despite their agility and high capabilities, CDPRs face challenges like control uncertainty, cable tension management, and limitations in loading accuracy. All of these difficulties represent important opportunities for exploration, particularly in areas like adaptive control for constitutively variable environments, multitasking with reduced human input, and fault-tolerant real-time uses. Further work could also focus on standardizing benchmarking frameworks to compare control strategies and developing scalable CDPR platforms for varied industrial needs.

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