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Max B. Schäfer*, Ellen Klein, Sophie Weiland, Konstantin Frenzel, and Peter P. Pott

Cable-driven parallel robots for human interaction: Approaches and applications

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Abstract: Cable-Driven Parallel Robots (CDPR) have gained increasing attention in human-machine-interaction, particularly in haptics and rehabilitation. Despite their different objectives, both fields share fundamental requirements such as safety, configurability and precise force control. This review provides an overview of existing CDPR implementations designed for human interaction, categorizing and analyzing systems based on their design principles and kinematic properties. Key motivations for using CDPR in these applications are discussed, along with current limitations and promising directions. The findings indicate that CDPR offer an underrated yet promising solution for human-machine-interaction.

Keywords: cable-driven parallel robots, haptic feedback, robot-assisted surgery, robot-assisted rehabilitation

1 Introduction

Robotic systems capable of applying forces to humans are used in various applications, including haptics and rehabilitation. While these two domains may seem distinct, they share fundamental requirements, such as safety, adaptability, dynamic performance and precise force control. Cable-Driven Parallel Robots (CDPRs) have emerged as a promising solution. From a theoretical perspective, CDPRs offer advantages over traditional robotic systems. Their cable-based actuation enables dynamic movements due to their lightweight design, which can enhance both user safety and interaction quality. Further, they offer high configurability and cost-effectiveness. These characteristics make them particularly suitable for applications, such as user interfaces for Virtual Reality (VR), telemanipulation in Robot-assisted surgery (RAS), surgical training environments, or for assisting patients in rehabilitation exercises. Despite their potential, CDPRs have so far only been used to a limited extent for human-machine interaction, and their advantages are often overlooked. While numerous research efforts have explored their feasibility, a comprehensive overview of existing implementations is still needed. This review aims to provide a clear perspective on the current state of CDPRs designed for human interaction, with a focus on haptic feedback and rehabilitation, identifying key motivations for their use, common limitations, and future directions.

2 Background

CDPRs are a subset of parallel robotic systems in which end-effectors are actuated by cables instead of rigid links. In contrast to rigid-limb parallel robots, CDPRs offer advantages such as lower weight, greater adaptability, and the possibility of larger workspaces. Their applications include industrial automation, large-scale motion platforms, exoskeleton assistance, and interactive rehabilitation systems.

The analysis of CDPRs requires consideration of both kinematics and cable force distribution. The kinematics define the relationship between cable lengths, end-effector position, and applied forces, ensuring controlled operation. Since cables can only transmit tensile forces, the cable force distribution is crucial. This necessitates the use of redundant actuation and strategies to optimize the distribution of cable forces. In-depth theoretical and practical insights into CDPR design and control are given by A. Pott [1]. There are several approaches to classifying CDPRs, including by number of cables, or end-effector degrees of freedom (DOF). In this work, a first categorization is based on application, considering only CDPRs that interact with humans, particularly Cable-Driven Haptic Devices (CDHDs) and CDPRs for rehabilitation purposes. CDHDs are designed to provide force feedback for applications

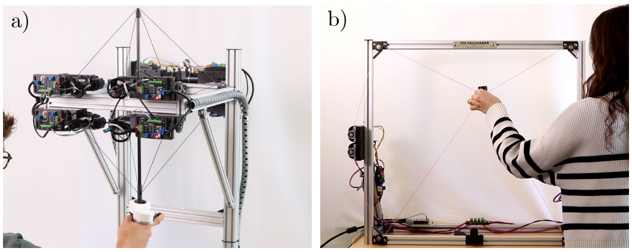

Figure 1: Cable-Driven Haptic Devices (CDHD): Falcon (a) and planar design (b) for telemanipulation and virtual reality [2].

***Corresponding author: Max B. Schäfer,** Institute of Medical Device Technology, University of Stuttgart, Pfaffenwaldring 9, Stuttgart, Germany, e-mail: max.schaefer@imt.uni-stuttgart.de
Sophie Weiland, formerly Inst. of Medical Device Technology, Univ. of Stuttgart, now Carl Zeiss AG, Oberkochen, Germany
Ellen Klein, Konstantin Frenzel, Peter P. Pott, Inst. of Medical Device Technology, Univ. of Stuttgart, Germany

such as VR training and teleoperation (see Figure 1), offering precise force rendering and high dynamics. In contrast, rehabilitation CDPRs focus on assisting or training patients with movement impairments, often integrating adaptive control strategies to ensure user safety and personalized therapy. The identified systems are then classified by their degree of redundancy [1]. The degree of redundancy $r_D = m - n$, where m is the number of cables and n is the number of controllable DOFs, determines the class: Incompletely Restrained Parallel Manipulator (IRPM) for $r_D \leq 0$, Completely Restrained Parallel Manipulator (CRPM) for $r_D = 1$, and Redundantly Restrained Parallel Manipulator (RRPM) for $r_D > 1$. At least $m = n + 1$ cables are needed for full end-effector control.

3 Methods

The objective of this study is to identify and analyze CDPRs designed for human interaction, specifically those capable of exerting forces in a controlled manner and in the form of force feedback. To compile the dataset of relevant CDPR implementations, a literature search was conducted using the scientific databases IEEE Xplore, PubMed, and Google Scholar. Only studies focusing on CDPRs designed for human interaction were included, while systems without direct human interaction or those not intended to provide force feedback were excluded.

4 Results

In Table 1, 40 identified systems are listed along with their key characteristics and applications. The findings demonstrate broad applicability, including VR, Mixed Reality, sports applications, and telesurgical robotics, highlighting the versatility of CDPRs. Nine systems explicitly designed for rehabilitation and four systems intended for RAS were identified. A notable trend is the use of multimodal feedback, including kinesthetic and tactile feedback. Most systems cover a force feedback range between 0 and 10 N, with only a few systems extending up to 300 N. Despite the frequent inclusion of force sensors, the literature regarding their implementation in hardware and control strategies remains incomplete.

5 Discussion

CDPRs are highly suited for human-machine-interaction. They are capable of providing precise and adjustable force feedback, making them ideal for haptic systems. Their high adaptability also allows them to address the diverse needs of rehabilitation, ranging from physical therapy to neurorehabilitation. Furthermore, CDPRs are cost-effective, with only few mechanical components, and their configurability makes them easily customizable. However, CDPRs face several challenges. The complexity of cable force distribution in redundant actuator designs presents difficulties. The fact that cables can only transmit tensile forces results in interactions almost always occurring within the volume defined by the cable attachment points. This, in turn, makes the realization of suitable user interactions challenging. Additionally, the cables themselves introduce constraints such as friction and wear. CDPRs offer a promising, yet underrated solution for human-interactive robotics. Future research could overcome these limitations, positioning CDPRs as a key technology, in particular when aiming for immersive haptic environments.

Author Statement

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Table 1: Overview of Cable-Driven Parallel Robots (CDPRs) designed for human interaction: Key characteristics, applications, and force feedback capabilities. The parameter m represents the number of cables, n is the number of controllable DOF, and the category denotes the classification based on the degree of redundancy. Sorting is done by affiliation.

Affiliation	**Device name**	**Ref.**	**m**	**n**	**Categ.**	**Application**	**Force in N**	**Force Sensor**	**Other**
Univ. Laval, CAN	-	[3]	4	3	CRPM	nonspecific	0-5	yes	-
Univ. Laval, CAN	-	[4]	3	3	IRPM	VR	-	-	rigid object contact
Univ. Laval, CAN	-	[5]	4	3	CRPM	VR	-	yes	-
Univ. Laval, CAN	CDLI	[6]	2x8	2x6	RRPM	VR	-	-	-
ETH Zürich, CHE	M 3-Rowing Simulator	[7]	4	3	CRPM	sport	-	yes	multimodal feedback
Beihang Univ., CHN	-	[8]	4	3	CRPM	VR	0-14,2	-	kinesthetic and tactile feedback
Beihang Univ., CHN	iFeel6-BH1500	[9]	8	6	RRPM	VR	0-37	-	-
Beijing Inst. of Technology, CHN	-	[10]	6	5	CRPM	RAS	-	yes	variable workspace
Northeast Electric Power Univ., CHN	-	[11]	8	6	RRPM	VR	-	yes	-
Southeast Univ., CHN	-	[12]	8	6	RRPM	VR	0-10	-	kinesthetic and tactile feedback
Centrale Nantes, FRA	-	[13]	6	4	RRPM	nonspecific	-	-	-
CEA LIST, FRA	ICARE 3D	[14, 15]	3	3	IRPM	VR	-	-	-
Sorbonne Univ., FRA	-	[16]	5	3	RRPM	nonspecific	-	-	overlay of VR and workspace
King's College London, GBR	-	[17]	8	7	CRPM	nonspecific	-	yes	-
Fraunhofer IPA, DEU	IPAnema 3 Mini	[18]	8	6	CRPM	nonspecific	-	yes	-
Fraunhofer IPK, DEU	STRING-MAN	[19]	7	6	CRPM	rehabilitation	-	yes	also with 10 cables
Univ. of Stuttgart, DEU	PlaCaRo	[2]	4	2	RRPM	nonspecific	0-5	no	-
Univ. of Stuttgart, DEU	FalCaRo	[2]	8	6	RRPM	RAS	0-5	no	Falcon design according to [20]
Univ. of Stuttgart, DEU	-	[21]	2	1	CRPM	nonspecific	0-5	no	-
Univ. of Stuttgart, DEU	STRIVE	[22]	-	-	IRPM	VR	-	no	now Haptive GmbH
Israel Inst. of Technology, ISR	-	[23]	3	2	CRPM	rehabilitation	-	no	four operating modes
Univ. of Bologna, ITA	WireMan	[24]	3	3	IRPM	visual impairment	-	-	body-worn
Univ. of Cassino, ITA	CALOWI	[25]	4	4	IRPM	rehabilitation	-	yes	-
Univ. of Padova, ITA	Feriba-3	[26]	4	3	CRPM	nonspecific	0-5	no	air lubrication
Univ. of Padova, ITA	Sophia-4 (-3)	[27]	4(3)	2	RRPM (CRPM)	rehabilitation	-	no	-
Univ. of Padova, ITA	PiRoGa5	[28]	6	5	CRPM	RAS	-	-	-
Univ. of Padova, ITA	NeReBot	[29]	3	3	IRPM	rehabilitation	0-50	-	-
Univ. of Padova, ITA	MariBot	[30]	3	3	IRPM	rehabilitation	0-50	no	-
Scuola Superiore Sant'Anna, ITA	-	[31]	6	5	CRPM	RAS	-	yes	-
Politecnico di Torino, ITA	WiRo-6.3	[32]	9	6	RRPM	nonspecific	0-10	-	-
Ritsumeikan Univ., JPN	-	[33]	7	6	CRPM	nonspecific	-	-	-
Tokyo Denki Univ., JPN	-	[34]	3	2	CRPM	nonspecific	0-5	no	-
Tokyo Inst. of Technology, JPN	SPIDAR	[35–38]	8	6+1	CRPM	VR/MR	-	-	numerous versions
Chonnam National Univ., KOR	-	[39]	8	6	RRPM	telerobotics	-	yes	-
Chonnam National Univ., KOR	-	[40]	8	6	RRPM	RAS	0-10	yes	-
Gwangju Inst. of Science and Technology, KOR	HapticPen	[41]	3	3	IRPM	nonspecific	0-4	-	body-worn
Gyeongsang National Univ., KOR	-	[42]	4	4	IRPM	rehabilitation	-	-	-
Pohang Univ. of Science and Technology, KOR	-	[43]	4	2	RRPM	VR	0-7	yes	movable attachment points
Delft Univ. of Technology, NLD	-	[44]	6	4	RRPM	nonspecific	-	-	-
Delft Univ. of Technology, NLD	-	[45]	4	3	CRPM	VR, sport	-	yes	-
Delft Univ. of Technology, NLD	-	[46, 47]	7	6	CRPM	nonspecific	-	-	-
National Univ. of Singapore, SGP	Hand-CARE	[48]	5	5	IRPM	rehabilitation	0-15	yes	linear workspace
Rehabilitation Inst. of Chicago, USA	CaLT	[49]	4	-	-	rehabilitation	0-45	-	3D position sensing
Rehabilitation Inst. of Chicago, USA	MACARM	[50]	8	6	RRPM	rehabilitation	max. 300	-	-
Ohio Univ., USA	CSHI	[51]	8(4)	6(3)	RRPM (CRPM)	nonspecific	-	yes	-
Mimic Technologies Inc., USA	Mantis Duo	[52]	2x4	2x3	CRPM	RAS	-	-	for bi-manual use

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