1

Introduction

1.1 The Evolution of Rigid–Flexible Coupling Robots

Rigid–flexible coupling robot (RFCR) is a class of robotic systems that integrate the characteristics of rigid structures and flexible materials. The core lies in the organic combination of rigid and flexible components to achieve coordinated regulation of stiffness, flexibility, and adaptability [1]. Based on the complementarity of rigid and flexible characteristics, RFCRs overcome the limitations of single rigid or flexible systems and serve as an important development direction in the robotics field to address the needs of complex tasks [2]. From the perspective of actuation and control methods, RFCRs can be roughly classified into the following categories: the "rigid actuation-flexible mechanism," the "flexible actuation-rigid support," the "smart material driven," and so on. These types of RFCRs have their respective advantages in different application scenarios.

For the "rigid actuation-flexible mechanism" type of RFCRs, they are the most mature in application and have the longest development history at the present stage. Such robots combine the advantages of traditional rigid robots and soft robots, typically driven by rigid drive units (such as motors, reducers, tracks, or gears) to actuate flexible or continuously deformable mechanical structures [3]. Traditional rigid robots use rigid components like metal skeletons and gear hinges to form joints, with power provided by rigid actuators such as motors. In contrast, soft robots employ flexible materials like silicone and elastomers, relying on pneumatic or solid-state actuators to achieve continuous deformation. The structural design of rigid-drive flexible-mechanism robots lies between the two extremes. Built on the high output force and precise control capabilities of rigid drives, they introduce flexible backbones or joints to achieve high redundancy and compliance. These robots typically feature more degrees of freedom and significant deformation capabilities, with structures that can bend or stretch arbitrarily.

COPYRIGHTED MATERIAL

They inherently possess compliance and environmental adaptability while maintaining the high output torque and speed of rigid drives, thus ensuring excellent interactive safety and high load-bearing capacity [4].

The mechanical structure of this type can be traced back to the mid-twentieth century. Its technological evolution runs through the interdisciplinary integration of mechanical engineering, control theory, materials science, and other disciplines, forming a complete context from theoretical exploration to engineering practice. RFCRs have been used widely in fields such as scientific research, industry, and people's livelihood [5].

In the 1970s, the team of Professor Hirose from the Tokyo Institute of Technology in Japan proposed the "Active Cord Mechanism (ACM)" and manufactured the world's first snake-like robot prototype, ACM-III [6].

In the 1980s, Shigeo Hirose and others developed the cable-driven continuum manipulator ELASTOR with an eight-segment flexible spring backbone [7]. Additionally, Wilson at Duke University in the United States proposed research on fluid-driven flexible arms [8].

In 1995, Pratt et al. [9] proposed the concept of series elastic actuators, introducing adjustable elastic components between rigid motors and flexible springs. In 2014, the team of Chen Xiaoping from the University of Science and Technology of China proposed the "pneumatic honeycomb network" structure [10]. By combining the honeycomb-type rigid–flexible structure with airbags, the structure achieves high compliance and high load-carrying capacity. Furthermore, Meng et al. [11] designed a flexible robotic arm. Utilizing a pneumatic honeycomb mechanism and airbags, this arm is capable of performing complex tasks such as opening doors, drawers, and twisting off bottle caps in daily life environments.

In addition, significant progress has also been made in the research of cable-driven RFCRs. In the 1980s, as shown in Figure 1.1, a video tape recorder system named SkyCam with four cables is designed, which is widely used in large-space shooting operations. Meanwhile, its maximum speed can reach 44.8 km/h [12]. In addition, in the famous Five-hundred-meter Aperture Spherical radio Telescope (FAST) project in China led by academician Nan Rendong and others, six steel cables are used to drive the 30-ton feed cabin, and in combination with the Stewart platform, a positioning accuracy of the millimeter level (3 mm) is achieved, as shown in Figure 1.2. This is a typical RFCR of the "rigid actuation-flexible mechanism" type [13]. As shown in Figure 1.3, Zhao et al. [14] proposed an under-constrained RFCR with variable angle and height cable mast. Hamida et al. [15] designed a cable-driven RFCR, which can be intended for upper-limb rehabilitation exercises. Meanwhile, four different topology solutions were also considered. Chen et al. [16] proposed a cable-driven parallel waist rehabilitation robot with two-level control algorithm to assist the patients with waist injuries to do some rehabilitation training. Tho et al. [17] designed an RFCR structure for the

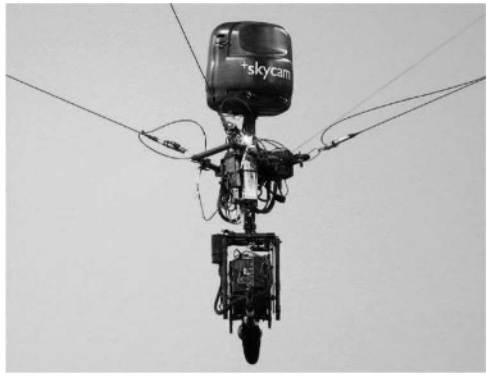


Figure 1.1 A video tape recorder system for large space.



Figure 1.2 Large spherical radio telescope. *Source*: Chinese Academy of Sciences, https://english.nao.cas.cn/research/researchdivisions/radioastronomy/202103/t20210323_266393.html, last accessed Nov. 21, 2025.

3D printing in a large workspace. Overall, in future applications, "rigid actuation-flexible mechanism" robots will increasingly serve in fields such as intelligent manufacturing, flexible production lines, and human–robot collaboration, as well as explore new scenarios like extraterrestrial planetary surface exploration and medical diagnostics [18].

The relevant research for the "flexible actuation-rigid support" type of RFCRs can be traced back to bionic explorations and breakthroughs in material technology in the late twentieth century [19]. The core idea is to achieve highly adaptive motion through flexible driving components while maintaining system stability using rigid supporting structures [2]. Such robots possess both soft and hard characteristics, ensuring load support while maintaining good compliance. For example, in the field of exoskeleton robots, actuation can be divided into electric,

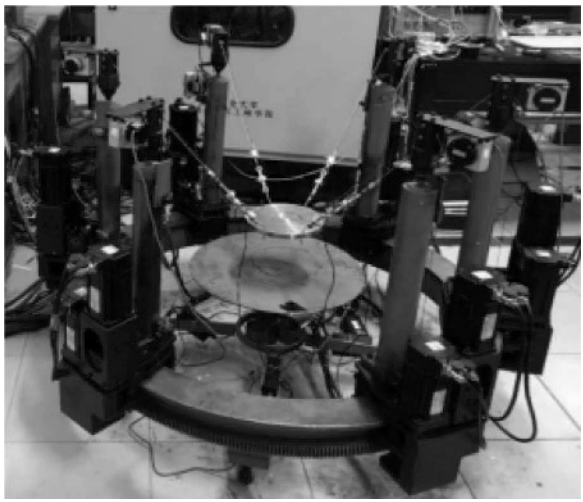


Figure 1.3 Under-constrained RFCR with variable angle and height cable mast.
Source: [14]/Springer Nature/CC BY 4.0.

pneumatic, hydraulic, or hybrid types, while structures can be categorized into rigid exoskeletons and flexible exoskeletons. Rigid exoskeletons use rigid metal structures for load-bearing, often being bulky and complex; flexible exoskeletons replace some rigid skeleton components with soft, lightweight materials, making the structure more portable and comfortable [20]. In continuous bending manipulators, similar classifications exist: cable-driven continuous arms can be divided into three categories: "pure flexible segmental drive," "rigid–flexible hybrid segmental drive," and "discrete rigid full drive." In short, "flexible drive-rigid support" robots refer to robotic systems that use flexible actuators to transmit power and rigid components to form load-bearing skeletons, belonging to the design paradigm of soft-hard coupled robotics [21].

As early as the 1950s, McKibben and others developed braided pneumatic artificial muscles, laying the foundation for flexible actuators [22]. In the 1960s, the first continuous bending robot prototypes emerged: Anderson and Horn's "Tensor Arm," designed with a cable-driven diving arm structure, is recognized as the first conceptual continuous robot prototype [23]. Over the following decades, continuous backbone robots and flexible drive technologies gradually diversified; in 1989, the US National Institute of Standards and Technology (NIST) introduced the first large-scale cable-driven parallel robot, "RoboCrane," for large-range handling tasks [24, 25].

During the mid-to-late 1990s, researchers made advancements in kinematic modeling and design innovation: Chirikjian [26] proposed the kinematic theory of continuous backbones, while Hirose and colleagues developed bionic snake robot

prototypes [27]. In 1999, Robinson and Davies formally defined the concept of "continuous robots" and completed their classification, marking the conceptual development of the flexible robotics field [28].

Entering the twenty-first century, "soft robotics" research became a hotspot—the term "soft robotics" was internationally adopted for the first time in 2008 to describe robots with compliant joints or flexible components [29]. In recent years, with breakthroughs in bionics and structural innovation, multiple key milestones have emerged: for example, China launched the major scientific research project "Tri-Co Robot" (flexible collaborative robot) in 2016 [30]; in 2023, Southern University of Science and Technology proposed an anisotropic stiffness structure (OASS) based on single-sided origami mechanisms, achieving an innovative structure with both rigidity and flexibility in different directions [31]. Harvard University's Wyss Institute (led by Conor Walsh) has made outstanding contributions in the field of flexible-driven exoskeletons (soft exoskeletons), with its developed soft cable-driven exoskeletons significantly improving gait [32–34]. Universities such as Carnegie Mellon University and the Georgia Institute of Technology have long engaged in deep research on soft robotics theory and control [35, 36]. In Europe, the Fraunhofer Institute for Production Technology (Fraunhofer IPA) team has led research on cable-driven parallel robots (such as the IPAnema series), proposing design concepts that significantly enhance load capacity, workspace, and dynamic performance in industrial scenarios [37, 38]. The team led by Liu Hongbin at the Institute of Automation, Chinese Academy of Sciences, has achieved groundbreaking results in minimally invasive flexible surgical robot technology (such as the development of minimally invasive flexible neurosurgical robots) [39]; the team led by Chen Xuefeng at Xi'an Jiaotong University has also made new progress in the design and modeling of flexible continuum robots, as shown in Figure 1.4 [40]. Additionally, the industrialization process of soft robotics is also accelerating further.

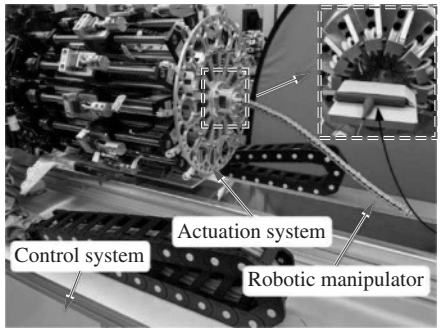


Figure 1.4 Continuum robotic system prototype. *Source*: [40]/IEEE/CC BY 4.0.

In terms of applications, continuous bending robots leverage their advantages of being long, narrow, and bendable, making them widely used in minimally invasive surgery and intraluminal operations [41]. For example, superconducting spiral continuous core tube robots are frequently employed in endoscopic and cardiac surgeries, as they can smoothly pass through the natural orifices of body cavities to achieve precise operations [42]. Additionally, variable-stiffness soft surgical robots enable surgeons to switch more flexibly between rigid and soft states during procedures [43]. Traditional rigid exoskeletons mostly use electric drive, but they suffer from heavy weight and poor comfort. Emerging flexible exoskeletons adopt lightweight flexible materials and cable-driven systems to provide close-fitting assistance for hand or lower limb movements. For instance, Harvard's soft exoskeleton "Soft Exosuit" uses flexible cables to generate auxiliary torque at the hip and ankle joints, which can improve foot drop and reduce walking burden [34]. Meanwhile, due to their high compliance, these robots can be applied in scenarios such as pipeline maintenance, marine exploration, or post-disaster search and rescue [44]. Japan's Land Equipment Development Agency has developed cable-driven snake robots for search and rescue in earthquake debris [27]; NASA and CMU teams in the United States have also researched flexible robots capable of moving within pipelines [45]. Evidently, robots that combine flexible drive and rigid support are gradually expanding from single manufacturing scenarios to a broader range of intelligent equipment and service fields. In summary, the future of "flexible actuation-rigid support" robots will evolve toward higher compliance, stronger load capacity, and greater intelligence, enabling them to accomplish complex tasks that traditional rigid robots struggle to handle [46–48].

For the "smart material-driven" type of RFCRs, this type of robot refers to robotic systems that utilize smart materials (such as shape memory alloys [SMAs], dielectric elastomers, and hydrogels) as driving units while incorporating rigid structures as skeletons or load-bearing frameworks [49]. This structure combines flexible deformation capabilities with certain mechanical stability, making it suitable for scenarios such as bionic execution, precise manipulation, wearable devices, and minimally invasive medical procedures.

With the development of material systems, typical manufacturing processes have also evolved continuously: early methods mostly employed compression molding and fiber winding (such as helical wound actuators), while recent advancements have introduced new techniques like layer-by-layer 3D/4D printing, soft lithography, and micro–nano-processing, enabling high integration of structures and materials [50, 51].

In terms of control strategies, early approaches relied mainly on open-loop heating or simple voltage driving [52]. As the technology has matured, model-based

closed-loop control, fuzzy control, and machine learning algorithms have emerged to compensate for the nonlinear hysteresis of intelligent materials and achieve precise positioning [53, 54].

As early as the 1980s, smart materials were initially applied to driving mechanisms, with SMAs being the main type, and rigid structures typically consisting of metal or plastic skeletons. In 1988, a prototype of a bionic gripper driven by an SMA spring emerged. In 1993, MIT developed a bionic finger structure based on SMA [55]. In addition, Nguyen et al. [56] show a 30-mg crawling robot driven by a high-frequency flexible SMA microactuator.

In the early twenty-first century, researchers began to systematically construct rigid–flexible coupled actuation structures, attempting to integrate precision rigid structures with flexible actuation materials in microrobots and medical devices. For example, Harvard University has developed microdevices with SMA and rigid hinges [57]. Teams such as those from Stanford University have integrated hydrogels into microfluidic rigid platforms to achieve soft operation ends [58].

Since the 2010s, various smart materials (dielectric elastomers, liquid crystal elastomers, carbon nanotubes, etc.) have been integrated into complex rigid frameworks, simultaneously improving control precision and load capacity; some have entered the practical application stage in medical, wearable, and bionic robotics. For example, in 2016, Harvard introduced the Octobot: some regions feature rigid casings, with fuel circuits embedded in flexible bodies, as shown in Figure 1.5 [59]. In 2019, MIT proposed a robotic arm with rigid connecting rods and flexible torsional muscles, enabling complex path grasping [60].

Since the 2020s, task-scenario-oriented development has flourished, including medical catheters, bionic soft arms, pipeline detection robots, and more [61]. Through the integration of structural design, material customization, and intelligent control, some rigid–flexible coupling structures have become commercially

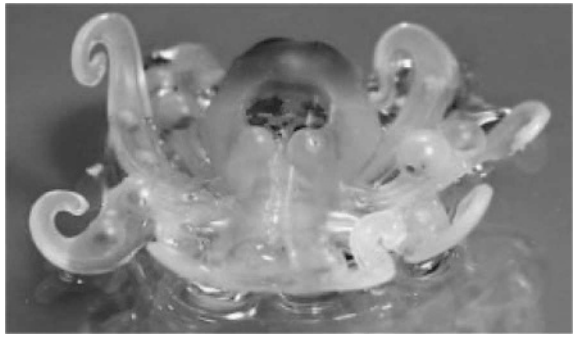


Figure 1.5 Octobot. *Source*: [59]/with permission of Springer Nature.

viable or entered mass testing phases. In 2021, the team led by Zhao Huichan at Tsinghua University proposed a rigid–flexible coupled soft pipeline robot, which combines rigid segments (control circuits and sensing modules) with dielectric elastomer actuators [62]. In 2023, the team led by Su Songjin utilized thermoresponsive hydrogels as driving units, with rigid frameworks restricting their deformation directions to achieve high-speed underwater swimming [63].

To sum up, "smart material-driven" type of RFCRs is rapidly evolving toward integration, miniaturization, and intelligence. In the future, such robots will further integrate multiple smart materials with complex rigid structures to achieve higher actuation performance and structural stability. Meanwhile, relying on advanced manufacturing technologies and intelligent control algorithms, robots will possess stronger environmental adaptability, autonomous sensing, and precise manipulation capabilities, with broad applications in cutting-edge fields such as minimally invasive medicine, wearable devices, soft bionics, and extreme environment exploration. This will drive the evolution of robotic systems toward high performance, multifunctionality, and autonomous intelligence [64].

1.2 The History and Development of Rigid–Flexible Coupling Hoisting Robots

Rigid–flexible coupling hoisting robot (RFCHR) is a special type of RFCR [65]. It is specifically developed to perform hoisting or lifting operations that involve complex dynamic interactions between rigid and flexible components. Unlike conventional rigid-body hoisting systems, the RFCHR incorporates flexible elements—such as compliant links, elastic joints, or cable-driven segments—which allow for enhanced adaptability, vibration suppression, and energy efficiency. The rigid components provide structural support and positional accuracy, while the flexible components enable safe interaction with variable loads and dynamic environments.

RFCHRs are particularly suited for tasks in construction, warehousing, and automated manufacturing where traditional rigid mechanisms may struggle with payload variations, dynamic disturbances, or constrained spaces. By leveraging the advantages of both rigidity and flexibility, RFCHRs offer improved performance in terms of precision, safety, and operational versatility. Research on RFCHRs typically focuses on dynamic modeling, control strategies, and structural optimization to ensure stable hoisting under changing conditions and external disturbances [66].

RFCHR is a large manipulator that combines rigid structures with flexible (cable/rope) actuation, which can be traced back to the 1980s. Early concepts

replaced rigid links with cables to achieve very large workspaces and high payload-to-weight ratios. For example, the SkyCam sports camera (late 1980s), as shown in Figure 1.1 [12]. In parallel, as shown in Figure 1.6, NIST in the United States began the RoboCrane project in 1989: a Stewart-platform-like crane using six cables to control a suspended end-effector. The RoboCrane enabled precise 6-DOF load placement under teleoperation or CNC, supporting tasks like welding, grinding, sawing, and assembly on construction sites [67, 68]. For instance, a scaled RoboCrane was used to assemble modular bridge sections with full 6-DOF control. Meanwhile, Xidian University pioneered cable cranes for astronomy. In 1999, they proposed the feed-cabin cable-driven support for the 500 m FAST radio telescope. Today FAST's movable feed is guided by multiple winches and cables, a celebrated early RFCHR application, as shown in Figure 1.2 [13].

Since entering the twenty-first century, research on RFCHR has flourished globally. Research institutions such as the NIST, Fraunhofer Institute for Applied Physic, French National Centre for Scientific Research, Xidian University, Hefei University of Technology, and China University of Mining and Technology have published numerous research achievements on the design, dynamic modeling, and control of RFCHRs [25, 69].

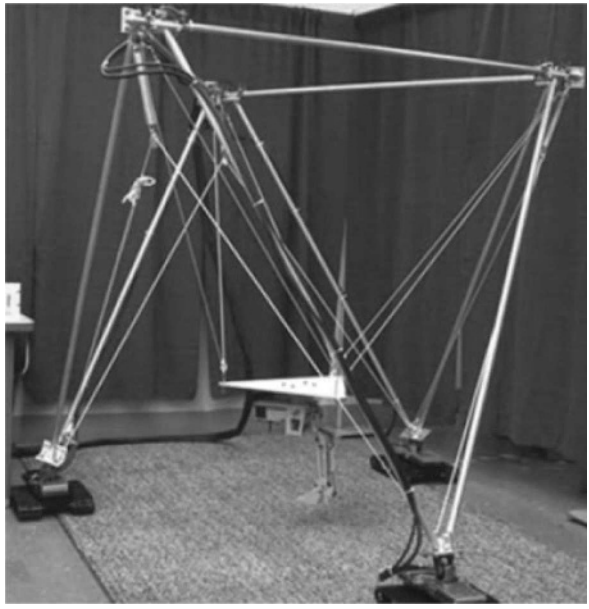


Figure 1.6 NIST RoboCrane model. *Source*: [67]/National Institute of Standards and Technology (NIST)/Public domain.

For instance, Japan's FALCON project and WARP system conduct high-speed motion research using cable-driven parallel robots and propose the system design principle that a cable-driven parallel robot with n degrees of freedom requires at n+1 cables [71]. In 2004, France's ONERA has developed the SACSO wind tunnel model, which uses a parallel robot with nine cables for model positioning and attitude control in wind tunnel tests [72]. In 2009, researchers at the University of Duisburg-Essen in Germany have established the SEGESTA experimental platform to study kinematic modeling, workspace calculation, tension distribution, and trajectory planning of cable robots [73]. In 2012, the Fraunhofer IPA Institute in Germany has developed the IPAnema series of cable-driven parallel robots for industrial applications such as construction and maintenance, as shown in Figure 1.7 [70].

In recent years, the high-strength steel cables or synthetic ropes as actuators are used in the RFCHR. Compared to rigid links, cables offer very light weight and very large reachable volumes. Some designs even incorporate spring elements or compliant joints for additional flexibility. In 2020, Tang and Chen demonstrate hybrid wave-compensation rigs for offshore hoisting: a 4-DOF cable-driven mechanism that flexibly adjusts to sea motion [74]. In addition, significant advancements in intelligent control and multirobot collaboration have further propelled the development of RFCHR. These breakthroughs have enhanced the robots' adaptability to dynamic environments, improved coordination accuracy in complex tasks, and expanded their application scenarios in fields such as intelligent manufacturing, large-scale structure construction, and emergency rescue [75]. For example, Shen et al. [76] present a model-based optimal boundary control design

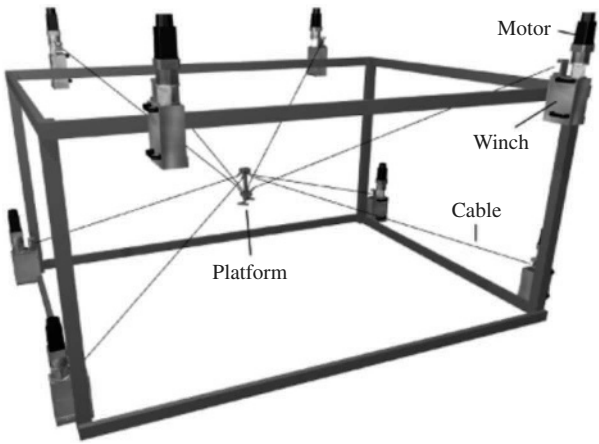


Figure 1.7 IPAnema series of cable-driven parallel robots. *Source*: [70]/National Institute of Standards and Technology (NIST)/Public domain.

for an aerial robotic system composed of a quadrotor carrying a flexible cable. Javier [77] proposed a new analytical model for the drum–cable interaction in mechanical systems actuated through cables, which can capture the extensibility of the cable and the drum–cable contact interaction. Taheri et al. [78] present a reinforcement learning-based policy optimization workflow for training and evaluating controllers of RFCHR, which can inspect the stability and performance in the whole operational envelope of the RFCHR for safe deployment on real machines. Zhu et al. [79] designed an intelligent RFCHR with path planning function, which has the characteristics of foldable assembly, wireless intelligent remote control, intelligent anticollision, dynamic path planning, laser setting out, and payload real-time monitoring. Teerapat et al. [80] proposed a motion compensation algorithm for multistep speed control to achieve precise displacement of RFCHR by dynamically optimizing the duration at each planned speed.

In addition, this field is also supported by dedicated conferences and literature. For example, in 2018, the "Cable-Driven Parallel Robots" symposium is held. Bin Zi's books such as *Design, Analysis and Control of Cable-Suspended Parallel Robots and Its Applications* have collected many research advancements [75]. Meanwhile, numerous patents reflect the maturing technology, including patents on multicable geometries, hybrid drives, and interference-avoiding mechanisms.

In summary, from early cable-camera systems and the RoboCrane in the 1990s, RFCHRs have grown into a broad field. Today, they embody a mix of crane-like hardware and advanced robotics: flexible structures for long reach, multicable parallel architectures, and complex control of coupled rigid–flexible dynamics. Applications span construction, logistics, and large-structure assembly. As of 2025, the trend continues toward integration of smart control (AI, vision feedback), lighter materials, and cooperative multirobot deployments [81].

1.3 The Applications of RFCHRs in Various Fields

1.3.1 Construction

Iturralde et al. [82] designed a new RFCHR, which can be used for the installation of curtain wall modules, as shown in Figure 1.8. Compared with manual installation, the adoption of RFCHR has significantly improved the efficiency of curtain wall installation, greatly shortened the construction period, reduced installation costs, and decreased the incidence of safety accidents. This is a typical example of RFCHR's application in the construction industry. Based on workspace and kinematic sensitivity, McDonald et al. [83] proposed a 3-DOF RFCHR for automated construction.

In addition, as an indispensable tool in the construction industry, tower cranes also represent a typical application of RFCHR, as shown in Figure 1.9 [84].



Figure 1.8 A RFCHR for the installation of curtain wall modules. *Source*: [82]/with permission of Elsevier.



Figure 1.9 Schematic diagram of tower crane. *Source*: [84]/with permission of Elsevier.

At present, the industrial application of tower cranes has been quite mature, and the current research focus lies in effectively solving the problem of swing suppression for tower crane loads in engineering applications. For instances, Sun et al. [85] designed an adaptive control scheme for underactuated tower cranes to achieve simultaneous slew/translation positioning and swing suppression. Besides, Wang et al. [86] proposed a new adaptive controller based on the neural network for tower cranes with obstacle avoidance, and the controller can

simultaneously achieve obstacle avoidance for tower crane lifting payload and swing suppression of the payload. Tian et al. [87] considered the change in cable length of RFCHR and proposed a real-time modified trajectory planning method for tower cranes with heavy-load lifting and lowering movements. In addition, exciting results have also been achieved in the research of the double-pendulum system.

In recent years, RFCHR has achieved remarkable breakthroughs in the construction field through technology integration and scenario expansion, especially in intelligent control and efficiency improvement.

1.3.2 Ocean

As shown in Figure 1.10, the RFCHR structure has garnered extensive and versatile applications in the domain of marine shipboard cranes. This innovative structural design, characterized by its unique combination of rotational flexibility and cable-driven hoisting mechanisms, has seamlessly integrated into the operational frameworks of various marine vessels, ranging from cargo ships to specialized-offshore engineering platforms. In this field, its mature applications are vividly demonstrated through its remarkable capabilities in efficiently handling heavy lifting tasks with high precision and reliability in the harsh marine environment. For instance, it enables shipboard cranes to smoothly execute complex operations such as the loading and unloading of oversized cargo containers, the precise positioning of marine engineering equipment during offshore construction, and the



Figure 1.10 Offshore ship-mounted tower crane. *Source*: CSSC South China Marine Machinery Co. http://www.scmmc.com.cn/men/productshow.php?cid=285&id=395, last accessed July 25, 2025.

stable hoisting of supplies in challenging sea conditions with strong winds and waves. These practical implementations not only highlight the advanced technical advantages of the RFCHR structure but also solidify its indispensable position in modern marine logistics and offshore engineering, driving the continuous improvement of marine crane operation efficiency and safety standards.

At present, both academia and industry have achieved good results in the design and application of RFCHR controllers. For example, Qian et al. [88] proposed an observer-based nonlinear feedback controller for offshore shipboard RFCHRs, which is used to achieve precise boom/trolley positioning of RFCHRs and fast load swing suppression against complex unknown external disturbances. Li et al. [89] proposed a self-adapting trajectory tracking controller, which can compensate the dead zone constraint, unknown gravity forces, and external disturbances. Wang et al. [90] designed a new triple-tagline system, which can suppress the payload swing in arbitrary directions.

In summary, RFCHR controllers are transforming marine and shipbuilding operations through improved precision, efficiency, and adaptability. Ongoing research and industrial collaboration continue to push the boundaries of these technologies, addressing both technical challenges and sustainability goals.

1.3.3 Storage

Warehousing is currently one of the most important and widely applied fields for rigid–flexible coupling lifting robots, which benefits from their unique advantages and compatibility with warehousing operations. In the warehousing environment, tasks such as cargo handling and stacking are arduous and require high efficiency and precision. Rigid–flexible coupling lifting robots combine the high load-bearing capacity of rigid structures with the flexibility of flexible structures, making them capable of easily meeting the handling needs of various types of cargo. Their rigid components ensure stability when lifting heavy goods, preventing shaking or imbalance caused by excessive weight; the flexible components allow the robot to freely navigate through complex warehouse spaces, accurately placing goods in designated storage locations and effectively improving the utilization rate of warehouse space.

Zargari et al. [91] designed a single RFCHR system that integrates actuators, cameras, and computer vision, which is used for fast and accurate scanning of storage racks in warehouses. Zhou et al. [65] designed an RFCHR for warehouse cargo hoisting and transportation and introduced a performance-optimized design approach for RFCHRs, taking into account cable deformation and stochastic loads.

An et al. [92] proposed a proposed a novel RFCHR with movable anchor points and enabled the RFCHR to achieve obstacle avoidance without changing the predetermined trajectory under different conditions through a self-designed collision

detection method and obstacle avoidance algorithm. Ha et al. [93] designed a new RFCHR tailored for logistics warehouses with high-level but short rack intervals, characterized by large working spaces, high operational repetition rates, and rapid task processing capabilities. This robot has been successfully tested and deployed in logistics warehouses, as shown in Figure 1.11.

In addition to the construction, ocean, and storage, RFCHRs are also widely applied in industrial manufacturing. On automotive production lines, they can accurately hoist various components to achieve efficient assembly, significantly enhancing production efficiency. In the medical field, they can assist in transporting medical equipment and even aid in the precise positioning of surgical instruments in some special scenarios. In logistics and transportation, they are used for rapid loading/unloading and transshipment of goods to optimize logistics processes. In power inspection, they help workers hoist inspection equipment to reach inaccessible high-altitude power facilities.

With continuous technological advancements, RFCHRs are expected to emerge in more emerging fields in the future. Their performance will continue to be optimized, and their intelligence level will gradually improve, enabling more precise, efficient, and safe operations. Through deep integration with other cutting-edge technologies, they will bring more innovative changes to various industries, drive

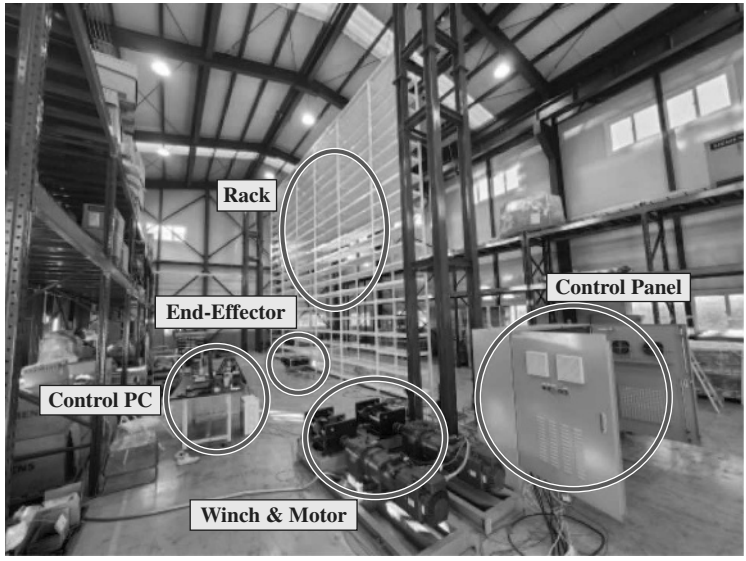


Figure 1.11 RFCHR suitable for logistics warehouses with high-level but short rack intervals. *Source*: [93]/with permission of Springer Nature.

industrial upgrading, and play an increasingly important role in global economic development.

Currently, research on RFCHRs still faces notable challenges and inadequacies across multiple domains, including mechanism design, dynamic analysis, uncertainty analysis, motion decoupling, control strategies, and industrial applications. In mechanism design, material and structural optimization is insufficiently addressed, with systematic methods for selecting flexible joint materials and controlling stiffness often lacking, leading to significant precision losses due to structural deformation and durability issues. Modular and reconfigurable designs are also underdeveloped, limiting adaptability to diverse scenarios and increasing maintenance costs due to poor replaceability of flexible components.

In dynamic analysis, simplified models such as beam elements or lumped mass approaches are frequently employed, overlooking high-order vibration modes of flexible bodies and causing inaccuracies in dynamic response predictions. In addition, regarding uncertainty analysis, existing models are often focused narrowly on parametric perturbations, while external disturbances and unmodeled dynamics are inadequately quantified. Real-time estimation methods for dynamic uncertainties, such as online deformation and disturbance compensation, are largely absent, with reliance instead placed on offline parameter identification.

In motion decoupling, traditional methods are rendered ineffective by strongly coupled multi-degree-of-freedom systems under large power angles or high impedance ratios, and dynamic decoupling strategies based on static models are lacking in adaptability to changing conditions.

Control strategies are challenged by the contradiction between real-time performance and computational burden, as high-frequency control requirements for flexible vibration suppression and trajectory tracking are exceeded by the capabilities of embedded systems. Traditional control methods exhibited poor robustness against uncertainties, while emerging techniques like deep reinforcement learning suffered from limited training data and generalization capabilities.

In industrial applications, reliability is compromised by short service lives of flexible components and frequent maintenance needs, which are compounded by challenges in fault diagnosis and the absence of online health monitoring. Environmental adaptability is affected by issues such as thermal deformation in high-temperature environments and sensor failures in harsh conditions, while engineering validation is insufficient, with limited long-term reliability data provided for lab-developed systems.

Overall, addressing these gaps requires interdisciplinary collaboration and innovations in multi-material design, refined dynamic modeling, real-time uncertainty estimation, adaptive control algorithms, and robust industrial validation to facilitate the transition from theoretical research to large-scale practical application.

1.4 Scope and Organization of This Book

This book centers on the novel design, mechanical principles, control strategies, development processes, and practical applications of RFCHRs, summarizing and extending the authors' work in this field. It can provide inspiration and directions for addressing the existing issues and shortcomings of RFCHRs. It introduces typical mechanical architectures and their practical applications, covering feed cable-suspended structures used in large radio telescopes, as well as under-constrained cable-suspended parallel robots with adjustable parameters, and cable-driven parallel robots for yard operations. The fundamental mechanics are systematically addressed, covering inverse kinematic and dynamic modeling of cable-suspended systems using Lagrange's equations, multi-objective optimization design for workspace and stiffness, and uncertainty analysis incorporating fuzzy parameters, random-interval variables, and hybrid uncertain models. These theoretical frameworks are validated through numerical simulations and experiments, such as trajectory planning using polynomial and cycloid methods, and fuzzy PID control strategies optimized by adaptive whale algorithms to enhance tracking accuracy. For performance improvement, novel designs like mechanical decoupling mechanisms (discretized pulleys and 3D-printed components) and hybrid-driven systems are proposed to mitigate inter-joint interference and nonlinear dynamics. Experimental platforms are developed, integrating high-precision motion capture, tension sensing, and servo-driven cable systems to verify complex trajectories (linear, spiral, and stacking) and validate force control strategies based on structural invariance principles. The book bridges theory and practice by addressing key challenges such as cable winding variability, measurement limitations, and prototype tolerances, providing case studies with numerical analyses and experimental validations. It encompasses advanced concepts like motion decoupling, adaptive control, and sensor integration, offering a comprehensive guide for both theoretical understanding and engineering implementation. The purpose of this book is to function as a textbook for postgraduate courses and a reference material for engineers in the field of RFCHRs. To achieve this goal, the book is structured as follows:

In Chapter 2, the mechanism designs and mechanics modeling of the three new RFCHRs are presented. The mechanism designs of three robots are carried out, and structural models are built to verify their effectiveness. The kinematic modeling is conducted, including the forward and inverse kinematic analysis, and the transformation matrices and vector equations of cable length are derived based on the Denavit–Hartenberg theory and geometric method. Moreover, the dynamic modeling is established based on the Lagrange method and Newton–Euler method, and the dynamic equations considering the inertia matrix, the matrices of centrifugal and Coriolis forces, and gravity matrix are derived.

In Chapter 3, motion decoupling and reconfigurable design of RFCHRs are presented. The coupling characteristics during joint rotation are analyzed, followed by the introduction of motion decoupling methods based on translational and rotational compensation, and the design of a 7-DOF cable-driven serial spray-painting robot featuring these decoupling mechanisms is presented, including a decoupling mechanism for yaw motion and rotational compensation mechanisms for roll motion, along with a tension-amplification mechanism using movable pulleys. Modular and reconfigurable mechanism design is introduced, using modular branches as basic components to reconfigure topological structures by adjusting the number of branches and connection points, enabling configurations from 2-DOF to 6-DOF. A dual-machine collaborative RFCHR mechanical prototype is developed, with kinematic and dynamic modeling conducted, including pose transformation matrices, Jacobian matrix derivation, and Lagrangian dynamic equations considering payload and component masses. The design enhances flexibility, adaptability, and task versatility for diverse applications.

In Chapter 4, the optimization design of RFCHRs is systematically presented, focusing on two distinct mechanisms and their performance enhancements. A multi-objective optimization is introduced for workspace and dexterity, establishing kinematic, static models, and performance indices. An adaptive adjustment inertia weight particle swarm optimization algorithm is proposed, outperforming traditional PSO and genetic algorithms. Then, based on the RFCHR in Chapter 2, the dynamic uncertainty and reliability under random/interval parameters are studied. A hybrid random-interval perturbation method is developed to quantify kinematic errors, validated through Monte Carlo simulations and experiments. The physical prototype demonstrates reduced response errors and improved robustness. Finally, the effectiveness of the optimized design is verified.

In Chapter 5, kinematic analysis of RFCHRs with uncertainty is presented. Kinematic uncertainty analysis with random parameters for a dual automobile cranes system is conducted using the modified hybrid random method, combining perturbation theory and Monte Carlo simulations to predict luffing angular response fields under narrowly distributed random payload parameters, demonstrating its efficiency and accuracy. For interval variables, the hybrid compound function/subinterval perturbation method is proposed to handle large bounded uncertainties by dividing interval variables into subintervals, improving accuracy compared to vertex methods and Monte Carlo methods with reduced relative errors. An evidence theory-based uncertainty analysis method is introduced for cable-driven parallel robots, quantifying epistemic uncertainties in cable lengths to calculate credibility and plausibility functions efficiently. Additionally, a hybrid

perturbation compound function-based moment method is developed to address hybrid random and interval parameters, modeling kinematic error propagation in collaborative systems. Numerical examples and comparisons validate the robustness of these methods in enhancing reliability and design accuracy for RFCHRs.

In Chapter 6, dynamic analysis of RFCHRs with uncertainty is presented. Static uncertainty analysis with fuzzy parameters is conducted using the compound function/fuzzy perturbation method (CFFPM) and modified CFFPM, transforming fuzzy parameters into interval variables via level-cut techniques to improve calculation accuracy and efficiency compared to the Monte Carlo method. For dynamic uncertainty analysis with hybrid random and interval parameters, a modified hybrid uncertain analysis method (MHUAM) is proposed, combining random interval perturbation and moment methods to model uncertainties in loads and structural parameters. Numerical examples validate that MHUAM efficiently predicts dynamic response fields with narrow uncertainties, outperforming traditional methods in computational cost. The chapter provides robust frameworks for uncertainty quantification, enhancing reliability in engineering applications.

In Chapter 7, trajectory planning and tracking control of RFCHRs are presented. Point-to-point trajectory planning for an under-constrained cable-suspended parallel robot is conducted using three algebraic methods, with the fifth-degree polynomial method proving optimal for smooth motion. A fuzzy PID control strategy based on an adaptive whale optimization algorithm is proposed, improving trajectory tracking accuracy for cable-driven parallel robots compared to traditional methods. A cable force control experimental platform is built, adopting a PID controller with structural invariance principle to achieve precise force control, validated by real-time monitoring and experiments. The chapter integrates planning, control, and experimentation to enhance robot performance in engineering applications.

In Chapter 8, the development and application of RFCHR platforms are presented. A 7-DOF RFCHR is designed with mechanical decoupling mechanisms like discretized pulleys and 3D-printed components, complemented by a fuzzy PID control system to address nonlinear dynamics. Experimental validation focuses on motion decoupling performance and trajectory tracking, demonstrating effective reduction of interjoint interference. A yard operations-oriented robot is also developed, integrating high-precision motion capture and tension sensors to execute linear, spiral, and task-space stacking trajectories. The chapter highlights the integration of mechanical design and control strategies, providing practical platforms for industrial hoisting and logistics tasks, and verifying their feasibility in real-world applications (Figure 1.12).

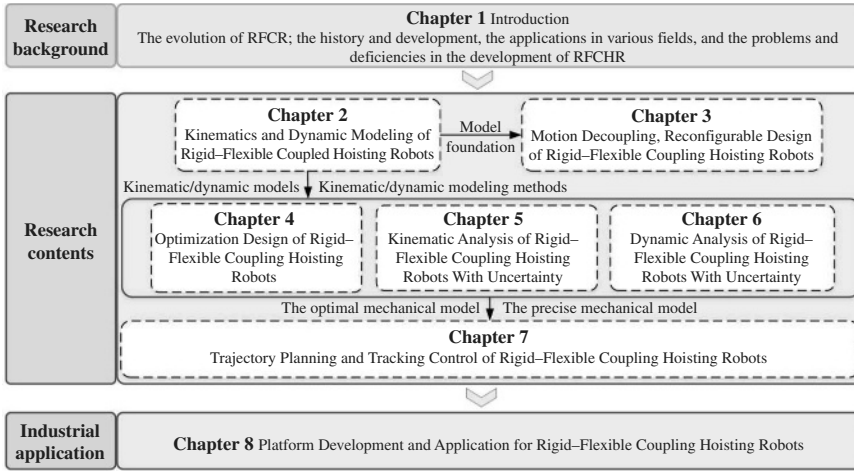


Figure 1.12 The main contents and chapter arrangement for this book.

References

1 Nandihal P V, Mohan A, Saha S K. Dynamics of Rigid-Flexible Robots and Multibody Systems. Singapore: Springer, 2022.

2 Li B, Li X, Gao H, et al. Advances in flexible robotic manipulator systems—Part II: planning, control, applications, and perspectives. IEEE/ASME Transactions on Mechatronics, 2024, 29(3): 1680–1689.

3 Yang Y, Wu Y, Li C, et al. Flexible actuators for soft robotics. Advanced Intelligent Systems, 2020, 2(1): 1900077.

4 Chen H, Zhu J Q, Cao Y, et al. Soft-rigid coupling grippers: collaboration strategies and integrated fabrication methods. Science China Technological Sciences, 2023, 66(11): 3051–3069.

5 Jiang X, Zhang J, Zhang Y, et al. Rigid and flexible structures coupled system study and enhanced vision-aided control for a versatile cable winding robot. IEEE/ASME Transactions on Mechatronics, 2024, 29(6): 4618–4629.

6 Hirose S, Umetani Y. Kinematic control of active cord mechanism with tactile sensors. Transactions of the Society of Instrument and Control Engineers, 1976, 12(5): 543–547.

7 Seeja G, Doss A S A, Hency V B. A survey on snake robot locomotion. IEEE Access, 2022, 10: 112100–112116.

8 Di Lallo A, Yu S, Slightam J E, et al. Untethered fluidic engine for high-force soft wearable robots. Advanced Intelligent Systems, 2024, 6(11): 2400171.

9 Pratt G A, Williamson M M. Series elastic actuators. Proceedings of the 1995 IEEE/RSJ International Conference on Intelligent Robots and Systems. Human Robot Interaction and Cooperative Robots. IEEE, 1995, 1: 399–406.

10 Sun H, Chen X P. Towards honeycomb PneuNets robots. Robot Intelligence Technology and Applications 2: Results from the 2nd International Conference on Robot Intelligence Technology and Applications. Springer International Publishing, 2014, 274: 331–340.

11 Hongjun M, Shupeng Z, Wei Z, et al. Design and control of a new pneumatic quadruped soft robot based on honeycomb structure. IEEE Access, 2024, 12: 98882–98899.

12 Tanaka M, Seguchi Y, Shimada S. Kineto-statics of SkyCam-type wire transport system. Proceedings of USA-Japan Symposium on Flexible Automation, Crossing Bridges: Advances in Flexible Automation and Robotics, 1988: 689–694.

13 Nan R. Five hundred meter aperture spherical radio telescope (FAST). Science in China Series G, 2006, 49: 129–148.

14 Zhao T, Zi B, Qian S, et al. Algebraic method-based point-to-point trajectory planning of an under-constrained cable-suspended parallel robot with variable angle and height cable mast. Chinese Journal of Mechanical Engineering, 2020, 33: 1–18.

15 Hamida I B, Laribi M A, Mlika A, et al. Multi-objective optimal design of a cable driven parallel robot for rehabilitation tasks. Mechanism and Machine Theory, 2021, 156: 104141.

16 Chen Q, Zi B, Sun Z, et al. Design and development of a new cable-driven parallel robot for waist rehabilitation. IEEE/ASME Transactions on Mechatronics, 2019, 24(4): 1497–1507.

17 Tho T P, Thinh N T. Using a cable-driven parallel robot with applications in 3D concrete printing. Applied Sciences, 2021, 11(2): 563.

18 Zhang Y, Li P, Quan J, et al. Progress, challenges, and prospects of soft robotics for space applications. Advanced Intelligent Systems, 2023, 5(3): 2200071.

19 Ma C, Song W, Zhao X, et al. Bioinspired soft robots with integrated biological motion mechanisms and rigid–flexible coupling systems. Small Methods, 2025, 9(7): 2402264.

20 Lee D, Song B, Park S Y, et al. Development and control of an electro-hydraulic actuator system for an exoskeleton robot. Applied Sciences, 2019, 9(20): 4295.

21 Calisti M, Picardi G, Laschi C. Fundamentals of soft robot locomotion. Journal of the Royal Society Interface, 2017, 14(130): 20170101.

22 Salahuddin B B. Hydrogel Based Braided Artificial Muscles. University of Wollongong, 2020.

23 Anderson V C, Horn R C. Tensor arm manipulator. United State Patent, 1970 (3,497,083).

24 James A, Roger B, Nicholas D. The NIST RoboCrane. Journal of Robotic Systems, 1993, 10: 709–724.
25 Qian S, Zi B, Shang W W, et al. A review on cable-driven parallel robots. Chinese Journal of Mechanical Engineering, 2018, 31(1): 1–11.
26 Chirikjian G S. Hyper-redundant manipulator dynamics: a continuum approximation. Advanced Robotics, 1994, 9(3): 217–243.
27 Hirose S, Fukushima E F. Snakes and strings: new robotic components for rescue operations. The International Journal of Robotics Research, 2004, 23 (4–5): 341–349.
28 Robinson G, Davies J B C. Continuum robots-a state of the art. Proceedings of the 1999 IEEE International Conference on Robotics and Automation (Cat. No. 99CH36288C). IEEE, 1999, 4: 2849–2854.
29 Mo X, Ouyang L, Xiong Z, et al. Advances in digital light processing of hydrogels. Biomedical Materials, 2022, 17(4): 042002.
30 Ding H, Yang X, Zheng N, et al. Tri-Co Robot: a Chinese robotic research initiative for enhanced robot interaction capabilities. National Science Review, 2018, 5(6): 799–801.
31 Zhu R, Fan D, Wu W, et al. Soft robots for cluttered environments based on origami anisotropic stiffness structure (OASS) inspired by desert iguana. Advanced Intelligent Systems, 2023, 5(6): 2200301.
32 Polygerinos P, Wang Z, Galloway K C, et al. Soft robotic glove for combined assistance and at-home rehabilitation. Robotics and Autonomous Systems, 2015, 73: 135–143.
33 Mosadegh B, Polygerinos P, Keplinger C, et al. Pneumatic networks for soft robotics that actuate rapidly. Advanced Functional Materials, 2014, 24(15): 2163–2170.
34 Awad L N, Bae J, O'donnell K, et al. A soft robotic exosuit improves walking in patients after stroke. Science Translational Medicine, 2017, 9(400): eaai9084.
35 Bao G, Fang H, Chen L, et al. Soft robotics: academic insights and perspectives through bibliometric analysis. Soft Robotics, 2018, 5(3): 229–241.
36 Zhao W, Zhang Y, Wang N. Soft robotics: research, challenges, and prospects. Journal of Robotics and Mechatronics, 2021, 33(1): 45–68.
37 Pott A, Mütherich H, Kraus W, et al. IPAnema: a family of cable-driven parallel robots for industrial applications. Cable-Driven Parallel Robots. Berlin: Springer, 2012: 119–134.
38 Miermeister P, Pott A. Modelling and real-time dynamic simulation of the cable-driven parallel robot IPAnema. New Trends in Mechanism Science: Analysis and Design. Dordrecht: Springer, 2010: 353–360.

39 Wang S, Zhao Q, Chen J, et al. Co-axial slender tubular robot (CAST): towards robotized operation for transorbital neurosurgery with minimal invasiveness. Proceedings of the 2024 IEEE International Conference on Robotics and Automation (ICRA). IEEE, 2024: 11571–11577.

40 Yang Z, Yang L, Sun Y, et al. A novel contact-aided continuum robotic system: design, modeling, and validation. IEEE Transactions on Robotics, 2024, 40: 3024–3043.

41 Omisore O M, Han S, Xiong J, et al. A review on flexible robotic systems for minimally invasive surgery. IEEE Transactions on Systems, Man, and Cybernetics: Systems, 2020, 52(1): 631–644.

42 Yang Z, Yang H, Cao Y, et al. Magnetically actuated continuum medical robots: a review. Advanced Intelligent Systems, 2023, 5(6): 2200416.

43 Lin B, Song S, Wang J. Variable stiffness methods of flexible robots for minimally invasive surgery: a review. Biomimetic Intelligence and Robotics, 2024, 4(3): 100168.

44 Tian Y, Chen C, Sagoe-Crentsil K, et al. Intelligent robotic systems for structural health monitoring: applications and future trends. Automation in Construction, 2022, 139: 104273.

45 Skibniewski M J. New directions and developments in robotics and site automation in the USA. Proceedings of the 17th International Symposium on Automation and Robotics in Construction. International Association for Automation and Robotics in Construction (IAARC), 2000.

46 Majidi C. Soft robotics: a perspective—current trends and prospects for the future. Soft Robotics, 2014, 1(1): 5–11.

47 Hartmann F, Baumgartner M, Kaltenbrunner M. Becoming sustainable, the new frontier in soft robotics. Advanced Materials, 2021, 33(19): 2004413.

48 Banerjee H, Tse Z T H, Ren H. Soft robotics with compliance and adaptation for biomedical applications and forthcoming challenges. International Journal of Robotics and Automation, 2018, 33(1): 68–80.

49 Li Y, Wang H, Li X, et al. Recent progress in soft robots: principles, designs, and applications. Smart Materials and Structures, 2024, 33(11): 115014.

50 Bhatt A T, Gohil P P, Chaudhary V. Primary manufacturing processes for fiber reinforced composites: history, development & future research trends. IOP Conference Series: Materials Science and Engineering. IOP Publishing, 2018, 330: 012107.

51 Rajabasadi F, Schwarz L, Medina-Sánchez M, et al. 3D and 4D lithography of untethered microrobots. Progress in Materials Science, 2021, 120: 100808.

52 Freire N M A, Estima J O, Cardoso A J M. A voltage-based approach without extra hardware for open-circuit fault diagnosis in closed-loop PWM AC regenerative drives. IEEE Transactions on Industrial Electronics, 2013, 61(9): 4960–4970.

53 Baziyad A G, Ahmad I, Salamah Y B, et al. Robust tracking control of piezo-actuated nanopositioning stage using improved inverse LSSVM hysteresis model and RST controller. Actuators, 2022, 11(11): 324.
54 Yuan Z, Zhou S, Zhang Z, et al. Piezo-actuated smart mechatronic systems: nonlinear modeling, identification, and control. Mechanical Systems and Signal Processing, 2024, 221: 111715.
55 Xia Y, He Y, Zhang F, et al. A review of shape memory polymers and composites: mechanisms, materials, and applications. Advanced Materials, 2021, 33(6): 2000713.
56 Nguyen X T, Calderon A A, Rigo A, et al. SMALLBug: a 30-mg crawling robot driven by a high-frequency flexible SMA microactuator. IEEE Robotics and Automation Letters, 2020, 5(4): 6796–6803.
57 Hussein H, Damdam A, Ren L, et al. Actuation of mobile microbots: a review. Advanced Intelligent Systems, 2023, 5(9): 2300168.
58 Wilson R E. Microfabricated Hydrogel Platforms to Compare Single Cells in 2D Vs 3D Engineered Microenvironments. Stanford University, 2019.
59 Wehner M, Truby R L, Fitzgerald D J, et al. An integrated design and fabrication strategy for entirely soft, autonomous robots. Nature, 2016, 536(7617): 451–455.
60 Huang H, Wang H, Fang C, et al. Grasping by Spiraling: Reproducing Elephant Movements with Rigid-Soft Robot Synergy. arXiv preprint arXiv:2504.01507, 2025.
61 Dheerthi N, Kumar A K, Sarveswaran S, et al. A comprehensive analysis of bio-inspired soft robotic arm for healthcare applications. Multidisciplinary Applications of AI Robotics and Autonomous Systems. IGI Global, 2024: 1–23.
62 Shao Q, Dong X, Lin Z, et al. Untethered robotic millipede driven by low-pressure microfluidic actuators for multi-terrain exploration. IEEE Robotics and Automation Letters, 2022, 7(4): 12142–12149.
63 Zhang D, Xu J, Liu X, et al. Advanced bionic attachment equipment inspired by the attachment performance of aquatic organisms: a review. Biomimetics, 2023, 8(1): 85.
64 Soori M, Dastres R, Arezoo B, et al. Intelligent robotic systems in Industry 4.0: a review. Journal of Advanced Manufacturing Science and Technology, 2024, 4: 2024007.
65 Zhou B, Li S, Zi B, et al. Performance analysis and optimization design of a rigid-flexible coupling hoisting robot considering cable deformation and random loading. Mechanical Systems and Signal Processing, 2025, 223: 111903.
66 Wang Z, Chen T, Zhang Y, et al. A robotic design framework for phase verification of overhead power transmission lines. Journal of Robotics, 2025, 2025(1): 7301970.
67 Bostelman R, Albus J, Dagalakis N, et al. Applications of the NIST RoboCrane. Proceedings of the 5th International Symposium on Robotics and Manufacturing. Maui, HI: NIST, 1994, 5: 1.

68 Lytle A M, Saidi K S, Bostelman R V, et al. Adapting a teleoperated device for autonomous control using three-dimensional positioning sensors: experiences with the NIST RoboCrane. Automation in Construction, 2004, 13(1): 101–118.

69 Sugahara Y, Chen G, Atsumi N, et al. A suspended cable-driven parallel robot for human-cooperative object transportation. ROMANSY 23-Robot Design, Dynamics and Control: Proceedings of the 23rd CISM IFToMM Symposium 23. Springer International Publishing, 2021: 109–117.

70 Schmidt V L. Modeling Techniques and Reliable Real-time Implementation of Kinematics for Cable-driven Parallel Robots Using Polymer Fiber Cables. Stuttgart: Fraunhofer Verlag, 2017.

71 Ming A. Study on multiple degree-of-freedom positioning mechanism using wires (part 1). International Journal of the Japan Society for Precision Engineering, 1994, 28: 131–138.

72 Bousquet J M. Survey of engine integration testing in ONERA wind tunnels. 41st AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, 2005: 3705.

73 Shang W, Zhang B, Zhang B, et al. Synchronization control in the cable space for cable-driven parallel robots. IEEE Transactions on Industrial Electronics, 2018, 66(6): 4544–4554.

74 Tang L, Chen Y. Dynamic model of four degree of freedom rope-driven rigid-flexible hybrid wave compensation device. Journal of Mechanical Science and Technology, 2020, 34: 1937–1948.

75 Zi B, Qian S. Design, Analysis and Control of Cable-Suspended Parallel Robots and Its applications. Singapore: Springer, 2017.

76 Shen Y, Franchi A, Gabellieri C. Aerial robots carrying flexible cables: dynamic shape optimal control via spectral method model. IEEE Transactions on Robotics, 2025, 41: 3162–3182.

77 González-Carbajal J. An analytical model for the drum-rope interaction in hoisting mechanisms and cable-driven systems. Mechanism and Machine Theory, 2025, 207: 105939.

78 Taheri A, Rankka A, Gustafsson P, et al. End-effector Cartesian velocity control for redundant loader cranes using reinforcement learning. IEEE Transactions on Robotics, 2024, 41: 484–496.

79 Zhu Y, Zhang X, Xu K, et al. Intelligent switch cabinet hoisting robot with path planning function. Proceedings of the 2022 IEEE International Conference on High Voltage Engineering and Applications (ICHVE). IEEE, 2022: 1–4.

80 Ku T K X, Zuo B, Ang W T. Robotic tower cranes with hardware-in-the-loop: enhancing construction safety and efficiency. Automation in Construction, 2024, 168: 105765.

81 Bouaouda A, Pannequin R, Charpillet F, et al. Dynamic modeling and AI-based control of a cable-driven parallel robot. IFAC-PapersOnLine, 2023, 56(2): 10021–10026.

82 Iturralde K, Feucht M, Illner D, et al. Cable-driven parallel robot for curtain wall module installation. Automation in Construction, 2022, 138: 104235.
83 McDonald E, Arsenault M, Beites S. Design of a 3-degrees-of-freedom cable-driven parallel robot for automated construction based on workspace and kinematic sensitivity. Journal of Mechanisms and Robotics, 2024, 16(2): 021006.
84 Zhang Z, Wong M O, Pan W. Virtual reality enhanced multi-role collaboration in crane-lift training for modular construction. Automation in Construction, 2023, 150: 104848.
85 Sun N, Fang Y, Chen H, et al. Slew/translation positioning and swing suppression for 4-DOF tower cranes with parametric uncertainties: design and hardware experimentation. IEEE Transactions on Industrial Electronics, 2016, 63(10): 6407–6418.
86 Wang K, Ma X, Li J. Neural network-based adaptive swing suppression control for tower cranes with obstacle avoidance. IEEE/ASME Transactions on Mechatronics, 2024, 30: 2177–2188.
87 Tian Z, Yu L, Ouyang H, et al. Swing suppression control in tower cranes with time-varying rope length using real-time modified trajectory planning. Automation in Construction, 2021, 132: 103954.
88 Qian Y, Fang Y. Switching logic-based nonlinear feedback control of offshore ship-mounted tower cranes: a disturbance observer-based approach. IEEE Transactions on Automation Science and Engineering, 2018, 16(3): 1125–1136.
89 Li F, Qian Y, Wu S. A self-adapting trajectory tracking control for double-pendulum marine tower crane considering constraint dead zone against seawave disturbances. Ocean Engineering, 2024, 309: 118358.
90 Wang S, Ren Z, Du J, et al. Payload swing suppression for offshore cranes using a novel triple-tagline system: theory and experiment. Proceedings of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment, 2020, 234(2): 547–557.
91 Zargari A, Castrejon Z A, Kim D, et al. Cable-driven parallel robot for warehouse monitoring tasks. Proceedings of the 2023 IEEE 13th Annual Computing and Communication Workshop and Conference (CCWC). IEEE, 2023: 1085–1090.
92 An H, Yuan H, Tang K, et al. A novel cable-driven parallel robot with movable anchor points capable for obstacle environments. IEEE/ASME Transactions on Mechatronics, 2022, 27(6): 5472–5483.
93 Ha S H, Woo S W, Kim M C, et al. A cable-driven parallel robot for high-rack logistics automation. International Journal of Control, Automation and Systems, 2024, 22(11): 3329–3340.