Engineering 47 (2025) 100–116

Contents lists available at ScienceDirect

Engineering

journal homepage: www.elsevier.com/locate/eng

Research
Mechanical Engineering—Review

A Review on Reconfigurable Parallel Mechanisms: Design, Analysis and Challenge

Lin Wang [a], James W. Zhang [b], Dan Zhang [a,*]

[a] Department of Mechanical Engineering, The Hong Kong Polytechnic University, Hong Kong 999077, China
[b] Department of Mechanical Engineering, McMaster University, Hamilton, ON L8S 4L8, Canada

ARTICLE INFO

Article history:
Received 30 July 2023
Revised 9 October 2023
Accepted 2 September 2024
Available online 22 October 2024

Keywords:
Reconfigurable parallel mechanism
Design synthesis
Performance index

ABSTRACT

Reconfigurable parallel mechanisms were first discovered in response to the growing demand for flexible and adaptive systems in various fields. Unlike traditional mechanisms, which are designed for specific tasks and have fixed topology and mobility characteristics, a reconfigurable parallel mechanism can be adapted to different situations by changing its structure, motion, and function. This adaptability enables a single mechanism to perform a wide range of tasks, reducing the need for multiple dedicated systems. This paper presents a comprehensive review of reconfigurable parallel mechanisms. The characteristics of their designs, analyses of their properties, and challenges they face are reported. The beginning of this paper features an introduction of reconfigurable parallel mechanisms and their classification into different types. Methods for synthesizing reconfigurable parallel mechanisms are discussed. A performance evaluation index related to reconfigurability, workspace, singularity, stiffness, and dynamics, among other indices, is presented. This review covers the challenges faced in the creation of systematic design theories, unified performance analyses, evaluation index systems, and in the implementation of reconfigurable parallel mechanisms, such as the development of efficient control strategies and integration with other technologies. The paper concludes with a discussion of future research directions for reconfigurable parallel mechanisms.

1. Introduction

Rapid advancements in science and technology and increasing demands for different applications, such as the service, manufacturing, aerospace, and production line automation industries, have resulted in there being a significant demand for robotic equipment. A wide variety of robots, including serial, parallel, and hybrid robots, has been designed, with some models exhibiting notable advantages and successful commercialization ability in a range of applications [1–4]. However, the constantly changing environmental and operating conditions have made tasks increasingly complex and diverse to complete. Hence, these tasks require robotic equipment with enhanced flexibility and adaptability. Traditional robotic equipment with immutable topology and mobility characteristics that are designed for specific tasks can no longer meet the needs of industrial applications. Therefore, reconfigurable parallel mechanisms with modifiable topologies and mobilities have been proposed to fulfill complex and diverse applications [5,6], such as those in medical care [7,8], aerospace [9,10], legged robot design [11–14], dexterous robotic hand design [15–17], manufacturing [18,19], low-voltage circuit breaker mechanism design [20], grasping device design [21–24] and reconfigurable linkage structure design in architecture [25–27]. Structural innovation in robot design is imperative to meet these changing requirements.

Reconfigurable parallel mechanisms are mechanical systems or devices with modifiable configurations and mobilities. These systems can adapt to different operating conditions or perform multiple functions without requiring significant redesigns or replacements of parts. Reconfigurable parallel mechanisms can be broadly classified into five categories: kinematotropic, metamorphic, origami-inspired, tensegrity, and other multimode mechanisms. The concept of kinematotropic mechanism was first introduced by Wohlhart [28]. He found that the mobility of this type of mechanism can change after passing through a specific singular configuration without changing the topology. Dai and

---

* Corresponding author.
E-mail address: dan.zhang@polyu.edu.hk (D. Zhang).

https://doi.org/10.1016/j.eng.2024.09.022

Rees Jones [29] developed a metamorphic mechanism in their research on decorative carton folds, which has changeable topology and variable mobility characteristics based on the principle of evaluation. These two types of mechanisms have enabled the study of reconfigurable parallel mechanisms. Mruthyunjaya [30] noted that the introduction of metamorphic mechanisms has greatly contributed to the innovative design of mechanisms. Metamorphic mechanisms are a large class of foldable and erectable mechanisms that originate from origami equivalent mechanisms [29]. These mechanisms can also be called origami metamorphic mechanisms. As such, they are in a way of behaviour of the origami mechanisms for their varieties [31]. These mechanisms include metamorphic classical mechanisms [32–34], metamorphic topological mechanisms [5,35,36], metamorphic origami mechanisms [29,31,37], metamorphic transformer mechanisms [38], and metamorphic parallel mechanisms [39–43]. Origami-inspired mechanisms, extracted from decorative carton folds were introduced in Ref. [29]. By using creases as rotation axes and paper panels as links, which are designed through folding techniques, a new foldable/erectable mechanism can be constructed. This type of mechanism is a key enabler of adaptability and transformation in architectural applications that provides the structural and functional versatility needed to create buildings that respond to changing needs, optimize space utilization, and offer energy efficiency while allowing for innovative and aesthetically appealing designs [44]. Typical examples of origami-inspired mechanisms include the Sarrus origami-inspired mechanism [45] and spherical metamorphic mechanisms [46]. Origami-inspired mechanisms can be expanded for use and folded for storage and transportation, which are advantageous characteristics [47]. In the contemporary landscape of robotics development, humans and robots have begun to coexist. This trend is prominent and transformative in the next generation of robotic systems. In response to the demands of the architecture and structural engineering domains, there has been a substantial body of research dedicated to the exploration of mechanisms with tensile integrity, which combine the favorable attributes of both rigid and soft structures [48–50]. In addition to the abovementioned reconfigurable parallel mechanisms, multimode mechanisms (also referred to as disassembly free reconfigurable parallel mechanisms) have been studied for their excellent adaptability characteristics in various working environments [51–54].

An extensive study has been conducted on methods for designing reconfigurable parallel mechanisms. These methods for synthesizing reconfigurable parallel mechanisms can be broadly classified into five categories: ① Amalgamating classical linkages; ② adding joints; ③ passing though controllable singular configurations [28,55–61]; ④ special trajectory planning [62]; and ⑤ variable actuation modes [63,64]. The amalgamation of classical linkages can be classified into two major families: Bennett-based linkages [32,53,54,65–70] and Bricard-related linkages [21,71–75]. By assembling these linkages and removing common links, while also rigidifying common joints, a novel reconfigurable parallel mechanism can be obtained. Other reconfigurable parallel mechanisms can be created by adding joints, such as several lower joints [11,32,76–79], reconfigurable joints [39–42,80–83], and lockable joints [35,84–87]. The use of reconfigurable joints can change joint properties by applying geometric constraints. The lockable joints can change the numbers of links and joints upon locking the joint.

Reconfiguration serves many purposes, including improving efficiency, reducing costs, increasing productivity, and enhancing performance. From the perspective of performance analysis, reconfiguration offers the merits of enlarging the workspace [88–90], improving the dynamic properties [91–93], changing the degree of freedom [23,24,32,86] and avoiding singular poses [94]. Reconfiguration has proven to be an effective method for improving the overall performance of a parallel mechanism with a range of benefits.

An enormous amount of research has aimed to address design method, performance measures, control strategies and optimization of reconfigurable parallel robots. However, only a paucity of effort has gone into the review of reconfigurable parallel mechanisms. An overview of the development of metamorphic mechanisms was provided by Zhang and Dai [5] in 2009. A review on trends in modular reconfigurable robots was presented by Brunete et al. [95]. Aimedee et al. [96] presented a thorough review of all reconfigurable mechanisms in 2016. Recently, a review on the new design concept of metamorphic mechanisms and their innovative application was reported in Ref. [6]. There is still a lack of reviews on the classification, design, performance analysis, and challenges of reconfigurable parallel mechanisms. In this work, these three aspects are studied to provide a reference for researchers in the field of reconfigurable parallel mechanisms. In addition, existing research problems and challenges are analyzed to promote related research.

2. Classification of reconfigurable parallel mechanisms

Over the past several decades, extensive research has been conducted on various types of reconfigurable parallel mechanisms, including kinematotropic, origami-inspired, tensegrity, and other multimode mechanisms. The rapid development of reconfigurable parallel mechanisms is driven by several key benefits, including the need for few actuators to operate in multiple motion modes and the time savings achieved through reconfiguration without the need for disassembly.

Recently, a significant number of reconfigurable parallel mechanisms have been designed and analyzed, leading to the proposal of various approaches for their effective implementation. These advancements in reconfigurable parallel mechanisms can greatly improve efficiency, reduce costs, and enhance performance across a range of applications. Table 1 shows a comparison of different types of reconfigurable parallel mechanisms regarding their advantage, disadvantage and reconfiguration strategy.

2.1. Kinematotropic mechanisms

As defined by Wohlhart [28], kinematotropic mechanisms change their global mobilities when passing a singularity position. The Wunderlich mechanism is an example of a kinematotropic mechanism, as shown in Fig. 1. Kinematotropic mechanisms can be introduced chiefly from two main families: single-loop mechanisms and multi-loop mechanisms. Single-loop kinematotropic mechanisms have gained increasing attention due to them having simpler structures and fewer joints than multi-loop kinematotropic mechanisms.

Reconfiguration Bricard plane-symmetric linkages were investigated by López-Custodio et al. [97] using the intersection of two concentric singular toroids, which were further assembled to create new reconfigurable linkages. With the same method, several specific Bricard linkages with various branches of reconfiguration were introduced in Ref. [98]. Feng et al. [73] demonstrated that 5R/4R (R denotes a revolute joint) linkages evolve from plane-symmetric Bricard linkages that can be bifurcated into Bennett linkages. By assembling Bennett linkages, a series of spatial single-loop overconstrained linkages was designed by Guo et al. [66] that can be utilized for synthesizing deployable mechanisms. Zhang and Dai [99] explored the bifurcation and trifurcation of a double-spherical 6R overconstrained linkage, and the results proved that it can reconfigure its configurations when transitioning through transitory positions and switching from spherical 4R

Table 1
Comparison of different types of reconfigurable parallel mechanisms.

Type	Advantage	Disadvantage	Reconfiguration strategy
Kinematotropic mechanism	Precise control	Limited adaptability for nonlinear movements with sudden changes	Controlled changes in joint angles
Metamorphic parallel mechanism	Variable mobility, variable topology, versatility, adaptability to various tasks, and mechanism branch change ability	Geometric constraints must be in the initial design stage	Constraint singularity with geometric constraints, metamorphic joints, and geometric limits
Origami-inspired metamorphic mechanism	Compact, lightweight, and efficient folding/unfolding abilities	Limited load-bearing capacity	Folding and unfolding abilities along predefined creases
Tensegrity mechanism	Highly resilient and adaptable to nonuniform terrain	Complex control and modeling	Cable tension and strut length adjustment
Other multimode mechanism	Varied branches for different tasks	Sophisticated control system requirements	Interchangeable components and modular assembly

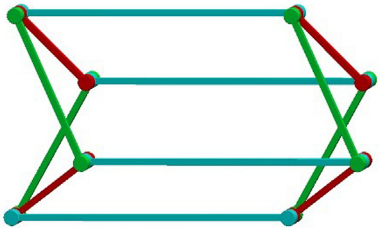
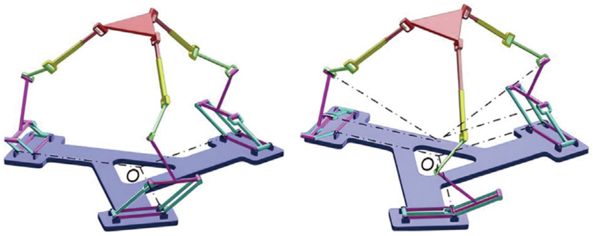
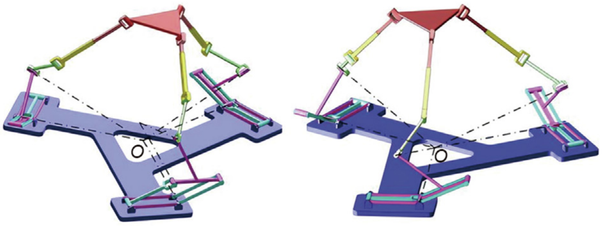


Fig. 1. Wunderlich mechanism as a kinematotropic mechanism.



Three translational DOFs

Two translational and one rotational DOFs



One translational and two rotational DOFs

Three rotational DOFs

Fig. 2. Four configurations of the reconfigurable parallel mechanism. Reproduced from Ref. [105] with permission.

linkages to serial kinematic chains. Liu et al. [53] proposed a systematic method based on algebra for designing single-loop 6R, 7R, and 8R Bennett-based mechanisms with multiple operations. Pfurner [100] synthesized a new single-loop 8R mechanism by combining two single-loop overconstrained 6R mechanisms and performed motion analysis. A single-loop 8R kinematotropic mechanism was created by Chai et al. [68], and the transitory positions were identified. Two types of 8R mechanisms, constructed using spherical and planar 4R linkages, were presented in Ref. [101]. Hsu and Ting [102] proposed an approach for systematically deriving overconstrained mechanisms using the RPRP linkage (P denotes a prismatic joint) as a unit. Kong [52] revealed the motion modes of a novel 7R spatial mechanism by addressing loop equations based on dual quaternions.

Other multiloop kinematotropic mechanisms have been proposed and explored. A queer-square-based mechanism was designed, and the effects of constraint singularity on multifurcation phenomena were studied by Qin et al. [55]. A network mechanism comprising four Bennett linkages was analyzed and further modified and assembled to construct five overconstrained linkages by Song et al. [65]. López-Custodio and Dai [103] introduced a new method for designing kinematotropic linkages using 2-degree of freedom (DOF) kinematic chains that created a Bohemian dome and obtained an example with this method. In another study, López-Custodio and Müller [104] proposed a strategy for synthesizing kinematotropic parallel mechanisms where the key is to combine an additional limb to change the mobility by applying constraints. Ye et al. [105] addressed the issue of designing novel reconfigurable parallel mechanisms that integrate reconfigurable limbs with diamond kinematotropic chains, as shown in Fig. 2.

2.2. Metamorphic parallel mechanisms

The design of a metamorphic mechanism involves the reconfiguration of its topology and alteration of its mobility due to geometric constraints during continuous movement. This adaptation enables the mechanism to function in various operational environments and fulfill different task requirements. The distinction between the metamorphic mechanism and the kinematotropic mechanism lies in the method of reconfiguration. While the topology and mobility of the former mechanism may be altered through controlled singular configurations or reconfigurable joints, these characteristics of the latter mechanism must pass through singular configurations to change its mobility without changing its topology [6].

Ma et al. [32] proposed the spherical-planar 6R metamorphic linkage and the Bennett-spherical 6R metamorphic linkage and identified the transformation conditions. The novel Bennett-plano-spherical hybrid linkage designed by Zhang and Dai [67] can act as a limb in the construction of a novel metamorphic parallel mechanism. Adding two revolute joints in a Bennett mechanism resulted in a new 6R metamorphic parallel mechanism [70]; then, the kinematic curves, furcation points and motion branches were determined. Kang et al. [76,77] introduced a new technique for creating two novel 7R metamorphic parallel mechanisms by adding an additional revolute joint to a Schatz linkage, and different motion branches and bifurcation points of the two mechanisms were evaluated by solving constraint equations. A biomimetic quadruped robot with a trunk involving an 8-bar metamorphic single-loop mechanism was constructed, and a corresponding control strategy was proposed by Tang and Dai [38]. Chai et al. [33] combined Bennett linkages in a serial manner to form six novel metamorphic parallel mechanisms and disclosed a relationship between the bifurcation and group representation of mechanisms.

Moreover, resorting to a joint with reconfigurability is another extremely beneficial approach for designing a metamorphic parallel mechanism. The variable revolute (vR) joint was first introduced by Wei and Dai [106], and a group of reconfigurable and deployable platonic mechanisms was constructed. Zhang et al. [80] explored different types of metamorphic mechanisms that employ origami-fold-based metamorphic kinematic pairs that can switch from the 3R mode to the Hooke joint mode. In addition, these scholars investigated the variable-axis (vA) joint and the S_vPS_v (S_v: source phase of vA joint) metamorphic limb [81] and Bennett plano-spherical linkages and their corresponding hybrid limbs with different motion branches [107]. Gan et al. [39–42,82] designed and investigated a novel reconfigurable Hook (rT) joint and developed the 3-(rT)C(rT), 3-(rT)PS, 3-R(rT)S, and 3SPS-1C(rT) (C: cylindrical joint; S: spherical joint) mechanisms. Additionally, the researchers introduced a reconfigurable revolute (rR) joint and 3(rR)PS mechanism and optimized their topologies for improved performance in Ref. [83]. A new family of metamorphic mechanisms with 3–6 DOFs was constructed with hybrid reconfigurable limbs in Ref. [108]. By considering the line dependence of screws and their embodied geometries, Wang et al. [109] designed a reconfigurable spherical joint and constructed metamorphic mechanisms. Zhao et al. [110] proposed the design of a large-scale multifingered hand for space with metamorphic mechanisms that serve as knuckle units where a lockable spherical joint is used. By considering the quotient operation of manifolds, Wei and Dai [43] generated novel metamorphic mechanisms comprising metamorphic joints, which are key factors in the transformation of reconfiguration from 1R2T to 2R1T (T: translation). Two different types of motion for the proposed metamorphic parallel mechanism are presented in Fig. 3.

2.3. Origami-inspired metamorphic mechanisms

With the overlapping results of art and engineering, origami-inspired metamorphic mechanisms have led to substantial progress in the innovative development of related mechanisms. There is another type of mechanism inspired by kirigami. These mechanisms are related but distinct paper art and engineering techniques. Kirigami encompasses the folding and cutting of paper to achieve three-dimensional structures. However, origami involves the folding of paper to achieve similar results. Origami-inspired metamorphic mechanisms use folding patterns to design structures with shapes or configurations that can be changed through folding and unfolding. One of the most notable examples is the Sarrus [111], which was derived from origami folding. Nelson et al. [112] described a compliant rolling-contact element inspired by origami that can transition from a flat state to a deployed state and can be applied in large-displacement angle, compliant, multistable revolute joints. Wang et al. [36] presented a method extracted from origami to construct an 8R mechanism. The inspired design procedure is shown in Fig. 4. The switching process of the obtained origami-inspired 8R mechanism is analyzed and illustrated in Fig. 5. Wei and Dai [37] proposed two 1-DOF planar-spherical overcostrained mechanisms and revealed their assembly conditions and geometric constraint.

Some kinematotropic mechanisms have been derived from origami. Qin and Dai [55] investigated the multifurcation phenomenon and the constraint singularity of a new mechanism derived from the conventional queer-square mechanism [28]. Kang et al. [56] identified six motion branches of the queer-square mechanism by the screw-algebra approach, which proved to be an effective and simple method for obtaining the constraint system in complex multiloop mechanisms.

Additionally, numerous studies have been conducted on metamorphic mechanisms derived from origami-inspired mechanisms. Salerno et al. [113] developed a novel 4-DOF grasp device used for minimally invasive surgery, which was formed by an origami-inspired parallel mechanism, an origami-inspired twisting part and a compliant gripper. Zhang and Dai [114] described the kirigami-fold-based 8R metamorphic mechanism and the evolved procedure of two types of 6R metamorphic linkages from the 8R mechanism. A design method for constructing Fulleroid-like deployable Archimedean mechanisms was proposed by Xiu et al. [115]; then, mobility and kinematic analyses were implemented. Wei and Dai [116] investigated 2-DOF dual-plane-symmetric spatial eight-bar linkages that can perform exact straight-line motion. By using these eight-bar linkages, a family of deployable platonic mechanisms with radially reciprocating motion was constructed. Barreto et al. [117] provided a method based on graph and group theories to create additional origami-inspired mechanisms with relatively high complexity and great mobility as building blocks for constructing multiloop origami-inspired spherical mechanisms. Tang and Dai [118] obtained an eight-bar linkage though the kinematic equivalence of an 8-kaleidocycle and explored its motion branch properties. In Ref. [119], an origami-inspired double-spherical linkage was presented and two motion modes (crank-rocker and double crank) were discovered. A new modeling method for reaction force analysis was provided by Qiu et al. [120], which is applicable to origami-inspired mechanisms.

2.4. Tensegrity mechanisms

Tensegrity mechanisms, which are intriguing types of reconfigurable structures, have gained increasing attention in various fields

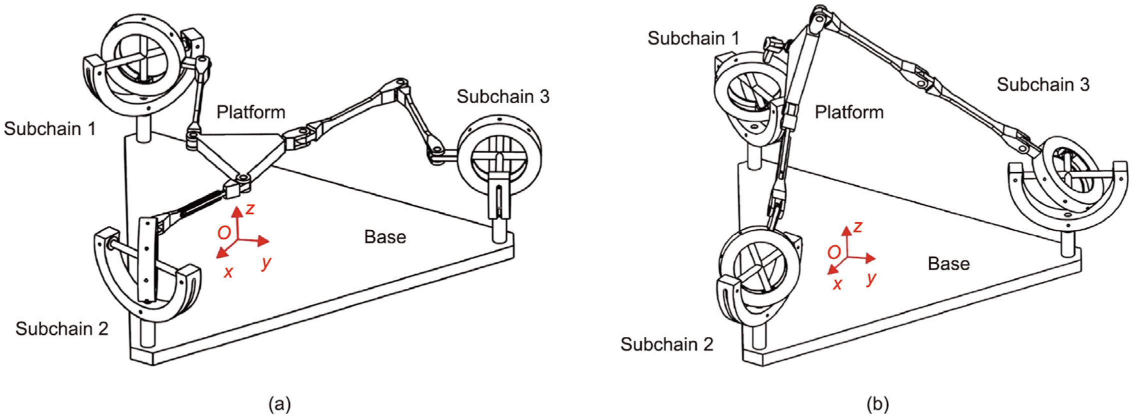


Fig. 3. Metamorphic parallel mechanisms with two motion types: (a) 1R2T (R: rotation; T: translation); (b) 2R1T. Reproduced from Ref. [43] with permission.

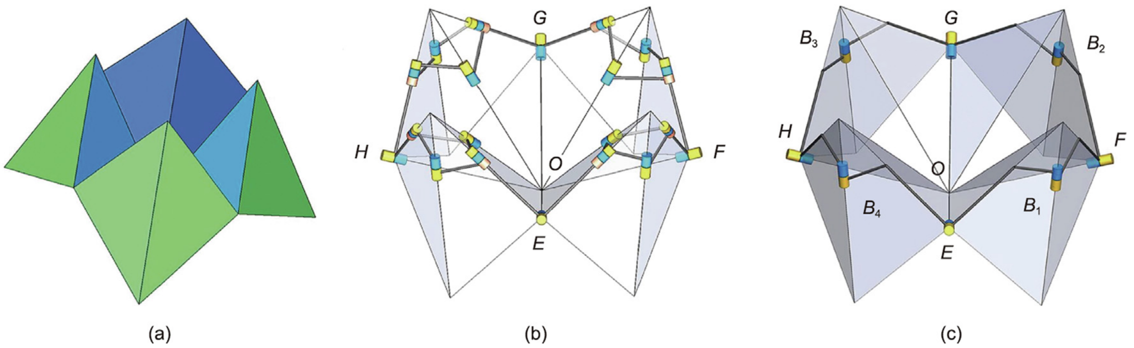


Fig. 4. Inspired design from origami to mechanisms: (a) an origami fold; (b) equivalent linkage of origami fold; (c) origami-inspired 8R mechanism. *E*, *F*, *G*, *H*, B_1–B_4: revolute joints; *O*: common vertex. Reproduced from Ref. [36] with permission.

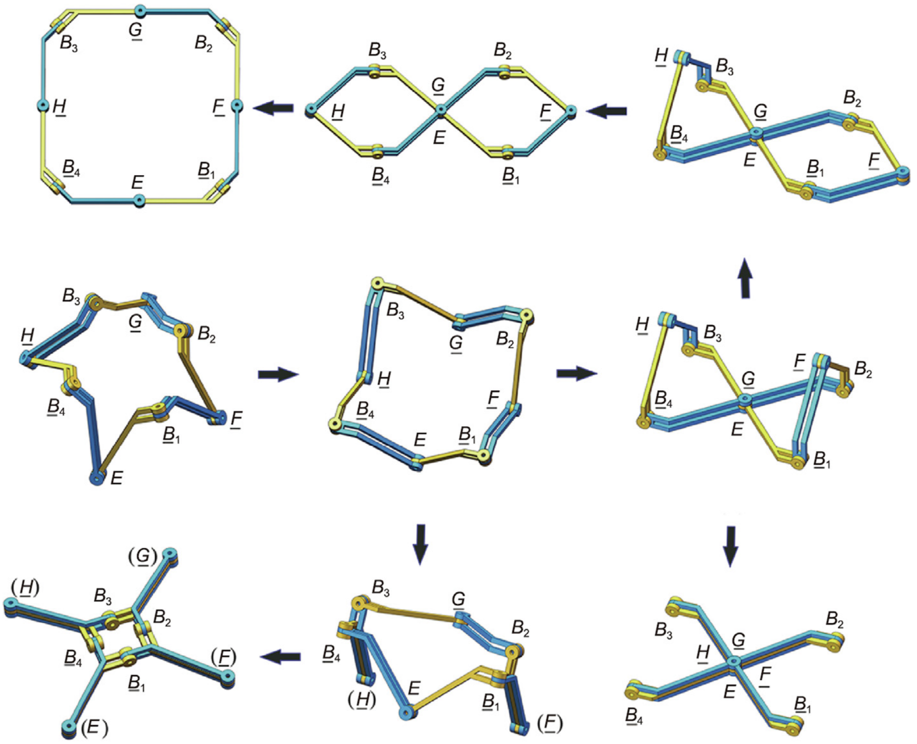


Fig. 5. Switch process of origami-inspired 8R mechanism. Reproduced from Ref. [36] with permission. The definitions of all the abbreviations in the figure could be found in the cited references.

in recent years. According to Refs. [121–124], a tensegrity structure is an assembly of compressive elements (struts) and tensile elements (cables and springs) held together in equilibrium. Tensegrity mechanisms have interesting inherent features, such as low inertia, natural compliance, and deployability.

In the field of robotics, Venkateswaran et al. [125] developed a robust bioinspired caterpillar-type piping inspection robot. This remarkable creation incorporated tensegrity mechanisms and four-bar wheel mechanisms, effectively addressing the challenge of maneuvering through pipe bends and junctions. Furthermore, Cimmino et al. [126] introduced the concept of utilizing tensegrity structures to construct renewable energy supply systems. Notably, the scholars designed wind generators capable of converting the strain energy stored in the cables of a wind-excited unit into electrical power, thus enabling sustainable energy solutions. In the context of space exploration, Khaled et al. [127] devised a groundbreaking miniature drilling rig based on the principles of tensegrity. This innovative rig is applicable in both earth and space drilling systems, enhancing the mobilities, reducing the drilling costs, and minimizing the environmental footprints of terrestrial drilling operations by reducing carbon emissions.

The analysis of tensegrity mechanisms presents a distinctive challenge compared to classical mechanisms due to the intricate nature of the equations required to satisfy static equilibrium conditions. Drawing inspiration from the insightful work of Wenger and Chablat, as documented in Ref. [128], a classification of solutions tailored to a specific class of planar tensegrity mechanisms is introduced in this study. This classification offers valuable insights into the kinematic behaviors of this mechanism and facilitates precise design and control strategies. In response to the multifaceted challenges posed by factors such as elastic deformation, geometric nonlinearity, friction, and redundant drives, Peng et al. [129] proposed a comprehensive approach for the mechanical modeling and control of tensegrity robots. The representation of this approach is depicted in Fig. 6, which provides a visual reference for its application. Exploring the realm of control algorithms

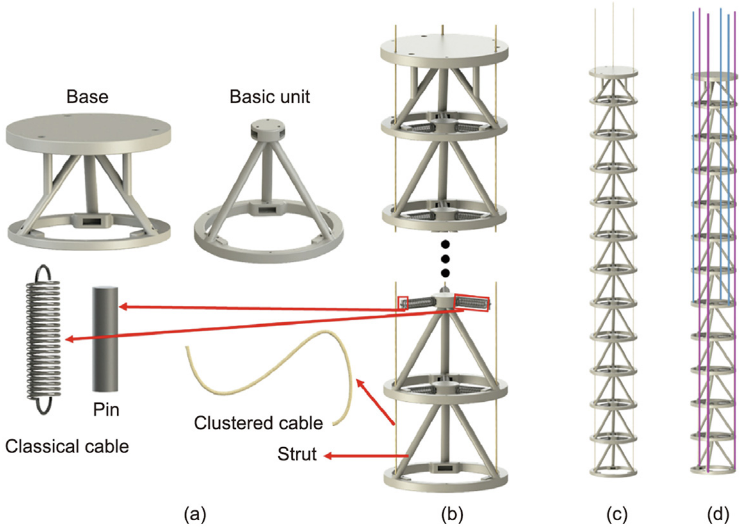


Fig. 6. Tensegrity continuum robot design: (a) components of the continuum robot; (b) connection mode between each unit; (c) the continuum robot with 3 clustered cables (CTCs); and (d) the continuum robot with 6 CTCs. Reproduced from Ref. [129] with permission.

for tensegrity robots, as expounded in Ref. [48], this research addresses the intricate task of path following in an active tensegrity structure. The aim of this endeavor is to achieve the desired tensegrity shape or end-effector position through advanced control methodologies. By exploring the complex kinematics of a 2-DOF tensegrity manipulator, composed of two X-mechanisms arranged in series, Furet and Wenger [49] investigated the unique challenges arising from the rotation of the X-mechanisms surrounding a variable instantaneous center. To enhance the output forces of twisted and coiled actuators, Zhou et al. [50] innovated the fabrication and force enhancement principles associated with multitwisted and coiled actuators. Compared to conventional single twisted and coiled actuators, this novel approach enables a remarkable increase in the output force, exceeding threefold, while utilizing the same fiber material.

2.5. Other multimode mechanisms

Multimode mechanisms are a broad category of reconfigurable parallel mechanisms that can exhibit multiple operation modes or configurations. These mechanisms can switch between different modes to perform various functions or adapt to different requirements. The transition between modes can be achieved through mechanical actuation, the use of shape-changing materials, or other methods. Kong [130] developed a 3-DOF multimode mechanism called DIRECTOR with two operation modes. To overcome constraint singularities when changing operation modes, brakes and timing belts were used. Li and Hervé [131] identified the geometric conditions for achieving bifurcation into its two working modes via group theory. Gogu [57] proposed a new approach and presented a family of T2R1 type parallel manipulators with bifurcated spatial motion. Nurahni et al. [132] designed a new ankle rehabilitation device. By switching between exercise modes, the device completes different movements for rehabilitation training. However, these multimode mechanisms without lockable joints must pass through constrained singular configurations so that the motion mode can be switched.

Multimode mechanisms with lockable joints have been extensively studied. Based on the previous effort of Kong [130], further contributions were made on a 3-DOF multimode reconfigurable mechanism with lockable joints in Ref. [133], which can switch between different operation modes without encountering constraint singular configurations or the self-motion of the subchain of a leg. Carbonari et al. [84] presented a class of reconfigurable modular parallel robots involving a locking system that enables changes in reconfiguration and mobility. Li et al. [85] proposed a new approach based on a block adjacency matrix to investigate the configuration transformation of multimode mechanism with a lockable joint. The synthesis of a reconfigurable mechanism with 1R2T and 2R1T modes achieved by a metamorphic joint with two lockable axes was presented in Ref. [35]. Flores-Mendez et al. [86] illustrated the synthesis of a 3T1R reconfigurable mechanism that integrated a reconfigurable platform with lockable revolute joints and a 3T parallel mechanism. Riabtsev et al. [87] proposed a novel 2-DOF lockable joint, and an analysis of several related kinematic indices was presented.

In addition, the use of a reconfigurable platform enables the mechanism to transform from one operation mode to another without constraint singularities. A reconfigurable platform generally consists of lower pairs and binary links that form single loops. Kong and Jin [134] designed a multimode translational/spherical mechanism realized by a Bricard linkage reconfigurable moving platform, as shown in Fig. 7. By locking one revolute joint of the Bricard linkage reconfigurable moving platform at different positions, the platform can perform five motion modes. Wang et al. [22] proposed a generalized parallel mechanism with a reconfigurable moving platform that can grasp heavy and large objects. Tian and Zhang [21,135] and Tian et al. [136] proposed systematic synthesis methods for constructing reconfigurable mechanisms with multiple operation modes by using a newly designed closed-loop reconfigurable platform, where the kinematic performance and functionality were greatly improved. Hoevenaars et al. [137] designed two types of 3-DOF mechanisms with reconfigurable platforms and analyzed the Jacobian systematically [24]. Wu and Dong [138] introduced a Hexa parallel mechanism that can output Schonflies motion. Haousa et al. [23] created a spherical parallel wrist that can be grasped in an invasive surgery by folding the top platform.

3. Analysis of reconfigurable parallel mechanisms

Recently, reconfigurable parallel mechanisms have been extensively developed because of their ability to reconfigure their configurations and change their output motions. These mechanisms

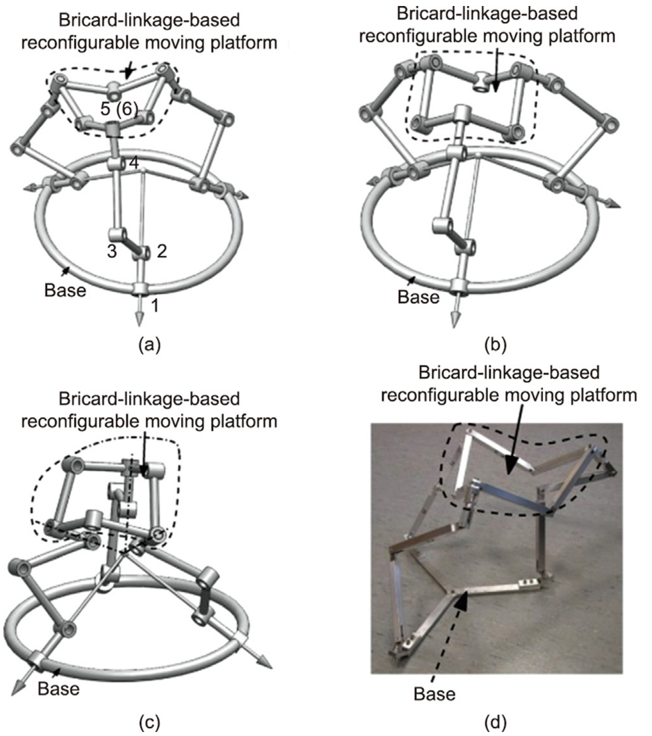


Fig. 7. Multi-mode mechanism: (a) general 3-DOF mode; (b) translation mode; (c) spherical mode; and (d) the prototype. Reproduced from Ref. [134] with permission.

have great potential for accommodating to complex and diverse task requirements. These mechanisms offer several advantages over traditional parallel mechanisms and have great potential. Performance analysis plays a significant role in the design, performance evaluation and optimization of reconfigurable parallel mechanisms and encompasses various aspects, including reconfiguration (determining all motion branches), workspace, singularity, dynamics, and stiffness, among other indices.

3.1. Reconfiguration

The complex structures and kinematics of reconfigurable mechanisms with variable operation modes have posed significant challenges for reconfiguration analysis. However, there is an urgent need to determine all the modes of motion of a reconfigurable mechanism for further control, optimization, and application. Extensive research has been conducted to identify the reconfigurability characteristics of reconfigurable mechanisms in terms of variable motion modes, resulting in the proposal of various methods.

Significantly, the overall kinematic behaviors, including variable operation modes can be described by analyzing the global kinematics of the reconfigurable mechanism. The algebraic geometry method is a widely used and effective approach [139–144]. Pfurner and Kong [69] performed an algebraic analysis of a 7R mechanism with variable degrees of freedom, providing insights into the identification of motion modes and transition configurations. Liu et al. [53] provided an efficient method for demonstrating the multimode characteristics of Bennett-based mechanisms with algebraic geometry tools.

The screw theory technique is used with the algebraic approach wherever necessary. In Ref. [32], the deployment of spherical motion and reconfiguration of a 6R mechanism were analyzed by utilizing screw theory. The results indicated a correlation between the solutions of the closed-loop equations and variable motion modes. Tian et al. [136,145] used screw theory to derive the constraint forces and couples in single-loop reconfigurable linkages, changing the configuration and mobility characteristics. Kang et al. [146] analyzed the multiple bifurcated reconfiguration characteristics of a double-loop 6R1P metamorphic mechanism by using screw theory and obtained the characteristics of six bifurcation points and corresponding motion branches. Finally, the reconfiguration transformation of the mechanisms is shown in Fig. 8.

To address the limitations of the tan-half-angle substitution of the algebraic geometry method in reconfiguration analysis, a dual quaternion-based approach [53,147,148] was employed for mechanisms with multiple operation modes. Liu et al. [54,149] introduced a unified kinematic mapping method based on dual quaternions and prime decompositions, which was demonstrated to be effective in analyzing the operation modes and motion characteristics of multiloop and single-loop mechanisms. An efficient approach using dual quaternions and natural exponential function substitutions was employed in Refs. [52,150–152] to demonstrate that the 7R mechanism has five motion modes and to reveal the transition conditions. The author later conducted a reconfiguration analysis in the configuration space using dual quaternions and tools from algebraic geometry and reported that the variable-DOF spatial 4G mechanism has one 2-DOF motion mode and one to two 1-DOF motion modes [150].

Additionally, Study's kinematic mapping can be utilized to derive algebraic constraint equations. The operation modes of the 4-RUU (4-R: 4-revolute joint; U: universal joint) mechanism were characterized in Ref. [153] by computing the constraint equations based on Study's kinematic mapping. The properties of the global kinematic behavior of the 3-RPS parallel mechanism was discussed, and its operation modes were detected through a primary decomposition of the ideal conditions corresponding to the constraint equations in Ref. [154]. Kong [155] performed a reconfigurable analysis of a 3-DOF parallel mechanism and a variable-DOF single-loop mechanism using kinematic mapping and algebraic geometry, resulting in the identification of switching points between different modes [156]. Later, Nayak et al. [157,158] obtained the operation modes of two typical 3-DOF parallel mechanisms by exploiting Study's kinematic mapping. In Ref. [159], the different motion modes and transition configurations were shown with the kinematic motion curves derived from kinematic mapping and the algebraic approach.

Several other methods have been used in different works. He et al. [79] used a numerical method to address the kinematic analysis of a single-loop 7R mechanism, and three operation modes were provided. The analysis results were verified by an algebraic approach. The numerical method was used in Ref. [34] to explore the multiple motion branches of three linkages derived from the Waldron linkage and Bricard linkage. Schadlbauer et al. [160] characterized the operation modes of low mobility parallel manipulators using the axodes method. The Denavit–Hartenberg (DH) matrix method was used in Ref. [73] to conduct a comprehensive kinematic analysis of the general plane-symmetric Bricard linkage, resulting in the presentation of distinct bifurcation behaviors. Ma et al. [161] employed the DH matrix method for kinematic analysis, mapping the kinematic curve of the close-loop equation to the configuration torus and revealing that the motion cycle and double points were the basis for linkage bifurcation.

3.2. Workspace

The evaluation of the workspace of a mechanism is a significant factor in determining the operating space and in the planning of its trajectory. Conventional parallel mechanisms have limited workspaces, leading to the need for research on methods to enlarge it.

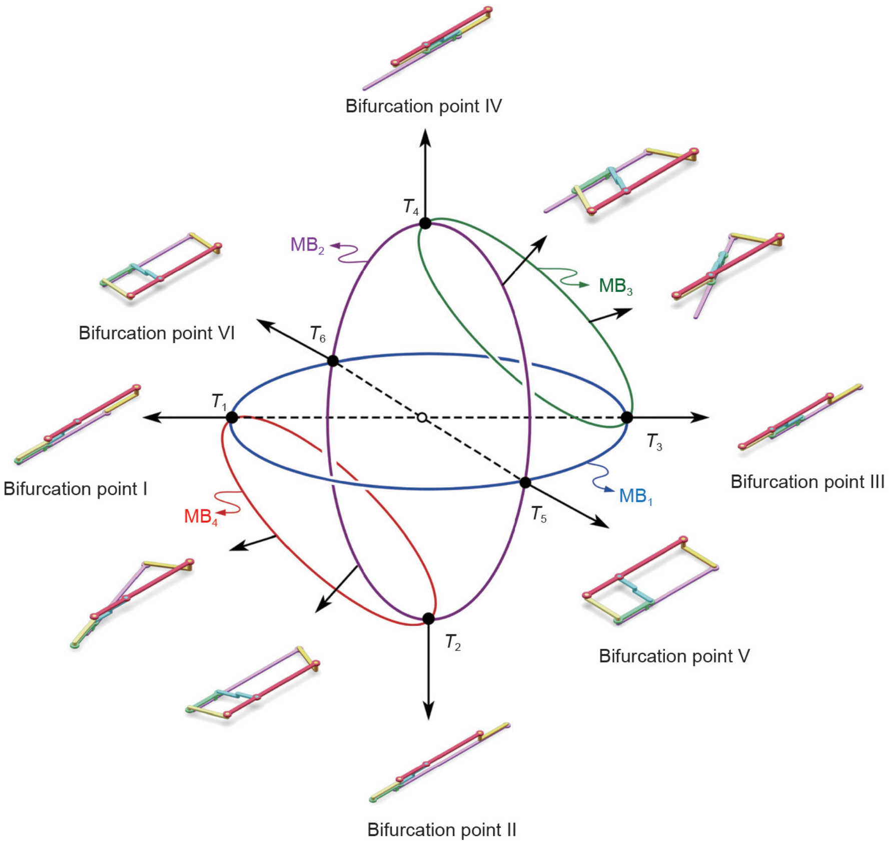


Fig. 8. Reconfiguration transformation of double-loop 6R1P metamorphic mechanism. T_1–T_6: bifurcation point I–VI; MB_1–MB_4: motion branch 1–4; Reproduced from Ref. [146] with permission.

The size and shape of the workspace are impacted by various factors, including the lengths of links, rotational angles of joints, and interference between components.

Nurahmi et al. [162–165] computed the workspace of a 3-rRPS (rR: reconfigurable revolute) metamorphic parallel mechanism with an algebraic geometry approach and Euler parametrization and reported that the shape of the workspace changes with the value of the joint parameters. Zhao et al. [166] reported the workspace of a novel Space Station Remote Manipulator System (SSRMS)-type reconfigurable mechanism with lockable passive telescopic links. A comparison of the reachability sphere maps of the four configurations was presented. The results in Fig. 9 show the effects of the two lockable passive telescopic links on the kinematic capabilities of the proposed manipulator. Wang et al. [167] reported a reconfigurable robotic hand composed of three flexible fingers and obtained its grasping workspace. The three-dimensions (3D) search method [168] was applied to find the workspace of the 3-RPRP mechanism without the need for complex kinematic modeling, making the process more intuitive and easier to control than before. Nayak et al. [169] investigated on the workspace of the 4-rRUU mechanism by differentiating the constraint equations with respect to the actuated joint variables.

The enlargement of the workspace can be primarily divided into the design stage and the optimization stage. Several strategies for enlarging the workspaces of parallel mechanisms have been explored. Viegas et al. [88] employed three techniques, namely, extending the drive range, enlarging the base translation and dynamic joint reconfiguration, and validating their effectiveness. Similarly, a moving base was used to increase the workspace of the robot in Ref. [89]. A redundant Delta-based reconfigurable mechanism was presented in Ref. [90]. The analysis results showed that the reconfiguration design improved in the operating workspace compared to that of the Delta robot. Additionally, Gao et al. [170] examined the workspace of a metamorphic hand by dissecting it into the palm and fingers. The simulation results indicated that the reconfiguration contributes to the workspace. To avoid the interference between cables and the surrounding environment, Zhang et al. [171] designed a new reconfigurable cable-driven parallel robot with a large workspace.

After designing the structure of the mechanism, another valid method for increasing the workspace is optimizing the parameters. Nayak et al. [172] visualized the translational workspace of the 4-rRUU mechanism and optimized its design parameters to enhance its performance by increasing its singularity- and interference-free workspace while reducing its size. A workspace analysis of a novel reconfigurable mechanism was carried out by Huang et al. [173], and the results were further used as an optimization index to improve the performance of the mechanism. Essomba et al. [174] revealed the impacts of the parameters of the mechanism on the workspace and optimized on these parameters to enhance its performance.

3.3. Singularity

Singularity analysis is a crucial aspect of the design and control of reconfigurable parallel mechanisms, because singularities can significantly impact the performance and stability characteristics of these systems. In a reconfigurable parallel mechanism, which is a type of robotic system with multiple configurations, singularities can occur in specific configurations or when transitioning

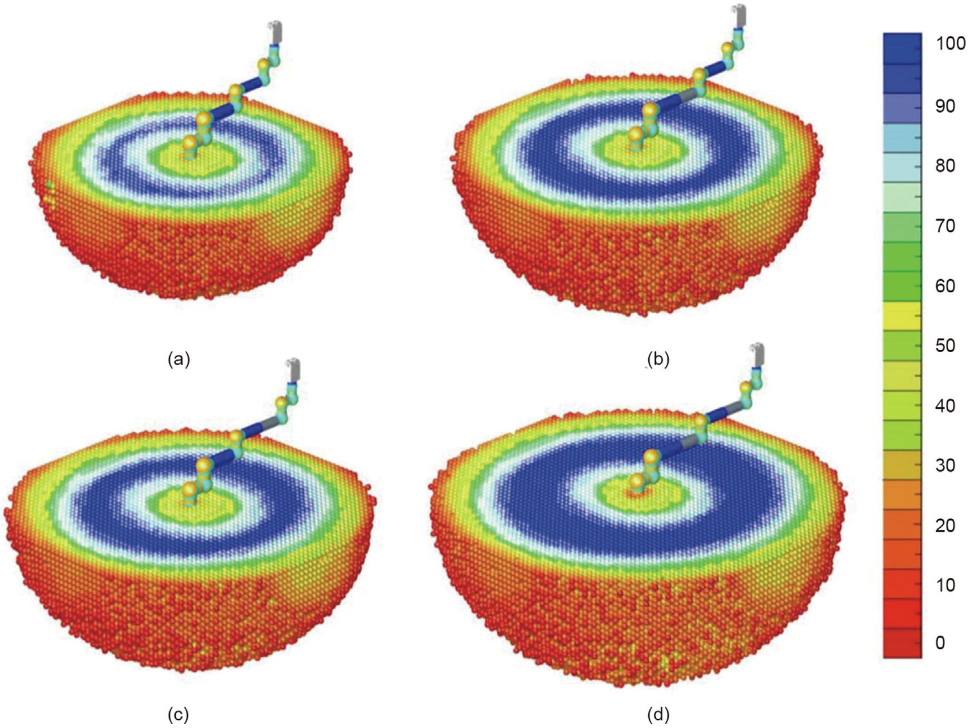


Fig. 9. A comparison of the reachability sphere maps for the four configurations. Reproduced from Ref. [166] with permission.

between configurations. Singularities are configurations in which the kinematic equations are undefined, resulting in losses of control and stability. In this literature review, we will examine the state of the art in the singularity analysis of reconfigurable mechanisms. There are several methods for singularity analysis, including analytical, simulation, and experimental methods. Singularity avoidance and detection are important aspects of singularity analysis, as they can improve the performance and stability characteristics of these mechanisms. Singularity analysis has a wide range of applications in the development of new mechanism design techniques, the improvement of control strategies, and the evaluation of the performance and stability properties of reconfigurable mechanisms.

Karimi et al. [175] described a new 3-RPR mechanism with self-reconfigurability that can change its geometry to avoid singularities, thus enlarging the workspace. Nurahmi et al. [176] conducted an actuation singularity study through a Jacobian matrix and plotted a singularity surface. Bouzgarrou et al. [177] used a new geometric method to investigate the singularity of the 3-CRS mechanism, which reflects the reconfiguration mode. The base of this approach is to simplify the analytical process by considering the relative geometric configurations of three planes formed by the distal links of the limbs. To reduce the computation time and overcome the limitations caused by singularities, Camacho-Arreguin et al. [178] introduced a new Fourier analysis-based methodology. The Jacobian matrix was decomposed to identify subcomponents for singularity detection; and later they were optimized for avoidance to modify the behaviors of reconfigurable mechanisms. Han et al. [179] studied the relationship between the inverse and forward singularities and configurations in three operation modes according to a screw-based Jacobian matrix. The analytical results were verified by the Grassmann geometry method. An approach for analyzing the forward, inverse and combined singularity of n-RRR (n: number of chains) planar configurable robots was generalized by Marchi et al. [180] based on the analysis results of the 3-RRR robot obtained with the bilateration method. Wei et al. [181] studied the singularities of deployable polyhedral mechanisms, which are closely related to multifurcation, as they both affect the behavior of the mechanism. Wang et al. [182] revealed three motion branches and two furcation points of the metamorphic remote-centre-of-motion (RCM) mechanism and proved that there was no actuation or constraint singularity in the workspace, except for furcation points. Wu and Bai [183] reported two types of singularity analyses of a redesigned reconfigurable 3-RRR spherical mechanism, and the results are shown in Fig. 10. Fig. 10(a) shows that the type-I singularity loci are at the boundaries of the regular workspace. Fig. 10(b) shows that the constraint singularities occur in the internal regular workspace. Fig. 10(c) shows that the actuation singularity loci are within and outside the reachable workspace. Then, the size of the dexterous workspace can be increased by removing all singular loci. Valero et al. [184] studied a reconfiguration strategy involving a 4-DOF 3UPS/RPU mechanism for avoiding type II singular configurations within a workspace. The singular condition of a redundant reconfigurable Delta-type parallel robot was analyzed in Ref. [90], which is relevant to the reconfiguration strategy. Li et al. [185] used the Grassmann line geometry method to illustrate all the singularity situations of a parameter reconfigurable parallel mechanism, which is necessary to properly control the actuators.

3.4. Dynamic properties

The dynamic properties of reconfigurable mechanisms refer to their motion behaviors, including the aspects of velocity, acceleration, stability, and response to external forces. These properties are crucial for the design and control of reconfigurable mechanisms, because they affect the overall performance and functionality of the system. The study of dynamic properties can help improve control strategies and develop new mechanism designs. Common techniques used to solve the dynamic modeling of parallel mechanisms include the Lagrange energy formulation, Newton Euler equations and the principle of virtual work. However, since a

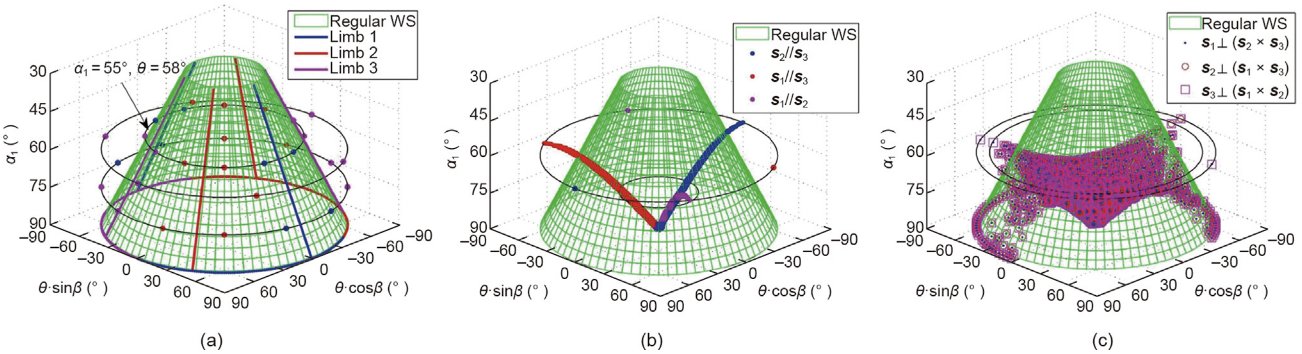


Fig. 10. The regular workspace and (a) type-I singularity loci; (b) constraint singularity loci; (c) actuation singularity loci. α_1: identical angle; θ: tilt angle; β: azimuth angle; $\boldsymbol{s}_1$–$\boldsymbol{s}_3$: stands for a vector normal to the plane determined by the vectors $\boldsymbol{v}_i$ and $\boldsymbol{w}_i$; $\boldsymbol{v}_i$ and $\boldsymbol{w}_i$ are unit vectors parallel to the revolute joints near the moving platform; WS: workspace; //: parallel; _|_: perpendicular. Reproduced from Ref. [183] with permission.

reconfigurable mechanism can change its topology and operation mode, the investigation of different kinematic and dynamic properties corresponding to various motion stages is a significant issue for metamorphic parallel mechanisms.

Chang and Jin [186] constructed the dynamic equations based on the Newton Euler formulation. Song et al. [187] developed a Newton Euler based approach for incorporating the impacts of force and geometric constraints on constrained metamorphic mechanisms. This approach resulted in a unified dynamics model and a systematic numerical iterative algorithm for solving dynamic equations. In Ref. [188], the dynamic equation of a self-reconfigurable robot was generated by the recursive Newton Euler method based on the global matrix description. An analytical investigation of the development of dynamic model for a metamorphic parallel mechanism with pure rotation and translation phases was performed by Ref. [189]. Tang et al. [190] derived a dynamic model of a virtual equivalent parallel mechanism using the Lagrange formulation. Gan and Dias [191] performed a unified dynamics analysis of a metamorphic parallel mechanism using screw theory with a focus on determining control input forces based on the virtual work principle. A unified inverse dynamics model depending on the virtual work principle was deduced by Rong et al. [192]. The dynamic analysis results of a 3-PXPS (X represents U or R joints) mechanism were obtained by using Adams software (MSC Software Corporation, USA), as shown in Fig. 11. Additionally, the instantaneous screw axis (ISA) method can derive the velocities and accelerations of the parallel mechanism without formulating a Jacobian matrix. Hence, the ISA is conveniently compatible with the parametrization of the operation mode through an algebraic geometry approach. Nurahmi and Gan [193] studied the dynamic behaviors of the 3-rRPS mechanism in two motion modes with this method.

The dynamic reliability of configuration transformation is a critical factor for ensuring the normal operation of metamorphic mechanisms with multiple configurations in engineering applications. Chen et al. [194] constructed a dynamic reliability model for different transition processes using a combination of the proposed method and the neural network-based Monte Carlo method. Wang [195] computed the largest Lyapunov exponent to evaluate the dynamic stability of a controllable metamorphic palletizing robot. The evaluation method was developed to consider multiple failure modes and random and interval variables in Ref. [196]. Song et al. [197] addressed the impacts of motion generated during a reconfiguration transition on the dynamic characteristics of a planar constrained metamorphic mechanism.

The purpose of studying dynamics is often closely related to the development and understanding of control strategies. Real-time control of reconfigurable parallel mechanisms is always a challenge. The mechanism must be able to change its configuration in real time, which requires high-speed and high-precision control, which can be difficult, especially for large and complex mechanisms. This process requires the use of advanced control algorithms and high-performance sensors and actuators. Several scholars have attempted to solve this problem. Nouri et al. [198] applied a neural network approach for the motion planning of reconfigurable manipulators and the multilayer perceptron-based neural network was used for training data. Huang et al. [199] used a fuzzy-proportion integration differentiation controller to manage a reconfigurable mechanism according to a dynamic model. Liu et al. [200] investigated the motion strategy based on motor time-sharing control, which was verified by experiment results with a prototype. Additionally, other studies on the control of reconfigurable mechanism can be found in Refs. [201–205].

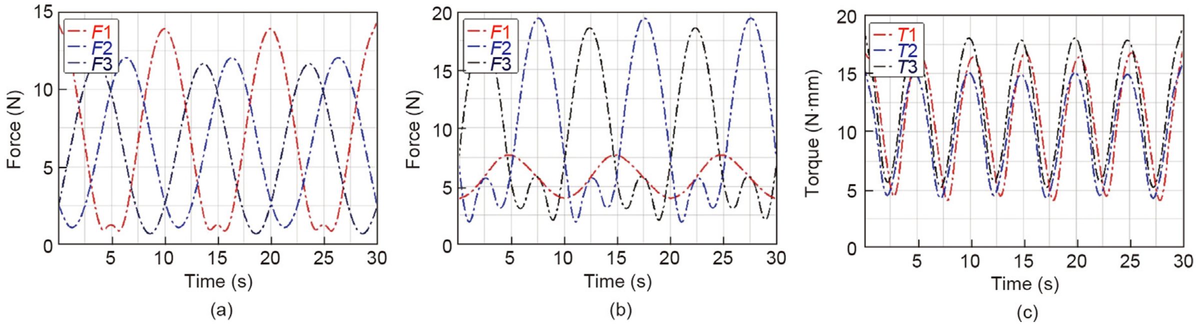


Fig. 11. Dynamics analysis results of the 3-PXPS metamorphic mechanism: (a) the driving force of 3-RPS metamorphic mechanism; (b) the driving force of 3-UPS metamorphic mechanism; (c) the driving torque of 3-UPS metamorphic mechanism. $F1$–$F3$: driving forces; $T1$–$T3$: driving torques. Reproduced from Ref. [192] with permission.

3.5. Stiffness

Stiffness analysis of reconfigurable mechanisms involves evaluating the rigidity and resistance to deformation of a mechanism under a load or force. A good understanding of the stiffness properties of a reconfigurable mechanism enables engineers to make informed design decisions, optimize performance, and ensure that the mechanism operates as intended under real-world conditions. Additionally, stiffness analysis can help identify potential failure points and inform the development of control strategies to enhance the overall reliability of a mechanism.

Zhao et al. [206] deduced the continuous stiffness matrix and the translational and rotational stiffness in any direction. Moosavian and Xi [207] introduced a new approach for statically improving the stiffness of a manipulator, which is achieved with lockable passive joints. The stiffness properties of an origami-type carton were investigated by Qiu et al. [208], who considered creases as revolute joints and panels as links. Zhang et al. [209] conducted a static stiffness analysis of a modular reconfigurable parallel robot, exploring the factors affecting stiffness and improving the overall stiffness. Zhao et al. [210] compared the stiffness model, which included the shear stiffness and the torsional stiffness, of a deployable articulated mast and its structural counterpart, and found that the stiffness significantly improved. To assess the stiffness of the Exechon-like parallel kinematic machines, Tang and Zhang [211] assembled an expanded kinetostatic model with the compliances of all joints and limbs involved; the numerical results proved the accuracy of the expanded stiffness model. The comparative stiffness analysis in Fig. 12 shows that the proposed Exechon–Variant mechanism has a rigidity performance that is competitive with that of the Exechon mechanism. In Ref. [212], the author presented a stiffness model considering the deformation of the main components caused by the actuation and constraints and the stiffness distributions within the subworkspace surrounding the desired trajectory. Zhao et al. [213] provided a theoretical stiffness analysis of n(3RRlS) reconfigurable series-parallel manipulators considering the virtual joint method and matrix structural analysis. You et al. [214] designed a new Stewart-type mechanism with enhanced stiffness by integrating reconfigurability and deduced a dimensionally homogeneous overall rotational stiffness matrix, formulating a stiffness optimization function. Huang et al. [215] analyzed the stiffness of a new 4-DOF reconfigurable mechanism.

3.6. Other indices

In addition to the abovementioned indices, other performance indices have been investigated. Gan et al. [216] presented motion/force transmission analysis by a screw-based method, based on which the parameters of the mechanism can be optimized. Ge et al. [217] later developed kinematic and error analysis techniques to determine the motion trajectory and motion accuracy of multistage metamorphic mechanism. Li et al. [218] explored a simple method for analyzing the constraint forces of metamorphic joints by transforming augmented Assur groups into Assur groups. Kumar and Rani [219] performed a stability analysis of a closed-loop system using Lyapunov theory and the Barbalat lemma.

4. Challenges and prospects

The challenges posed by designing and implementing reconfigurable parallel mechanisms are related to the balance between the benefits of reconfigurability and the practical limitations of design, control, and implementation. Reconfigurable parallel mechanisms have several advantages over traditional mechanisms, including increased flexibility, adaptability, and versatility. However, these advantages come at the cost of increased design and control complexity, maintaining stability and reliability, and high adaptability to changing tasks, which can be challenging to manage.

A key challenge in reconfigurable parallel mechanisms is the complexity of the mechanism itself. The mechanism must be designed to change its configuration in a manner that is safe, efficient, and reliable. This design requires the use of multiple actuated joints, which increases the complexity levels of design and control. In addition, the mechanism must be able to withstand the demands of repeated reconfigurations, heavy loads, and harsh environments, which requires a robust design that accounts for the durability and reliability of the mechanism. The reconfigurable parallel mechanism must be integrated with other systems, such as sensors, actuators, and control systems. This process requires careful design and coordination, which can be difficult, as it requires the integration of multiple systems with different requirements and specifications. Although several different approaches have been developed to address this challenge in the design of reconfigurable parallel mechanisms, there is still a lack of research on systematic and general design theory. A comprehensive design method considering the functional requirements of changing environments, the configuration transition and the variable mobility of reconfigurable parallel mechanisms needs to be explored in depth.

A further challenge facing reconfigurable parallel mechanisms is the lack of unified performance analysis and evaluation index systems. Existing studies on the performance analysis and evaluation of reconfigurable parallel mechanisms have followed the methods applied to conventional parallel mechanisms. These techniques have been adjusted appropriately for use in reconfigurable parallel mechanisms. In particular, the key issues in reconfigurable parallel mechanisms are determining the theory of reconfigurability, determining the influence of the controllable singular configuration on the mechanisms, and comparing the performance evaluation indices corresponding to different modes. Therefore, it is necessary to establish a general performance index system and comprehensive analytical method.

Finally, the cost of reconfigurable parallel mechanisms is a significant barrier to their adoption. The development and production of these mechanisms can be expensive, and it may be difficult to justify their costs for some applications.

Overall, the challenge of reconfigurable parallel mechanisms is to balance the benefits of reconfigurability with the practical limitations of design, control, and implementation. This process requires a comprehensive understanding of the design, performance, and operational requirements of the mechanism, in addition to a strong focus on developing advanced control algorithms and high-performance sensors and actuators.

The prospects and trends of reconfigurable parallel mechanisms are highly dependent on advancements in various fields, such as robotics, control engineering, mechatronics, and materials science. Some of the trends and prospects for reconfigurable parallel mechanisms are as follows:

(1) The use of these mechanisms in innovative applications should be increased. Reconfigurable parallel mechanisms are being used in a growing number of fields, such as space exploration, underwater operation, mechanical manipulation, manufacturing, printing, ground walking, agriculture, power inspection, micromanipulation, microassembly, and medical health. The application fields of reconfigurable parallel mechanisms can be further expanded with the proposal of additional new structures.

(2) Therefore, theoretical research on the design, evolution and bifurcation of reconfigurable parallel mechanisms must be conducted. A general performance evaluation index system needs to be formed. In addition, advancements in control algorithms need

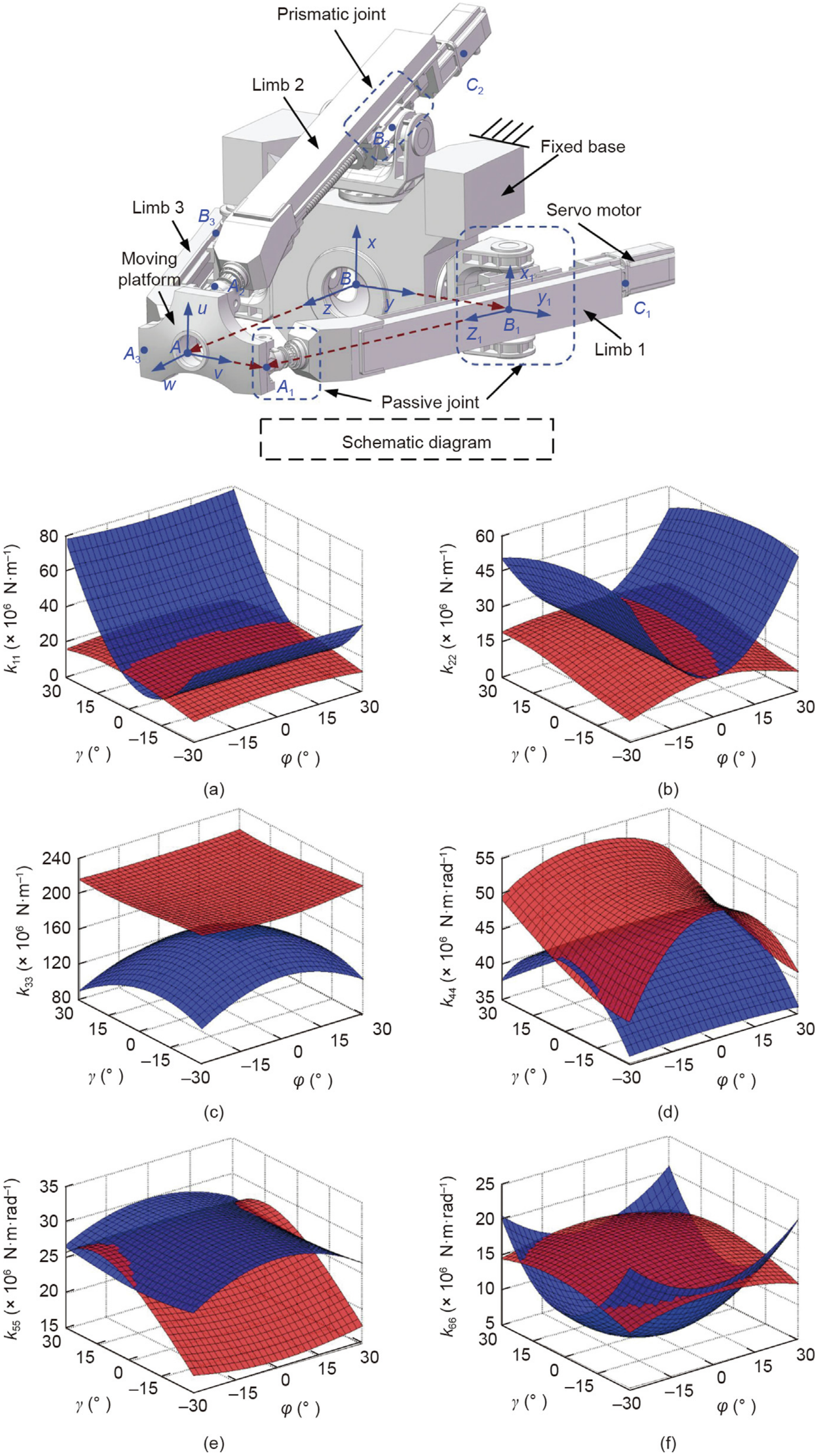


Fig. 12. Stiffness mappings of the Exechon-like parallel kinematic machines (red for the Exechon, blue for the Exechon–Variant): (a) linear stiffness values along u-axis; (b) linear stiffness values along v-axis; (c) linear stiffness values along w-axis; (d) angular stiffness values about u-axis; (e) angular stiffness values about v-axis; (f) angular stiffness values about w-axis. γ: nutation angle; φ: precession angle. Reproduced from Ref. [211] with permission. The definitions of all the abbreviations in the figure could be found in the cited references.

to be developed, which should improve the performance of reconfigurable parallel mechanisms. This research will increase their accuracy, efficiency, and reliability.

(3) These mechanisms should be integrated with other technologies. The integration of reconfigurable parallel mechanisms with other technologies, such as artificial intelligence and the

Internet of Things, is expected to increase their capabilities regarding real-time adaptation, predictive maintenance, energy efficiency, enhanced precision and accessibility, and applications in robotics used in the field of agriculture, manufacturing, aviation and surgery robotics.

(4) The focus on sustainability should be increased. The trend toward sustainability is expected to drive the development of reconfigurable parallel mechanisms. The energy efficiency and environmentally friendliness characteristics of these mechanisms can be increased through design.

In general, the prospects and trends for reconfigurable parallel mechanisms are positive, as these mechanisms offer a range of benefits over traditional mechanisms and are being used in a growing number of applications. The future of reconfigurable parallel mechanisms will be shaped by advancements in technology and the increasing demand for flexible and adaptable systems.

5. Conclusions

In conclusion, extensive progress has been made in reconfigurable parallel mechanisms in recent years. This research has been driven by the increasing need for complex and versatile systems for a range of applications. Herein, the literature review highlights the various types of reconfigurable parallel mechanisms that have been proposed and their respective design methods. The reconfigurability characteristics of different types of mechanisms are discussed. Several commonly used performance indices and analytical methods are discussed. Finally, the challenges and trends of reconfigurable mechanisms are presented.

The future of reconfigurable parallel mechanisms is promising, as continued research and development in this field should lead to further advancements and innovations. This research will include integrating advanced control algorithms and the developing new materials that are lighter, stronger, and more flexible than those that currently exist, resulting in even more versatile and adaptable reconfigurable parallel mechanisms. Additionally, the development of new sophisticated and intelligent systems will allow reconfigurable parallel mechanisms to operate autonomously and in real-world environments.

Acknowledgments

The authors would like to thank the financial support from the Research Institute for Artificial Intelligence of Things (RIAIoT), the Research Institute for Advanced Manufacturing (RIAM), the Research Institute for Intelligent Wearable Systems (RI-IWEAR), and the Research Centre of Textiles for Future Fashion (RCTFF) at the Hong Kong Polytechnic University.

References

[1] Westerland L. The extended arm of man: a history of the industrial robot. Informationsförlaget; 2000.

[2] Clavel R. DELTA, a fast robot with parallel geometry. In: Proceedings of the 18th International Symposium on Industrial Robots; 1988 Apr 26–28; Lausanne, Switzerland. Bedford; IFS Publications; 1988. p. 91–100.

[3] Gough VE, Whitehall SG. Universal tire test machine. In: Proceedings of the 9th international automobile technical congress FISITA. Lodon: ImechE; 1962. p. 117–37.

[4] Neumann KE. Tricept applications. In: Proceedings of the 3rd Chemnitz Parallel Kinematics Seminar; 2002 May 23–25; Zwickau, Germany. Verlag Wissenschaftliche Scripten; 2022. p. 547–51.

[5] Zhang LP, Dai JS. An overview of the development on reconfiguration of metamorphic mechanisms. In: Proceedings of the ASME/IFToMM International Conference on Reconfigurable Mechanisms and Robots; 2009 Jun 22–24; London, UK. Piscataway: IEEE; 2009. p. 8–12.

[6] Kang X, Dai J. Theoretical difficulties and research progresses of mechanism reconfiguration in mechanisms—evolution connotation, furcation principle, design synthesis and application of metamorphic mechanisms. Chin Mech Eng 2020;31(1):57–71.

[7] Luo H, Wang S. Multi-manipulation with a metamorphic instrumental hand for robot-assisted minimally invasive surgery. In: Proceedings of the 2011 5th IEEE/ICME International Conference on Complex Medical Engineering; 2011 May 21–25; Harbin, China. Piscataway: IEEE; 2011. p. 363–8.

[8] Gan XM, Zhao GL, Zhang Q, Di WX. Design and analysis of a new type of wheelchair pedal mechanism. Mach Des Manuf 2019;8:239–42.

[9] Zhang WX, Ding XL, Dai JS. Design and stability of operating mechanism for a spacecraft hatch. Chin J Aeronauti 2009;22(4):453–8.

[10] Xiao L, Xu Z, Wang K, Kang B, Wang A, Zhao H. Modular design of space expandable capsule based on origami-inspired structures and stretchable mechanism. In: Proceedings of the ASME 2021 International Mechanical Engineering Congress and Exposition; 2021 Nov 1–5; Online. New York city: ASME; 2021. p. V004T04A017.

[11] Tang Z, Qi P, Dai JS. Mechanism design of a biomimetic quadruped robot. Ind Robot 2017;44(4):512–20.

[12] Zhang CS, Dai JS. Continuous static gait with twisting trunk of a metamorphic quadruped robot. Mech Sci 2018;9(1):1–14.

[13] Zhang CS, Dai JS. Trot gait with twisting trunk of a metamorphic quadruped robot. J Bionics Eng 2018;15(6):971–81.

[14] Zhang CS, Zhang C, Dai JS, Qi P. Stability margin of a metamorphic quadruped robot with a twisting trunk. J Mech Robot 2019;11(6):064501.

[15] Wei GW, Dai JS, Wang SX, Luo HF. Kinematic analysis and prototype of a metamorphic anthropomorphic hand with a reconfigurable palm. Int J Humanoid Robot 2011;8(3):459–79.

[16] Wei GW, Stephan F, Aminzadeh V, Würdemann H, Walker R, Dai JS, et al. DEXDEB-application of DEXtrous robotic hands for DEBoning operation. In: Röhrbein F, Veiga G, Natale C, editors. Gearing Up and Accelerating Cross-fertilization between Academic and Industrial Robotics Research in Europe: Technology Transfer Experiments from the ECHORD Project. Cham: Springer; 2014. p. 217–35.

[17] Cui L, Dai JS. Posture, workspace, and manipulability of the metamorphic multifingered hand with an articulated palm. J Mech Robot 2011;3(2):021001.

[18] Guo XN, Zhang M. The design of a metamorphic corned making mechanism used in pulp packaging. Mach Des Res 2014;30(4):21–3.

[19] Rong Y, Qu MK. Design of manipulator with variable performances based on metamorphic mechanism. J Mech Eng 2018;54(15):41–51.

[20] Pucheta MA, Butti A, Tamellini V, Cardona A, Ghezzi L. Topological synthesis of planar metamorphic mechanisms for low-voltage circuit breakers. Mech Based Des Struct Mach 2012;40(4):453–68.

[21] Tian CX, Zhang D. Design and analysis of novel kinematically redundant reconfigurable generalized parallel manipulators. Mech Mach Theory 2021;166:104481.

[22] Wang L, Fang YF, Li LQ. Design and analysis of the gripper mechanism based on generalized parallel mechanisms with configurable moving platform. Front Mech Eng 2021;16(4):765–81.

[23] Haouas W, Dahmouche R, Fort-Piat NL, Laurent GJ. 4-DoF spherical parallel wrist with embedded grasping capability for minimally invasive surgery. In: Proceedings of the 2016 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS); 2016 Oct 9–14; Daejeon, Republic of Korean. Piscataway: IEEE; 2016. p. 2363–8.

[24] Lambert P, Langen H, Schmidt RM. A novel 5 DOF fully parallel robot combining 3T1R motion and grasping. In: Proceedings of ASME 2010 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference; 2010 Aug 15–18; Montreal, QC, Canada. New York city: ASME; 2011. p. 1123–30.

[25] Christoforou EG, Phocas MC, Müller A, Georgiou L. A versatile reconfigurable mechanisms framework for applications in architecture. J Intell Robot Syst 2023;108(2):14.

[26] Christoforou EG, Phocas MC, Müller A, Matheou M, Georgiou L. Robotics and reconfigurable mechanisms in architecture towards the synthesis and control of reconfigurable buildings. In: Petrič T, Ude A, Žlajpah L, editors. Advances in service and industrial robotics. Cham: Springer; 2023. p. 486–95.

[27] Phocas MC, Christoforou EG, Theokli C, Petrou K. Reconfigurable linkage structures and photovoltaics integration. J Build Eng 2021;43:103201.

[28] Wohlhart K. Kinematotropic linkages. In: Lenarčič J, Parenti-Castelli V, editors. Recent advances in robot kinematics. Cham: Springer; 1996. p. 359–68.

[29] Dai JS, Rees Jones J. Mobility in metamorphic mechanisms of foldable/erectable kinds. J Mech Des 1999;121(3):375–82.

[30] Mruthyunjaya TS. Kinematic structure of mechanisms revisited. Mech Mach Theory 2003;38(4):279–320.

[31] Dai JS, Jones JR. Matrix representation of topological changes in metamorphic mechanisms. J Mech Des 2005;127(4):837–40.

[32] Ma XS, Zhang KT, Dai JS. Novel spherical-planar and Bennett-spherical 6R metamorphic linkages with reconfigurable motion branches. Mech Mach Theory 2018;128:628–47.

[33] Chai XH, Kang X, Gan DM, Yu HY, Dai JS. Six novel 6R metamorphic mechanisms induced from three-series-connected Bennett linkages that vary among classical linkages. Mech Mach Theory 2021;156:104133.

[34] Chai XH, Dai JS. Three novel symmetric Waldron–Bricard metamorphic and reconfigurable mechanisms and their isomerization. J Mech Robot 2019;11(5):051011.

[35] Wei J, Dai JS. Group method for synthesis of metamorphic parallel mechanism with 1R2T and 2R1T reconfiguration. In: Proceedings of the 2018 International Conference on Reconfigurable Mechanisms and Robots (ReMAR); 2018 Jun 20–22; Delft, Netherlands. Piscataway: IEEE; 2018. p. 1–6.

[36] Wang RQ, Song YQ, Dai JS. Reconfigurability of the origami-inspired integrated 8R kinematotropic metamorphic mechanism and its evolved 6R and 4R mechanisms. Mech Mach Theory 2021;161:104245.
[37] Wei GW, Dai JS. Origami-inspired integrated planar-spherical overconstrained mechanisms. J Mech Des 2014;136(5):051003.
[38] Tang Z, Dai JS. Metamorphic mechanism and reconfiguration of a biomimetic quadruped robot. In: Proceedings of the ASME 2018 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference; 2018 Aug 26–29; Quebec, QC, Canada. New York city: ASME; 2018. p. V01AT02A039.
[39] Gan DM, Dai JS, Liao QZ. Constraint analysis on mobility change of a novel metamorphic parallel mechanism. Mech Mach Theory 2010;45(12):1864–76.
[40] Gan DM, Dai JS, Dias J, Seneviratne L. Reconfigurability and unified kinematics modeling of a 3rTPS metamorphic parallel mechanism with perpendicular constraint screws. Robot Comput-Integr Manuf 2013;29(4):121–8.
[41] Gan DM, Dai JS, Liao QZ. Mobility change in two types of metamorphic parallel mechanisms. J Mech Robot 2009;1(4):041007.
[42] Gan DM, Dai JS, Dias J, Seneviratne L. Constraint-plane-based synthesis and topology variation of a class of metamorphic parallel mechanisms. J Mech Sci Technol 2014;28(10):4179–91.
[43] Wei J, Dai JS. Reconfiguration-aimed and manifold-operation based type synthesis of metamorphic parallel mechanisms with motion between 1R2T and 2R1T. Mech Mach Theory 2019;139:66–80.
[44] Shen T, Nagai Y. An overview of folding techniques in architecture design. World J Eng Technol 2017;5(3):12–9.
[45] Cundy HM, Rollett AP. Mathematical models. New York city: Tarquin Publications; 1951.
[46] Dai JS, Ding XL, Zou HJ. Fundamentals and categorization of metamorphic mechanisms. J Mech Eng 2005;41(6):7–12.
[47] Zhang W, Lu S, Ding X. Recent development on innovation design of reconfigurable mechanisms in China. Front Mech Eng 2019;14(1):15–20.
[48] Hrabačka M, Bulín R, Hajžman M. New actuation planning method for the analysis and design of active tensegrity structures. Eng Struct 2023;293:116597.
[49] Furet M, Wenger P. Kinetostatic analysis and actuation strategy of a planar tensegrity 2-X manipulator. J Mech Robot 2019;11(6):060904.
[50] Zhou D, Liu Y, Deng J, Sun J, Fu Y. Force enhanced multi-twisted and coiled actuator and its application in temperature self-adaptive tensegrity mechanisms. IEEE/ASME Trans Mechatron 2022;27(5):3964–76.
[51] Liu Y, Yao YA, Kong XW, Li YZ. Type synthesis of reconfigurable single-loop mechanisms based on planar rhombus mechanisms. Mech Mach Theory 2023;181:105170.
[52] Kong XW. Reconfiguration analysis of multimode single-loop spatial mechanisms using dual quaternions. J Mech Robot 2017;9(5):051002.
[53] Liu K, Yu JJ, Kong XW. Synthesis of multi-mode single-loop Bennett-based mechanisms using factorization of motion polynomials. Mech Mach Theory 2021;155:104110.
[54] Liu K, Yu J, Kong XW. Structure synthesis and reconfiguration analysis of variable-degree-of-freedom single-loop mechanisms with prismatic joints using dual quaternions. J Mech Robot 2022;14(2):021009.
[55] Qin Y, Dai JS, Gogu G. Multi-furcation in a derivative queer-square mechanism. Mech Mach Theory 2014;81:36–53.
[56] Kang X, Zhang XS, Dai JS. First- and second-order kinematics-based constraint system analysis and reconfiguration identification for the queer-square mechanism. J Mech Robot 2018;11(1):011004.
[57] Gogu G. Maximally regular T2R1-type parallel manipulators with bifurcated spatial motion. J Mech Robot 2011;3(1):011010.
[58] Kong XW. Type synthesis of 3-DOF parallel manipulators with both a planar operation mode and a spatial translational operation model. J Mech Robot 2013;5(4):041015.
[59] Kong XW, Gosselin CM, Richard PL. Type synthesis of parallel mechanisms with multiple operation modes. J Mech Des 2007;129(6):595–601.
[60] Bonev I, Briot S, Wenger P, Chablat D. Changing assembly modes without passing parallel singularities in non-cuspidal 3-RPR planar parallel robots. In: Proceedings of the Second International Workshop on Fundamental Issues and Future Research Directions for Parallel Mechanisms and Manipulators; 2008 September 21–22; Montpellier, France; 2008. p. 1–4.
[61] Pagis G, Bouton N, Briot S, Martinet P. Enlarging parallel robot workspace through type-2 singularity crossing. Control Eng Pract 2015;39:1–11.
[62] Wenger P. Cuspidal and noncuspidal robot manipulators. Robotica 2007;25(6):677–89.
[63] Arakelian V, Briot S, Glazunov V. Increase of singularity-free zones in the workspace of parallel manipulators using mechanisms of variable structure. Mech Mach Theory 2008;43(9):1129–40.
[64] Caro S, Chablat D, Hu Y. Algorithm for the actuation mode selection of the parallel manipulator NAVARO. In: Proceedings of the ASME 2014 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference; 2014 Aug 17–20; Buffalo, NY, USA. New York city: ASME; 2015. p. V05BT08A063.
[65] Song CY, Feng HJ, Chen Y, Chen IM, Kang RJ. Reconfigurable mechanism generated from the network of Bennett linkages. Mech Mach Theory 2015;88:49–62.
[66] Guo HW, Song XK, Li LF, Deng ZQ, Liu RQ, Geng JS. Type synthesis of deployable single-loop overconstrained linkages based on Bennett linkages. Mech Mach Theory 2018;120:1–29.
[67] Zhang KT, Dai JS. Screw-system-variation enabled reconfiguration of the Bennett plano-spherical hybrid linkage and its evolved parallel mechanism. J Mech Des 2015;137(6):062303.
[68] Chai XH, Zhang CS, Dai JS. A single-loop 8R linkage with plane symmetry and bifurcation property. In: Proceedings of the International Conference on Reconfigurable Mechanisms and Robots (ReMAR); 2018 Jun 20–22; Delft, the Netherlands. Piscataway: IEEE; 2018. p. 1–8.
[69] Pfurner M, Kong XW. Algebraic analysis of a new variable-DOF 7R mechanism. In: Wenger P, Flores P, editors. New trends in mechanism and machine science. Cham: Springer; 2016. p. 71–9.
[70] Song YQ, Ma XS, Dai JS. A novel 6R metamorphic mechanism with eight motion branches and multiple furcation points. Mech Mach Theory 2019;142:103598.
[71] Song XK, Guo HG, Chen JJ, Yuan WH, Xu YN. Double-layer deployable mechanical network constructed of threefold-symmetric Bricard linkages and Sarrus linkages. J Mech Robot 2021;13(6):061010.
[72] Wang JY, Kong XW. Deployable mechanisms constructed by connecting orthogonal Bricard linkages, 8R or 10R single-loop linkages using S joints. Mech Mach Theory 2018;120:178–91.
[73] Feng HJ, Chen Y, Dai JS, Gogu G. Kinematic study of the general plane-symmetric Bricard linkage and its bifurcation variations. Mech Mach Theory 2017;116:89–104.
[74] Song CY, Chen Y, Chen IM. Kinematic study of the original and revised general line-symmetric Bricard 6R linkages. J Mech Robot 2014;6(3):031002.
[75] Lu SN, Zlatanov D, Ding XL, Zoppi M, Guest SD. Reconfigurable chains of bifurcating type III Bricard linkages. In: Ding XL, Kong XW, Dai JS, editors. Advances in reconfigurable mechanisms and robots II. Mechanisms and machine science. Cham: Springer; 2015. p. 3–14.
[76] Kang X, Feng HJ, Dai JS, Yu HY. High-order based revelation of bifurcation of novel Schatz-inspired metamorphic mechanisms using screw theory. Mech Mach Theory 2020;152:103931.
[77] Kang X, Ma X, Dai JS, Yu H. Bifurcation variations and motion-ruled-surface evolution of a novel Schatz linkage induced metamorphic mechanism. Mech Mach Theory 2020;150:103867.
[78] Lee CC, Hervé JM. The metamorphic Bennett linkages. In: Proceedings of the 14th IFToMM World Congress. 2015 Oct 25–30; Taipei, China. New York city: Curran Associates, Inc.; 2017. p. 3470.
[79] He XY, Kong XW, Chablat D, Caro S, Hao GB. Kinematic analysis of a single-loop reconfigurable 7R mechanism with multiple operation modes. Robotica 2014;32(7):1171–88.
[80] Zhang KT, Dai JS, Fang YF. Topology and constraint analysis of phase change in the metamorphic chain and its evolved mechanism. J Mech Des 2010;132(12):121001.
[81] Zhang KT, Dai JS, Fang YF. Geometric constraint and mobility variation of two $3S_vPS_v$ metamorphic parallel mechanisms. J Mech Des 2013;135(1):011001.
[82] Gan DM, Dai JS, Caldwell DG. Constraint-based limb synthesis and mobility-change-aimed mechanism construction. J Mech Des 2011;133(5):051001.
[83] Gan DM, Dias J, Seneviratne L. Unified kinematics and optimal design of a 3rRPS metamorphic parallel mechanism with a reconfigurable revolute joint. Mech Mach Theory 2016;96(Part 2):239–54.
[84] Carbonari L, Callegari M, Palmieri G, Palpacelli MC. A new class of reconfigurable parallel kinematic machines. Mech Mach Theory 2014;79:173–83.
[85] Li DL, Li CX, Zhang ZH, Kong XW. Block adjacency matrix method for analyzing the configuration transformations of metamorphic parallel mechanisms. In: Proceedings of the 2014 ASME Design Engineering Technical Conferences & Computers and Information in Engineering Conference; 2014 Aug 17–20; Buffalo, NY, USA. New York city: ASME; 2015. p. V05AT08A062.
[86] Flores-Mendez JD, Schiøler H, Madsen O, Bai SP. Design of a dynamically reconfigurable 3T1R parallel kinematic manipulator. In: Proceedings of the 2018 International Conference on Reconfigurable Mechanisms and Robots (ReMAR); 2018 Jun 20–22; Delft, the Netherlands. Piscataway: IEEE; 2018. p. 1–8.
[87] Riabtsev M, Petuya V, Urízar M, Macho E. Design and analysis of an active 2-DOF lockable joint. Mech Based Des Struct Mach 2022;50(8):2736–59.
[88] Viegas C, Tavakoli M, de Almeida AT. A novel grid-based reconfigurable spatial parallel mechanism with large workspace. Mech Mach Theory 2017;115:149–67.
[89] Mishra AK, Del Dottore E, Sadeghi A, Mondini A, Mazzolai B. SIMBA: tendon-driven modular continuum arm with soft reconfigurable gripper. Front Robot AI 2017;4:4.
[90] Balmaceda-Santamarıa AL, Chavez-Toruño AE. Redundant reconfigurable delta-type parallel robot. In: Proceedings of the 2019 IEEE 4th International Conference on Advanced Robotics and Mechatronics (ICARM); 2019 Jul 3–5; Toyonaka, Japan. Piscataway: IEEE; 2019. p. 292–7.
[91] Coppola G, Zhang D, Liu KF. A 6-DOF reconfigurable hybrid parallel manipulator. Robot Comput-Integr Manuf 2014;30(2):99–106.
[92] Rizk R, Fauroux JC, Mumteanu M, Gogu G. A comparative stiffness analysis of a reconfigurable parallel machine with three or four degrees of mobility. J Mach Eng. 2006;6(2):45–55.

[93] Fisher R, Podhorodeski RP, Nokleby SB. Design of a reconfigurable planar parallel manipulator. J Robot Syst 2004;21(12):665–75.

[94] Zein M, Wenger P, Chablat D. Non-singular assembly-mode changing motions for 3-RPR parallel manipulators. Mech Mach Theory 2008;43(4):480–90.

[95] Brunete A, Ranganath A, Segovia S, de Frutos JP, Hernando M, Gambao E. Current trends in reconfigurable modular robots design. Int J Adv Robot Syst 2017;5:1–21.

[96] Aimedee F, Gogu G, Dai JS, Bouzgarrou C, Bouton N. Systematization of morphing in reconfigurable mechanisms. Mech Mach Theory 2016;96(Part 2):215–24.

[97] López-Custodio PC, Dai JS, Rico JM. Branch reconfiguration of Bricard linkages based on toroids intersections: plane-symmetric case. J Mech Robot 2018;10(3):031002.

[98] López-Custodio PC, Dai JS, Rico JM. Branch reconfiguration of Bricard linkages based on toroids intersections: line-symmetric case. J Mech Robot 2018;10(3):031003.

[99] Zhang KT, Dai JS. Reconfiguration of the plane-symmetric double-spherical 6R linkage with bifurcation and trifurcation. Proc Inst Mech Eng 2016;230(3):473–82.

[100] Pfurner M. Synthesis and motion analysis of a single-loop 8R-chain. In: Proceedings of the 2018 International Conference on Reconfigurable Mechanisms and Robots (ReMAR); 2018 Jun 20–22; Delft, the Netherlands. Piscataway: IEEE; 2018. p. 1–7.

[101] Wang JY, Bai GH, Kong XW. Single-loop foldable 8R mechanisms with multiple modes. In: Wenger P, Flores P, editors. New trends in mechanism and machine science. Cham: Springer; 2016. p. 503–10.

[102] Hsu KL, Ting KL. Overconstrained mechanisms derived from RPRP loops. J Mech Des 2018;140(6):062301.

[103] López-Custodio PC, Dai JS. Design of a variable-mobility linkage using the bohemian dome. J Mech Des 2019;141(9):092303.

[104] López-Custodio PC, Müller A. Synthesis of kinematotropic parallel manipulators by inclusion of additional motion generators. Multibody Syst Dyn 2022;56(1):69–89.

[105] Ye W, Fang YF, Zhang KT, Guo S. A new family of reconfigurable parallel mechanisms with diamond kinematotropic chain. Mech Mach Theory 2014;74:1–9.

[106] Wei G, Dai JS. Reconfigurable and deployable platonic mechanisms with a variable revolute Joint. In: Lenarčič J, Khatib O, editors. Advances in robot kinematics. Cham: Springer; 2014. p. 485–95.

[107] Zhang KT, Liu C. Design and analysis of a novel reconfigurable parallel manipulator with kirigami-inspired Bennett plano-spherical linkages and angular pouch motors. J Mech Robot 2021;13(4):040911.

[108] Ye W, Fang YF, Zhang KT, Guo S. Mobility variation of a family of metamorphic parallel mechanisms with reconfigurable hybrid limbs. Mech Mach Theory 2016;41:145–62.

[109] Wang RQ, Kang X, Dai JS. A novel reconfigurable spherical joint based on linear independence of screws and its resultant metamorphic mechanisms. Mech Mach Theory 2021;164:104351.

[110] Zhao C, Guo HW, Liu RQ, Deng ZQ, Li B. Design and kinematic analysis of a 3RRlS metamorphic parallel mechanism for large-scale reconfigurable space multifingered hand. J Mech Robot 2018;10(4):041012.

[111] Sarrus PT. Note sur la transformation des mouvements rectilignes alternatifs en mouvements circulaires; et réciproquement,. Comptes. Rendus. Acad Sci Paris 1853;36:1036–8.

[112] Nelson TG, Lang RJ, Magleby SP, Howell LL. Curved-folding-inspired deployable compliant rolling-contact element (D-CORE). Mech Mach Theory 2016;96(Part 2):225–38.

[113] Salerno M, Zhang KT, Menciassi A, Dai JS. A novel 4-DOF origami grasper with an SMA-actuation system for minimally invasive surgery. IEEE Trans Robot 2016;32(3):484–98.

[114] Zhang KT, Dai JS. A kirigami-inspired 8R linkage and its evolved overconstrained 6R linkages with the rotational symmetry of order two. J Mech Robot 2014;6(2):021007.

[115] Xiu HH, Wang KY, Xu T, Wei GW, Ren L. Synthesis and analysis of Fulleroid-like deployable Archimedean mechanisms based on an overconstrained eight-bar linkage. Mech Mach Theory 2019;137:476–508.

[116] Wei GW, Dai JS. A spatial eight-bar linkage and its association with the deployable platonic mechanisms. J Mech Robot 2014;6(2):021010.

[117] Barreto RLP, Morlin FV, de Souza MB, Carboni AP, Martins D. Multiloop origami inspired spherical mechanisms. Mech Mach Theory 2021;155:104063.

[118] Tang Z, Dai JS. Bifurcated configurations and their variations of an 8-bar linkage derived from an 8-kaleidocycle. Mech Mach Theory 2018;121:745–54.

[119] Liu WQ, Chen Y. A double spherical 6R linkage with spatial crank-rocker characteristics inspired by kirigami. Mech Mach Theory 2020;153:103995.

[120] Qiu C, Zhang KT, Dai JS. Repelling-screw based force analysis of origami mechanisms. J Mech Robot 2016;8(3):031001.

[121] Fuller RB, inventor; Fuller RB, assignee. Tensile-integrity structures. United States Patent US3063521. 1962 Nov 13.

[122] Skelton R, de Oliveira M. Tensegrity systems. Cham: Springer; 2009.

[123] Motro R. Tensegrity systems: the state of the art. Int J Space Structures 1992;7(2):75–83.

[124] Lessard S, Castro D, Asper W, Chopra SD, Baltaxe-Admony LB, Teodorescu M, et al. A bio-inspired tensegrity manipulator with multi-DOF, structurally compliant joints. In: Proceedings of the 2016 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS); 2016 Oct 9–14; Daejeon, Republic of Korean. Piscataway: IEEE; 2016. p. 5515–20.

[125] Venkateswaran S, Furet M, Chablat D, Wenger P. Design and analysis of a tensegrity mechanism for a bio-inspired robot. In: Proceedings of the ASME 2019 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference; 2019 Aug 18–21; Anaheim, CA, USA. New York city: ASME; 2015. p. V05AT07A026.

[126] Cimmino MC, Miranda R, Sicignano E, Ferreira AJM, Skelton RE, Fraternali F. Composite solar façades and wind generators with tensegrity architecture. Compos Part B 2017;115:275–81.

[127] Khaled MS, Chen MH, Losoya EZ, Rodriguez LA, Gildin E, Skelton RE. Tensegrity laboratory drilling rig for earth and space drilling, mining, and exploration. Int J Solids Struct 2022;252:111785.

[128] Wenger P, Chablat DC. Kinetostatic analysis and solution classification of a class of planar tensegrity mechanisms. Robotica 2019;37(7):1214–24.

[129] Peng HJ, Yang H, Li F, Yang CZ, Song NN. A unified framework for mechanical modeling and control of tensegrity robots. Mech Mach Theory 2024;191:105498.

[130] Kong XW. Type synthesis of 3-DOF parallel manipulators with both a planar operation mode and a spatial translational operation mode. J Mech Robot 2013;5(4):041015.

[131] Li QC, Herve JM. Parallel mechanisms with bifurcation of schoenflies motion. IEEE Trans Robot 2009;25(1):158–64.

[132] Nurahmi L, Caro S, Solichin M. A novel ankle rehabilitation device based on a reconfigurable 3-RPS parallel manipulator. Mech Mach Theory 2019;134:135–50.

[133] Kronig L. Overview of biomimetics and artiomemetics in robotics. Report. Edinburgh: Heriot-Watt University. 2010.

[134] Kong XW, Jin Y. Type synthesis of 3-DOF multi-mode translational/spherical parallel mechanisms with lockable joints. Mech Mach Theory 2016;96(Part 2):323–33.

[135] Tian CX, Zhang D. A new family of generalized parallel manipulators with configurable moving platforms. Mech Mach Theory 2020;153:103997.

[136] Tian CX, Zhang D, Tang HY, Wu CW. Structure synthesis of reconfigurable generalized parallel mechanisms with configurable platforms. Mech Mach Theory 2021;160:104281.

[137] Hoevenaars AGL, Lambert P, Herder JL. Kinematic design of two elementary 3DOF parallel manipulators with configurable platforms. In: Thomas F, Gracia AP, editors. Computational Kinematics. Cham: Springer; 2013. p. 315–22.

[138] Wu G, Dong H. Kinematics of a 6-RUU parallel robots with reconfigurable platforms. In: Zeghloul S, Romdhane L, Laribi MA, editors. Computational Kinematics. Cham: Springer; 2017. p. 331–9.

[139] Arponen T, Müller A, Piipponen S, Tuomela J. Kinematical analysis of overconstrained and underconstrained mechanisms by means of computational algebraic geometry. Meccanica 2014;49(4):843–62.

[140] Arponen T, Müller A, Piipponen S, Tuomela J. Computational algebraic geometry and global analysis of regional manipulators. Appl Math Comput 2014;232:820–35.

[141] Arponen T, Piipponen S, Tuomela J. Kinematical analysis of wunderlich mechanism. Mech Mach Theory 2013;70:16–31.

[142] Schadlbauer J. Algebraic methods in kinematics and line geometry doctoral thesis [dissertation]. Innsbruck: University of Innsbruck, 2014.

[143] Stigger T, Nayak A, Caro S, Wenger P, Pfurner M, Husty ML. Algebraic analysis of a 3-RUU parallel manipulator. In: Lenarcic J, Parenti-Castelli V, editors. Advances in robot kinematics 2018. Cham: Springer; 2008. p. 141–9.

[144] Yu JJ, Jin Z, Kong XW. Identification and comparison for continuous motion characteristics of three two-degree-of-freedom pointing mechanisms. J Mech Robot 2017;9(5):051015.

[145] Tian CX, Fang YF, Guo S, Qu HB. Structure synthesis of reconfigurable parallel mechanisms with closed-loop metamorphic linkages. Proc Inst Mech Eng 2018;232(7):1303–16.

[146] Kang X, Lei H, Li B. Multiple bifurcated reconfiguration of double-loop metamorphic mechanisms with prismatic joints. Mech Mach Theory 2022;178:105081.

[147] Rea P, Ruggiu M, Müller A. On the kinematic analysis of an orthogonal Bricard 6R mechanism. In: Proceedings of the ASME 2022 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference; 2022 Aug 14–17; St. Louis, MO, USA. New York city: ASME; 2022. p. V007T07A022.

[148] Shabani A, Porta JM, Thomas F. A branch-and-prune method to solve closure equations in dual quaternions. Mech Mach Theory 2021;164:104424.

[149] Liu K, Kong XW, Yu JJ. Operation mode analysis of lower-mobility parallel mechanisms based on dual quaternions. Mech Mach Theory 2019;142:103577.

[150] Kong XW. A variable-DOF single-loop 7R spatial mechanism with five motion modes. Mech Mach Theory 2018;120:239–49.

[151] Kong XW, Muller A. A single-loop 7R spatial mechanism that has three models with the same instantaneous DOF but different finite DOF. In: Proceedings of the ASME International Design Engineering Technical Conferences and Computers and Information in Engineering Conference; 2018 Aug 26–29; Quebec, QC, Canada. New York city: ASME; 2018. p. V05BT07A070.

[152] Kong XW. Variable degree-of-freedom spatial mechanisms composed of four circular translation joints. J Mech Robot 2021;13(3):031007.

[153] Nurahmi L, Caro S, Wenger P, Schadlbauer J, Husty M. Reconfiguration analysis of a 4-RUU parallel manipulator. Mech Mach Theory 2016;96(Part 2):269–89.

[154] Schadlbauer J, Walter DR, Husty ML. The 3-RPS parallel manipulator from an algebraic viewpoint. Mech Mach Theory 2014;75:161–76.

[155] Kong XW. Reconfiguration analysis of a 3-DOF parallel mechanism using Euler parameter quaternions and algebraic geometry method. Mech Mach Theory 2014;74:188–201.

[156] Kong XW, Pfurner M. Type synthesis and reconfiguration analysis of a class of variable-DOF single-loop mechanisms. Mech Mach Theory 2015;85:116–28.

[157] Nayak A, Stigger T, Husty ML, Wenger P, Caro S. Operation mode analysis of 3-RPS parallel manipulators based on their design parameters. Comput Aided Geom Des 2018;63:122–34.

[158] Nayak A, Caro S, Wenger P. Comparison of 3-[PP]S parallel manipulators based on their singularity free orientation workspace, parasitic motions and complexity. Mech Mach Theory 2018;129:293–315.

[159] He XY, Kong XW, Hao GB, Ritchie J. Design and analysis of a new 7R single-loop mechanism with 4R, 6R and 7R operation modes. In: Ding XL, Kong XW, Dai JS, editors. Advances in reconfigurable mechanisms and robots II. Cham: Springer; 2015. p. 27–37.

[160] Schadlbauer J, Nurahmi L, Husty M, Wenger P, Caro S. Operation modes in lower-mobility parallel manipulators. In: Kecskeméthy A, Flores FG, editors. Interdisciplinary Applications in Kinematics. Cham: Springer; 2014. p. 1–9.

[161] Ma XS, Zhang XS, Dai JS. Motion cycle and configuration torus with their relationship to furcation during reconfiguration. J Mech Robot 2018;10(5):051006.

[162] Nurahmi L, Gan DM. Workspace transition of 3-rRPS metamorphic parallel mechanism in hyperboloid configuration. In: Proceedings of the ASME 2018 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference; 2018 Aug 26–29; Quebec, QC, Canada. New York city; ASME; 2018. p. V05AT07A053.

[163] Nurahmi L, Gan DM. Reconfiguration of a 3-(rR)PS metamorphic parallel mechanism based on complete workspace and operation mode analysis. J Mech Robot 2020;12(1):011002.

[164] Nurahmi L, Gan DM. Operation mode and workspace of a 3-rRPS metamorphic parallel mechanism with a reconfigurable revolute joint. In: Proceedings of the 2018 International Conference on Reconfigurable Mechanisms and Robots (ReMAR); 2018 Jun 20–22; Delft, the Netherlands. Piscataway: IEEE: 2018. p. 1–9.

[165] Nurahmi L, Husty M, Gan DM. Forward kinematics and singularities of a 3-(rR)PS metamorphic parallel mechanism. In: Proceedings of the 2020 USCToMM Symposium on Mechanical Systems and Robotics; 2020 May 14–16; Rapid City, SD, USA. Cham; Springer; 2020. p. 68–77.

[166] Zhao JD, Zhao ZY, Yang XH, Zhao LL, Yang GC, Liu H. Inverse kinematics and workspace analysis of a novel SSRMS-type reconfigurable space manipulator with two lockable passive telescopic links. Mech Mach Theory 2023;180:105152.

[167] Wang F, Li DL, Li HY. Mechanism design and kinematic analysis of a robotic modular finger and reconfigurable hand. In: Proceedings of the 2021 IEEE International Conference on Robotics and Biomimetics (ROBIO); 2021 Dec 27–31; Sanya, China. Piscataway: IEEE; 2022. p. 1923–8.

[168] Li RQ, Zhao JW, Fan DB, Liang SJ, Song ST, Bai SP. Design and workspace analysis of reconfigurable 3-RPRP spherical parallel mechanisms. In: Proceedings of the 2018 International Conference on Reconfigurable Mechanisms and Robots (ReMAR); 2018 Jun 20–22; Delft, the Netherlands. Piscataway: IEEE: 2018. p. 1–8.

[169] Nayak A, Caro S, Wenger P. Operation modes and workspace of a 4-rRUU parallel manipulator. In: Uhl A, editor. Advances in mechanism and machine science. Cham: Springer; 2019. p. 649–57.

[170] Gao ZG, Wei GW, Dai JS. Inverse kinematics and workspace analysis of the metamorphic hand. Proc Inst Mech Eng 2015;229(5):965–75.

[171] Zhang N, Shang WW, Cong S. Design and analysis of an under-constrained reconfigurable cable-driven parallel robot. In: Proceedings of the 2017 IEEE International Conference on Cybernetics and Intelligent Systems (CIS) and IEEE Conference on Robotics, Automation and Mechatronics (RAM); 2017 Nov 19–21; Ningbo, China. Piscataway: IEEE; 2018. p. 13–8.

[172] Nayak A, Caro S, Wenger P. Kinematic analysis and design optimization of a 4-rRUU parallel manipulator. In: Proceedings of the Advances in Mechanism and Machine Science Proceedings of the 15th IFToMM World Congress on Mechanism and Machine Science. 2019. p. 10.1007/978-3-030-20131-9. hal-02353780.

[173] Huang GY, Guo S, Zhang D, Qu HB, Tang HY. Kinematic analysis and multi-objective optimization of a new reconfigurable parallel mechanism with high stiffness. Robotica 2018;36(2):187–203.

[174] Essomba T, Hsu Y, Sandoval Arevalo JS, Laribi MA, Zeghloul S. Kinematic optimization of a reconfigurable spherical parallel mechanism for robotic-assisted craniotomy. J Mech Robot 2019;11(6):060905.

[175] Karimi A, Masouleh MT, Cardou P. Avoiding the singularities of 3-RPR parallel mechanisms via dimensional synthesis and self-reconfigurability. Mech Mach Theory 2016;99:189–206.

[176] Nurahmi L, Husty M, Gan DM. Forward kinematics and singularities of a 3-(rR)PS metamorphic parallel mechanism. In: Larochelle P, McCarthy JM, editors. Forward kinematics and singularities of a 3-(rR)PS metamorphic parallel mechanism. Cham: Springer; 2020. p. 68–77.

[177] Bouzgarrou C, Koessler A, Bouton N. Singularity analysis and reconfiguration mode of the 3-CRS parallel manipulator. In: Proceedings of the 2020 IEEE International Conference on Robotics and Automation (ICRA); 2020 May 31–Aug 31; Paris, France. Piscataway: IEEE; 2020. p. 10384–90.

[178] Camacho-Arreguin J, Wang MF, Dong X, Axinte D. A novel class of reconfigurable parallel kinematic manipulators: concepts and Fourier-based singularity analysis. Mech Mach Theory 2020;153:103993.

[179] Han YC, Zhou CZ, Guo W. Singularity loci, bifurcated evolution routes, and configuration transitions of reconfigurable legged mobile lander from adjusting, landing, to roving. J Mech Robot 2021;13(4):040903.

[180] Marchi T, Mottola G, Porta JM, Thomas F, Carricato M. Position and singularity analysis of a class of planar parallel manipulators with a reconfigurable end-effector. Machines 2021;9(1):7.

[181] Wei G, Chen Y, Dai JS. Synthesis, mobility, and multifurcation of deployable polyhedral mechanisms with radially reciprocating motion. J Mech Des 2014;136(9):091003.

[182] Wang Z, Zhang WX, Ding XL. Design and analysis of a novel metamorphic remote-centre-of-motion mechanism with parallelogram joints. Mech Mach Theory 2022;176:105038.

[183] Wu GL, Bai SP. Design and kinematic analysis of a 3-RRR spherical parallel manipulator reconfigured with four–bar linkages. Robot Comput-Integr Manuf 2019;56:55–65.

[184] Valero F, Díaz-Rodríguez M, Vallés M, Besa A, Bernabéu E, Valera A. Reconfiguration of a parallel kinematic manipulator with 2T2R motions for avoiding singularities through minimizing actuator forces. Mechatronics 2020;69:102382.

[185] Li D, Guo S, Chen Y. Kinematic performance and task planning analysis of a parameter reconfigurable parallel mechanism. In: Proceedings of the 2019 IEEE International Conference on Robotics and Biomimetics (ROBIO); 2019 Dec 6–8; Dali, China. Piscataway: IEEE; 2020. p. 545–52.

[186] Chang BY, Jin GG. Kinematic and dynamic analysis of a 3PUS-S(P) parallel metamorphic mechanism used for bionic joint. In: Ding XL, Kong XW, Dai JS, editors. Advances in reconfigurable mechanisms and robots II. Cham: Springer; 2015. p. 471–80.

[187] Song YY, Chang BY, Jin GG, Wei Z, Li B, Zhu YJ. Research on dynamics modeling and simulation of constrained metamorphic mechanisms. Iran J Sci Technol Trans Mech Eng 2021;45(2):321–36.

[188] Huang J, Ge WM, Wang XF, Liu J. Structure design and dynamic modelling of a novel modular self-reconfigurable robot. In: Proceedings of the 2016 IEEE International Conference on Mechatronics and Automation; 2016 Aug 7–10; Harbin, China. Piscataway: IEEE; 2016. p. 2284–9.

[189] Gan DM, Dai JS, Dias J, Seneviratne L. Joint force decomposition and variation in unified inverse dynamics analysis of a metamorphic parallel mechanism. Meccanica 2016;51(7):1583–93.

[190] Tang HY, Zhang JW, Pan LQ, Zhang D. Optimum design for a new reconfigurable two-wheeled self-balancing robot based on virtual equivalent parallel mechanism. J Mech Des 2023;145(5):053302.

[191] Gan DM, Dias J, Seneviratne LD. Unified inverse dynamics of variable topologies of a metamorphic parallel mechanism using screw theory. In: Proceeding of the ASME 2013 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference; 2013 Aug 4–7; Portland, OR, USA. New York city: ASME; 2014. p. V06BT07A064.

[192] Rong Y, Zhang XC, Qu MK. Unified inverse dynamics for a novel class of metamorphic parallel mechanisms. Appl Math Model 2019;74:280–300.

[193] Nurahmi L, Gan DM. Dynamic analysis of the 3-rRPS metamorphic parallel mechanism based on instantaneous screw axis. In: Proceedings of the ASME 2019 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference; 2019 Aug 18–21; Anaheim, CA, USA. New York city: ASME; 2019. p. V05AT07A064.

[194] Chen HQ, Wang RG, Dong YC, He SM. Dynamic reliability analysis for configuration transformation of a controllable metamorphic palletizing robot. Proc Inst Mech Eng 2022;236(10):5208–22.

[195] Wang RG. Dynamic stability study of a novel controllable metamorphic palletizing robot mechanism. J Mech Eng 2017;53(13):39–47.

[196] Wang RG, Chen HQ, Dong YC, He SM. Reliability analysis and optimization of dynamics of metamorphic mechanisms with multiple failure modes. Appl Math Model 2023;117:431–50.

[197] Song YY, Chang BY, Jin GG, Wei Z, Li B. An approach for the impact dynamic modeling and simulation of planar constrained metamorphic mechanism. Shock Vib 2020;2020(2020):1–18.

[198] Nouri Rahmat Abadi B, Carretero JA. Modeling and real-time motion planning of a class of kinematically redundant parallel mechanisms with reconfigurable platform. J Mech Robot 2023;15(2):021004.

[199] Huang GY, Zhang D, Tang HY, Kong LY, Song SM. Analysis and control for a new reconfigurable parallel mechanism. Int J Adv Robot Syst 2020;17(5):172988142093132.

[200] Liu XY, Zhang CY, Ni C, Lu CH. A reconfigurable multi-mode walking-rolling robot based on motor time-sharing control. Ind Robot 2019;47(2):293–311.

[201] Ding W, Detert T, De La Cruz J, Corves B. Reconfiguration analysis and motion planning of a novel reconfigurable mobile manipulator torso. In: Proceedings of the 2018 IEEE International Conference on Robotics and Automation (ICRA); 2018 May 21–25; Brisbane, QLD, Australia. Piscataway: IEEE; 2018. p. 6961–6.

[202] Kulandaidaasan Sheba J, Elara MR, Martínez-García E, Tan-Phuc L. Trajectory generation and stability analysis for reconfigurable klann mechanism based walking robot. Robotics 2016;5(3):13.

[203] Syamlan AT, Nurahmi L, Tamara MN, Pramujati B. Dynamic trajectory planning of reconfigurable suspended cable robot. Int J Dyn Control 2020;8(3):887–97.

[204] Essomba T, Sandoval J, Laribi MA, Zeghloul S. Multi-objective optimization of a reconfigurable spherical parallel mechanism for tele-operated craniotomy. In: Kuo CH, Lin PC, Essomba T, Chen GC, editors. Robotics and Mechatronics. Cham: Springer; 2019. p. 454–64.

[205] De La Cruz J, Ding W, Huesing M, Corves B. Mobility transition control of a reconfigurable mobile manipulator torso. In: Uhl T, editor. Advances in mechanism and machine science. Cham: Springer; 2019. p. 2651–60.

[206] Zhao TS, Wang C, Liu X, Bian H, Zhao YZ. Stiffness and singularity analysis of foldable parallel mechanism for ship-based stabilized platform. Robotica 2014;34(4):913–24.

[207] Moosavian A, Xi FF. Design and analysis of reconfigurable parallel robots with enhanced stiffness. Mech Mach Theory 2014;77:92–110.

[208] Qiu C, Aminzadeh V, Dai JS. Kinematic and stiffness analysis of an origami-type carton. In: Proceedings of the ASME 2013 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference. Volume 6B: 37th Mechanisms and Robotics Conference; 2013 Aug 4–7; Portland, OR, USA. New York city: ASME; 2014. p. V06BT07A026.

[209] Zhang QS, Li RQ, Li Q, Liang JJ. Analysis of the stiffness of modular reconfigurable parallel robot with four configurations. In: Kubota N, Kiguchi K, Liu H, Obo T, editors. Intelligent robotics and applications. Cham: Springer; 2016. p. 198–209.

[210] Zhao LH, Wang H, Chen GL, Huang SZ. Sequentially assembled reconfigurable extended joints: self-lockable deployable structure. J Aerosp Eng 2018;31(6):04018103.

[211] Tang TF, Zhang J. Conceptual design and comparative stiffness analysis of an Exechon-like parallel kinematic machine with lockable spherical joints. Int J Adv Robot Syst 2017;14(4):1–13.

[212] Tian HB, Ma HW, Xia J, Ma K, Li ZZ. Stiffness analysis of a metamorphic parallel mechanism with three configurations. Mech Mach Theory 2019;142:103595.

[213] Zhao C, Guo HW, Zhang D, Liu RQ, Li B, Deng ZQ. Stiffness modeling of n (3RRlS) reconfigurable series-parallel manipulators by combining virtual joint method and matrix structural analysis. Mech Mach Theory 2020;152:103960.

[214] You JJ, Xi FF, Shen HP, Wang JY, Yang XL. A novel Stewart-type parallel mechanism with topological reconfiguration: design, kinematics and stiffness evaluation. Mech Mach Theory 2021;162:104329.

[215] Huang GY, Zhang D, Kong LY, Zou Q. Kinematic and performance analysis of a novel reconfigurable parallel mechanism. In: Proceedings of the 2021 7th International Conference on Mechatronics and Robotics Engineering (ICMRE); 2021 Feb 3–5; Budapest, Hungary. Piscataway: IEEE; 2021. p. 180–4.

[216] Gan DM, Dai JS, Dias J, Seneviratne LD. Variable motion/force transmissibility of a metamorphic parallel mechanism with reconfigurable 3T and 3R motion. J Mech Robot 2016;8(5):051001.

[217] Ge Z, Xie LC, Yang SK, Zhu SY, Cao YZ, Liu YW. Kinematics and error analysis of single motor driving multi-stage metamorphic mechanism. IOP Conf Series Mater Sci Eng 2019;677(5):052108.

[218] Li SJ, Wang HG, Yang Q. Constraint force analysis of metamorphic joints based on the augmented Assur groups. Chin J Mech Eng 2015;28(4):747–55.

[219] Kumar N, Rani M. A new hybrid force/position control approach for time-varying constrained reconfigurable manipulators. ISA Trans 2021;110:138–47.