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REVIEW ARTICLE

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Recent development on innovation design of reconfigurable mechanisms in China

Abstract Reconfigurable mechanisms can deliberately reconfigure themselves by rearranging the connectivity of components to meet the different requirements of tasks. Metamorphic and origami-derived mechanisms are two kinds of typical reconfigurable mechanisms, which have attracted increasing attention in the field of mechanisms since they were proposed. Improving the independent design level, innovation, and international competitive powers of reconfigurable mechanical products is important. Summarizing related significant innovation research and application achievements periodically will shed light on research directions and promote academic exchanges. This paper presents an overview of recent developments in innovation design of reconfigurable mechanisms in China, including metamorphic and origami mechanisms and their typical applications. The future development trends are analyzed and forecasted.

Keywords innovation design, reconfigurable mechanisms, metamorphic mechanisms, origami-derived mechanisms, development trends

1 Introduction

Mechanism theory is one of the fundamental subjects of the invention, design, and analysis of modern mechanism and the theoretical foundation of the development of modern advanced mechanical equipment and robots. As a kind of modern mechanism, reconfigurable mechanisms are attracting increasing research for their variable configurations, which can meet multiple functional requirements or adapt to variable operating conditions. Metamorphic mechanisms and origami-derived mechani sms are two kinds of typical reconfigurable mechanisms originating from bionic principle and art of origami, respectively. They have become research hotspots in the mechanism field in recent years for designing reconfigurable mechanical equipment and robots. In this paper, the latest developments, cutting-edge research focuses, and research progress on innovation design of metamorphic mechanisms and origami-derived mechanisms in China are summarized to present the development of reconfigurable mechanisms in recent years. Future development tendencies are analyzed and forecasted.

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2 Originality

2.1 Originality of metamorphic mechanisms

Metamorphic mechanisms form a class of mechanisms that can change configurations sequentially, with a resultant change in the number of effective links and mobility of movement, to perform different tasks under specific working conditions and requirements. Unlike the traditional mechanism, the metamorphic mechanism displays the characteristics of variable topology and variable degree of mobility. The metamorphic mechanism is superior to the tradition mechanism in solving the contradictions among economy, adaptation, and efficiency. The concept of the metamorphic mechanism was first introduced based on the occurrence of reconfiguration in 1996 by Jian S. Dai, who conducted a research project on Unilever's automatic packing line with Rees Jones and Hiroshi Makino; their findings led to a new era of modern mechanism development. The related paper reporting the achievement of the project was awarded "Best Paper" honors at the 25th ASME Biennial Mechanisms and Robotics Conference in 1998 [1].

Since then, metamorphic mechanisms have rapidly received extensive attention in the field of mechanisms from more than 30 universities and academies due to their reconfigurability and utilization of the biological evolution principle. Research on metamorphic mechanisms has resulted in great improvements in the fundamentals, analytical approaches, and structure synthesis methods [2]. At the same time, a large number of applications have been developed, such as metamorphic hands [3,4], operating metamorphic mechanism for a spacecraft hatch [5], metamorphic parallel mechanism platform with redundant drives [6], and broken strand reposition metamorphic mechanism for extra-high-voltage power transmission lines [7].

2.2 Originality of origami mechanisms

Origami is an ancient oriental art but also an emerged frontier subject that fuses several basic disciplines such as mathematics, mechanisms, mechanics, and materials. The diversified modern mechanisms derived from origami can be transformed between a compact configuration (planar) and a 3D structure with a certain functional shape through folding and unfolding. Therefore, the origami-derived mechanism can be expanded to the working state and folded to facilitate storage and transportation. This feature reveals the great potential of origami in daily life, medical treatment, military, aerospace engineering, architecture, and other fields. It has also resulted in increasing attention of academic and engineering experts.

The applications of different scales of derivative mechanisms will also change accordingly. Small-scale origami-derived mechanisms are mainly used in biomedical devices and micro-robot systems [8,9]; medium-sized origami-derived mechanisms have been adopted in flexible mechanisms, actuators, and teaching aids [10,11]; and large-scale origami-derived mechanisms are widely used in the fields of aerospace and architecture [12,13]. With the development of social economy, origami and its derivative mechanisms display broad application prospects. The design, analysis, and optimization of origami have received increasing concern by the academic community, and origami has gradually developed into a novel cross-disciplinary subject.

3 Development of innovation design

3.1 Innovation design and application development of metamorphic mechanisms

Innovation design provides distinct potential mechanisms to designers in any given category. Metamorphic mechanisms have difficulty in directly referring to the design theories of traditional mechanisms due to their multiple configurations, which restrict the developments of metamorphic mechanisms from topological representation and analysis to innovative design and widespread application. This difficulty has motivated many researchers to propose various structural analysis methods.

Liu [14] classified the mechanisms as close chains, open chains, and variable chains. Variable chains have the characteristics of multiple topology and degree of freedom. On the basis of the representation of variable kinematic joints, graphs, and finite state machine, he proposed a methodology for the configuration synthesis of mechanisms with variable chains. Furthermore, Yan and Kang [15] expressed the topology states of variable kinematic joints symbolically as joint sequences, graphically as digraphs, and mathematically as matrices, thereby providing a logical foundation for the systematic structural synthesis regarding the kinematic joints and mechanisms with variable topologies. They further proposed a design methodology subject to topological constraints, coordinate sequence of motion characteristics, and mobility criterion. In addition, a method for designing new metamorphic mechanisms was proposed using variable kinematic pairs to replace traditional common kinematic pairs [16,17].

Recognizing that the concept of metamorphic mechanisms was based on the biological evolution principle, Zhang et al. [18,19] proposed the metamorphic elements and metamorphic evolutionary techniques for the first time. Beginning with the analysis of the working characteristics and the topology change in metamorphic mechanisms, the genetic configuration model for metamorphic mechanisms was established by integrating the structural composition principle with topological configuration decomposition. The configuration synthesis methodology based on the biological concept was subsequently proposed with a procedure for evolutionary synthesis. Wang and Dai [20] established a mathematical model of a metamorphic equation, which indicates the relationship among a work-stage matrix, an origin metamorphic matrix, and a variational metamorphic matrix. The type of synthesis of metamorphic mechanism can be converted to solve the group of metamorphic equations, which leads to the formation of all work-stage matrices, the origin metamorphic matrix, and variational metamorphic matrices. Zhang et al. [21] analyzed the constraint variation in the metamorphic mechanism on the basis of the unified description of the generalized constraints in the design process of the mechanism. Configuration transformation of the metamorphic mechanisms and the design principle of metamorphic kinematic pairs were later achieved. A configuration synthesis methodology of metamorphic mechanisms was proposed. The essence of this method is to realize variation and coupling of the mechanism of the adjacent configuration by applying metamorphic kinematic pairs based on the functions, constraints, and sequence of the configurations. Li and Dai [22] presented a new type of modularized structural theory and formation method of multi-mobility metamorphic mechanisms. They analyzed the formation of planar metamorphic mechanisms based on the developed augmented Assur group by applying the structural forming rules of general planar mechanisms formed by the Assur group. The degenerated equivalent Assur group in the metamorphic process and the corresponding kinematic characteristics were investigated and discussed to provide references for the synthesis of metamorphic mechanisms.

Metamorphic mechanisms have been widely used for innovative designs, especially in robotics. Dai et al. [3,4] developed innovative forms of a multi-fingered dexterous hand with variable structure and degree of mobility. Compared with a traditional robot hand, the palm of the proposed hand is moveable and reconfigurable, thereby enhancing the dexterity and range of applications of the hand. The hand has been successfully used for deboning and muscle extraction, paper-and-board packaging in the food industry, and grasping of flexible objects [23,24]. Ding and Xu [25] developed a novel metamorphic hybrid wheel-legged rover that possesses the advantages of the two manners of locomotion of walking in four-leg mode and moving in wheeled-vehicle mode. The width of the body of the novel rover can be altered due to its special body mechanism, and the rover has high capability to adapt to complex terrain. Dai and Sun [26] also studied the discontinuous-constraint metamorphic mechanism for a gecko-like robot and analyzed its kinematic and dynamic features.

3.2 Innovation design and application development of origami-derived mechanisms

In the late 19th century, the first international origami conference was held in Paris, which created a precedent on the theoretical study of origami. Since then, studies on the design of origami and its derivatives have rapidly developed. In this field, artists have created abundant origami-based structures. Mathematicians are devoted to the mapping algorithm between the 2D crease distribution and the 3D origami configuration. Engineers apply origami-derived mechanisms to practical applications, such as geometric architecture, reconfigurable robot, and biomedical devices. Internationally, National Aeronautics and Space Administration, European Space Agency, Institute of Space and Aeronautical Science, National Space Development Agency, Harvard University, Massachusetts Institute of Technology, Oxford University, Cambridge University, and Tokyo University have engaged in the related research on origami-derived mechanisms. Several research results show that origami and its derived mechanisms have great potential applications on large-space deployable and foldable structures and reconfigurable robots.

The study of origami-derived mechanism in China is still at the initial stage. Research on the theoretical study of origami is limited. The classification and terminology of origami are not yet summarized and unified. However, in recent years, several researchers have made some breakthroughs in the research fields of origami design, which have occupied a certain position in the field of basic theoretical research of origami and its derived mecha nisms.

Several researchers in China and abroad have carried out extensive work on the mapping between the 2D crease distribution with consideration of geometric constraints and the shape of 3D origami models. A variety of crease patterns were proposed. The current study on design mainly focus on creasing design with or without considering panel thickness, crease distribution and folded shape mapping, and a combination of various types of creases.

Chen et al. [27] developed a comprehensive kinematic model for rigid origami of thick panels by identifying a spatial linkage model that is kinematically equivalent to the rigid origami of a zero-thickness sheet. In the model, the thick-panel counterparts to four-, five-, and six-crease vertex origami patterns are overconstrained spatial linkages. The synthesis can be used for origami patterns consisting of a mixture of vertices with various creases. The approach, which is effective for typical origami, can be readily applied to fold real engineering structures [27]. The same team also analyzed the design of origami-derived mechanisms, which can transfer multiple movement stages [28]. Wang et al. [29] proposed a crease plane design method to obtain a generalized Miura origami crease unit that can fit a specified surface, which can combine one or two types of crease lines in a reproducible process. Folding produces various types of cylindrical structures.

Cai et al. [30,31] employed the theory of spherical trigonometry to analyze Miura origami with variable angle and variable length, and they discussed the variation in parameters during the moving process from the perspective of geometric relations. They also established a new method to study the rigid foldability of multi-vertex cylindrical origami patterns. The rigid foldability can then be obtained by analyzing the folding angles via the quaternion rotation sequence method for multi-vertex crease origami and calculating the coordinates of all vertices through the dual quaternion method. Chen and Feng [32] presented a numerical analysis and finite element simulation on the folding behavior of deployable origami mechanisms and then established the equivalent pin-jointed structure with the redundant constraint equation. A nonlinear iterative algorithm was formulated to predict the folding behavior. Xu et al. [33] developed a parametric model method and simulated the deployment mechanism of inflatable antenna structures. The penalty function method was used to discriminate interference during the process of deploying and folding. The deploying process of three different kinds of folding mechanisms was analyzed, and the software for simulating the deploying movement was developed. Qiu et al. [34] addressed the folding behavior of origami-derived mechanisms by considering the geometric design and material property, and they developed mathematical models to predict the folding moment and folding stiffness of origami cartons. Lu et al. [35,36] constructed a kirigami-derived deployable network by linking type III Bricard linkages, which can be reconfigured in multiple ways.

An et al. [37] described a physics-based finite element simulation scheme to predict programmable self-folding of temperature-sensitive hydrogel tri-layers. Patterning creases are highlighted, such as folding of Randlett's flapping bird and the crane. The folding mechanisms expand the implementation and application of reconfigurable structures.

4 Development trend and prospect

4.1 Development trend and prospect of metamorphic mechanisms

Although the study of metamorphic mechanisms was developed for less than 20 years, it has resulted in many achievements in a variety of aspects. However, some unsolved key theoretical issues, which currently restrict metamorphic mechanisms from achieving appropriate product functions and restraint further development of metamorphic mechanisms, should be addressed. Issues that are worthy of further studies are outlined below:

1) Methods for synthesizing metamorphic mechanisms must be investigated in association with the characteristics of variable constraint and multi-configuration to invent novel mechanical products. In addition, the metamorphosis principle and key factors that allow reconfiguration should be understood in detail to enable construction of an innovative design system. Both the singularity configuration of metamorphic mechanisms and its effect on reconfiguration through the applied method should be studied to realize the desired functionality.

2) Compliant component design methodology, motion planning, and control strategy should be studied in detail. The flexible metamorphosis principle can be adopted to solve the instability caused by energy mutation of the entire mechanism system at the moment of reconfiguration, as well as to realize the compliance of reconfiguration and stability of control system. Therefore, priorities in the development of the metamorphic mechanism to achieve the essence of metamorphosis promote an innovative design system and focus on resolving key scientific problems, such as composite synthesis methodology, singularity analysis, bifurcation during configuration transformation, flexibility of movement, controllability, and comprehensive evaluation.

3) The concept of metamorphic mechanisms was proposed in accordance with the principle of biological evolution, which has provided important inspiration to the development of metamorphic mechanisms. Therefore, the evolution principle must be further researched based on biological evolution theory, especially the function of variable topological structure and multi-degree of mobility. Research on metamorphic mechanisms should be inextricably linked with bioscience to encourage the convergence of the two fields and promote related research directions.

4) The lack of applied research on metamorphic mechanisms restrains the development of relevant theory. Therefore, the applied field should be broadened further to include mechanical equipment with complex environmental adaptability and multiple functions.

4.2 Development trend and prospect of origami-derived mechanisms

1) In the topological planning and design of creases, current research mainly focused on designing the distribution of creases on a fully expanded sheet. However, in this case, the fully developed configuration of the origami will be flat, which is inconsistent with the functional shape requirements of most spacecraft and robotic mechanisms. Engineering applications are often limited by function rather than form. Use of a planar configuration as the initial state of design will highly limit the practical application and development of origami-derived mechanisms. In addition, the combination of folding vertices is relatively simple. Research on the combination of different types of creases with consideration of the geometric constraints is required.

2) Studies on the mechanism of motion analysis considering the geometric constraints of the components are limited. When folding complex origami, even though the crease has been calculated by the design algorithm, partial theoretical results cannot be realized due to the rigidity of components. The folding movement is largely dependent on repeated experiments and manual intervention, which cannot be automatically completed at the moment. Automating the design of folding motion sequence of the multi-degree of freedom origami-derived mechanism is a challenge in future research.

3) The majority of origami-derived mechanisms are used in the range of 10 cm to 10 m. Given that the origami-derived mechanism can be folded compactly and deployed to a certain shape, this feature makes it suitable for use in large-scale aerospace mechanisms, micro-medical devices, and medical robots. However, the scale effects involved in large-scale design, the difficulties of minimal manufacturing, and motion accuracy are rarely considered. Solving the extremely large and mini-sized design problems will effectively expand the applications of origami-derived mechanisms.

4) In the stiffness analysis of the origami-derived mechanisms, the mechanism is treated as a structure with a certain shape and then analyzed by finite element methods. Influence of the distribution of creases on the structural stiffness is not considered in the design stage.

This step will limit the configuration design of the origami-derived mechanism and its application in spacecraft-like structures, which have high stiffness requirements.

5) As a typical multi-loop closed-chain mechanism, the driving efficiency of the origami-derived mechanism, which should be considered, is almost ignored in the current study. Selection of the most suitable joint for driving and designing the driving mode, which is appropriate for the origami-derived mechanism, is important in the design process.

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