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Current Status and Development Strategy of the Flexible Metamorphic Mechanism

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Abstract: *The metamorphic mechanisms are a class of mechanisms with variable topological structures, and have been the research focus of mechanisms since their inception. As a new research direction for metamorphic mechanisms, flexible metamorphic mechanisms possess both reconfigurability and flexibility, expanding the application scenarios of metamorphic mechanisms. Firstly, the research on the determination conditions, configuration change, kinematics and dynamics of flexible metamorphic mechanisms is reviewed. Secondly, list representative application achievements in recent years and discuss their advantages and disadvantages. Finally, the shortcomings of the current stage of research were pointed out, and future development trends were prospected.*

Keywords: *Metamorphic mechanism; Flexible metamorphic mechanism; Configuration change; Kinematics; Dynamics*

1. Introduction

With the development of the level of science and technology, industrial production has basically realized mechanization and automation. Current research on mechanical devices is moving towards dexterity, flexibility and miniaturization. As a new type of mechanism with variable degrees of freedom and variable number of effective members, the metamorphic mechanism proposed by Dai and J. J. Rees , which can present different motion characteristics in different working stages by changing its own configuration, has been widely used in practical production life[1]. Rigid metamorphic mechanism are difficult to perform some tasks that require high flexibility, such as slide clamping and body pushing. The flexible metamorphic mechanism proposed by Daniel W. Carroll expands the study of metamorphic mechanism from rigid bodies to flexible bodies that are also dexterously variable, highly flexible, and wear-resistant[2]. The research on rigid metamorphic mechanism is relatively mature, while the research on the conceptual configuration description, kinematics and dynamics modeling of flexible metamorphic mechanism is still insufficient. This paper review the theoretical research results of flexible metamorphic mechanism in the last decade. By citing representative application examples, we analyze the current state of research on flexible metamorphic mechanism and provide an outlook on the development trend of this research area.

2. Definition

A metamorphic mechanism initially refers to a mechanism that can change its structure by altering the connections during unfolding or folding. The definition of a metamorphic body is being refined as research progresses. Dai proposed the metamorphic mechanisms principle[3]. It defines that a metamorphic mechanism should have the ability to move even after a topological change is triggered by the metamorphic mode during motion, resulting in a consequent change in mobility. Li introduces the origin and significance of the metamorphic mechanism with respect to the current progress and proposed decision conditions and five metamorphic methods[4].

The flexible metamorphic mechanism is based on the rigid metamorphic structure with the addition of a flexible element, which has the advantages of both flexible mechanisms and metamorphic mechanisms[5]. Flexible elements are generally referred to as flexible components or flexible joints. Flexible components include flexible connecting rods, spring-loaded tie rods, etc. Flexible joints include elastic hinges, rubber bushings, tension springs, and so on. The flexible metamorphic mechanism contains at least one flexible element and relies on elastic deformation of the element to accomplish a change in conformation during metamorphosis of the mechanism. A comparison of the

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characteristics of the flexible metamorphic mechanism and the rigid metamorphic mechanism is listed in Table 1.

Table 1: Characteristics of Rigid Metamorphic Mechanisms and Flexible Metamorphic Mechanisms.

	Rigid Metamorphic Mechanisms	Flexible Metamorphic Mechanisms
Components Types	Rigid components	Flexible components and rigid components
Joints	Traditional joints	Traditional joints and soft joints
Configuration Change	Rigid shock	Soft shock
Number of Components	Large	Small
Wear and Tear	High	Low
Range of motion	Large	Small
Application Scenarios	Wide	Limited

3. Theoretical Research

Configuration change is an important feature of metamorphic mechanisms. Kinematics and dynamics is related to the practical application of flexible metamorphic mechanisms. The study of the theory related to flexible metamorphic mechanisms will be presented next from these two aspects.

3.1. Configuration Change and Description

Configuration description is an important part of the structural science of metamorphic mechanisms, as well as the basis for their kinematics and dynamics research. The configuration of a flexible metamorphic mechanism is generally represented using topological maps and matrices.

The topological map method can clearly describe the connection between the components of the metamorphic mechanism, and can also visually compare the splitting and merging of components before and after the metamorphic, which is the most commonly used method for the description of the configuration. The topological map method is concise and intuitive, but it is not directly applicable to calculations. Depending on whether the different building blocks in the topological map are connected or not, Li uses the Boole matrix to represent the configuration of the metamorphic mechanism[6]. Dai provides a new approach for modeling topological transformations of metamorphic mechanisms by introducing the process of dissipative matrix multiplication to represent configuration changes[7]. This method is built based on the adjacency matrix of a monochromatic topological map, and thus is only applicable to single-hinged mechanisms, and has some limitations when confronted with compound-hinged mechanisms. Zhang proposes a metamorphic mechanism representation based on the generalized correlation matrix of two-color topological maps, which can efficiently express the connection between compound-hinged metamorphic components and joints[8].

For a flexible metamorphic mechanism, its topological map must express not only the elements contained in a rigid metamorphic mechanism, but also flexible elements such as flexible components and flexible joints of motion. It complicates the expression of the adjacency matrix as well. Li Dong-fu describes the configuration of flexible metamorphic bodies by combining the regular numbering method with the monochromatic topological map method[9]. This method allows for a detailed description of the topology, but is inconvenient for the representation of configuration changes due to the large number of matrices it introduces. Zhang proposes a topological map representation method applied to flexible metamorphic mechanisms and the corresponding adjacency matrix and its operations[10]. The topological map of the method has different symbols for rigid and flexible components, and the edges connecting the two components are assigned to represent the joint information. The corresponding adjacency matrix of the topological map of the flexible metamorphic mechanism is constructed according to the types of components and coupling types, and a corresponding mathematical operation analysis method is proposed to express the process of configuration change. Shujun Li proposes an augmented adjacency matrix containing the axial relations of kinematic chain joints to describe the topology of a metamorphic mechanism[11].The method provides more structural information with fewer elements and more intuitively reflects the topology of the kinematic chain through the adjacency matrix, and is applicable to planar mechanisms as well as spatial hybrid metamorphic mechanisms with open and closed loops. The above methods can describe the relationship between the components of a flexible metamorphic mechanism, but cannot analyze the

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kinematic properties of the metamorphic structure. Based on the Screw Theory[12] , Zhonghai Zhang further proposed a screw algebraic analysis method for the kinematic properties of the metamorphic mechanism and verified it on a new 4-URU parallel metamorphic mechanism [13]. Bai Ping proposed a new matrix expression method to accurately describe the structural information of a metamorphic mechanism. When the component number is determined, the matrix and the structure of the component have a unique certainty with each other, which is conducive to the procedural design of the metamorphic mechanism[14]. Tian proposed a design method for configuration synthesis based on functional analysis to synthesize the source metamorphic mechanism into the desired form based on the degrees of freedom necessary for the different stages of operation [15]. The method simplifies the design process of the metamorphic mechanism and provides a new idea for the practical application of the metamorphic mechanism.

3.2. Kinematics and dynamics

During the motion of a flexible metamorphic mechanism, the configuration of the mechanism is constantly changing, so the kinematics of a metamorphic mechanism must be studied in conjunction with its configuration change. The goal of the theoretical study of the dynamics of flexible metamorphic mechanisms is to establish a dynamical model that includes all configurations, and kinematic analysis is the basis for the study of the dynamics of flexible metamorphic mechanisms.

Since the introduction of the metamorphic mechanism, the kinematics and dynamics of rigid metamorphic mechanisms have been studied with more significant results [16]. Little research has been done on the kinematics and dynamics of flexible metamorphic mechanisms. Dongfu Li studied the description of the kinematics of flexible metamorphic mechanisms and derived a kinematic analysis method effectively applicable to any one configuration of flexible metamorphic mechanisms[17]. At the same time, the dynamics modeling method of flexible metamorphic mechanism is studied, and the dynamics model of the full-configuration flexible metamorphic mechanism is derived, which lays the foundation for the dynamics analysis. Yang Yi proposed an umbrella foldable compliant metamorphic mechanism, as shown in Figure 1, and utilized the pseudo-rigid-body modeling method for its topology, kinematics, steady-state analysis and kinematics simulation[18]. This proves that the pseudo-rigid-body modeling method is suitable for the analysis and design of flexible metamorphic mechanisms. After discretizing the flexible components, Jin Guoguang establishes a dynamics model for any configuration based on the first type of Lagrangian equations and constructs the dynamics equations based on the configuration change matrices when the number of rods increases and decreases[19]. Shujun Li proposed a new method based on augmented Assur groups into a single-drive metamorphic mechanism[20]. It promotes the establishment of the compositional system of metamorphic mechanisms. At the same time, it provides a new way for the kinematic analysis of spatial metamorphic mechanisms. Based on the second kind of Lagrange equations, Liu established the full constitutive dynamics equations of a two-link flexible metamorphic mechanism and carried out kinematic analyses[21]. Wang introduced the concept of homomorphism into the study of metamorphic mechanisms, designed a homomorphic metamorphic mechanism with the same shape but different topology, and analyzed the kinematics of the evolved homomorphic mechanism[22].

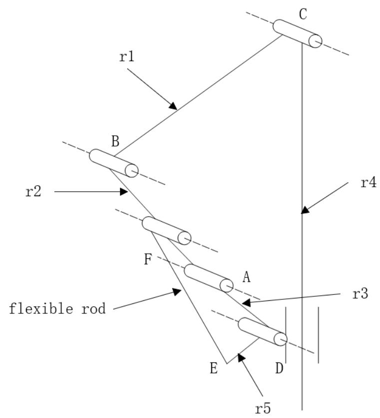

Figure 1: An umbrella foldable compliant metamorphic mechanism.

Due to the structural peculiarities of the flexible metamorphic mechanism, the deformations generated in the components during the conformational changes lead to high nonlinear in the dynamical equations, which will potentially lead to chaos phenomena in the motion. Jin Guoguang taked the two-link flexible metamorphic mechanism as the research object, establishes the dynamical equations and derives its Lyapunov exponent and phase configure, and determined the existence of chaos phenomenon in the configuration change of this flexible metamorphic mechanism[23]. The presence of chaos phenomena may lead to unanticipated changes in the actual use of flexible metamorphic mechanisms, adding uncertainty to the safety of engineered systems.

4. Application

Metamorphic mechanisms are highly expandable, foldable, and combinationally reconfigurable than conventional mechanisms due to their variable degrees of freedom and structure. During metamorphic reconfiguration, the flexibility of the component can play the role of power buffer, energy storage, and realize smooth switching between different configurations, which has a wide range of applications in the fields of aerospace, robotics, and manufacturing systems. In aerospace technology, the limitations of payload and geometry of launch vehicles inevitably require the use of a large number of extendable and assembled structures with high demands on the reliability and flexibility of the mechanisms. Zhao designed a space grasping manipulator based on a 3RRlS metamorphic cell in response to the inconvenience of grasping hovering targets in space[24]. Yu Shize took the elephant trunk as a bionic object, proposed a flexible joint with the function of "two turns and one shift", designed and manufactured a bionic flexible robotic arm for aerospace narrow space operation [25].

Flexible metamorphic mechanisms have a wide range of applications in the field of robot design. Ernesto et al. designed a new 3 degree-of-freedom centralized parallel mechanism by isotropy in operation based on origami structure[26]. WEI designed a novel metamorphic anthropomorphic manipulator[27], as shown in Figure 2. The topology of the palm changes during operation, increasing its flexibility and usability. Li Xianzhi designed an underdriven metamorphic manipulator with a spring as a flexible component, which realizes the whole process of grasping, handling and releasing by configuration change[28]. GAN designed a novel parallel metamorphic mechanism with three reconfigurable rTPS scaffolds, which has flexible joints with "three turns and one shift" [29].Matteo designed a three-finger metamorphic manipulator that transmits motion by a flexible hinge and compared it to a rigid hinge in a grip test, demonstrating the dexterity of a three-finger flexible metamorphic manipulator[30]. Xu Dongming investigated the structural advantages of the origami type metamorphic mechanism by combining the related theories of extensible surfaces, and designed a metamorphic solar wing with single degree of freedom, large folding ratio, and modularization[31]. Xu designed a metamorphic mechanism unit that builds a multi-stage ordered deployable/retractable mechanism under the action of friction and driving force[32]. Due to the design of the friction self-locking surface, it reduces the impact effect during metamorphic process. Inspired by the phenomenon of metamorphic cells in nature, Steven designed a self-folding origami "exoskeleton" to expand and change the functionality of the robot[33]. The design of deformable robots using origami metamorphic structures, which have the characteristics of small size and high functionality, has made considerable progress in structural design. Because of the lack of an effective drive mechanism, the robot usually requires a complex external drive system. J Li designed a soft body metamorphic origami robot based on electrostatic attraction, as shown in Figure 3, which generates time-varying electrostatic force by AC voltage to trigger the vibration of the origami structure, and the inertia force triggered by vibration generates the traction force to make the robot move forward[34].

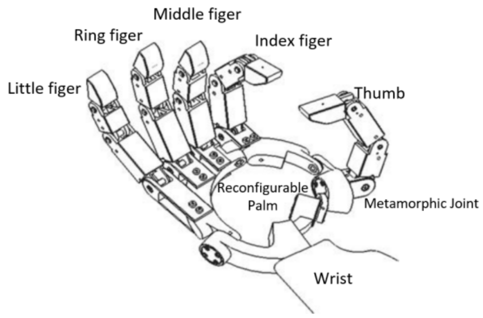

Figure 2: A metamorphic anthropomorphic hand with a reconfigurable palm.

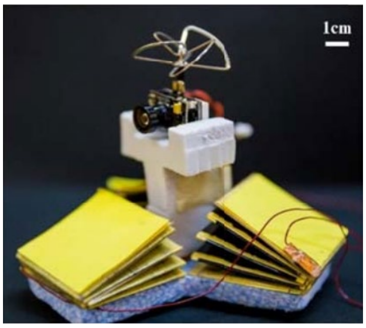

Figure 3: A soft body metamorphic origami robot based on electrostatic attraction.

5. Potential research directions

In summary, the flexible metamorphic mechanism mechanism has been studied for many years, and some results have been achieved in terms of configuration description, kinematics as well as dynamics. However, most of the research results are related to the conformational description and motion analysis of flexible metamorphic mechanisms. In order to improve the accuracy and performance of flexible metamorphic mechanisms in practical applications, many related researches need to be further advanced. The problems and trends of the previous study are as follows.

The components and joints in the flexible metamorphic mechanism are in the process of high-frequency motion, and the dynamics modeling of the flexible metamorphic mechanism is made more complicated due to the small deformation motions generated by the characteristics of the selected flexible materials.

When facing complex application scenarios, such as high temperature, high pressure, long time bending, etc., flexible metamorphic mechanism has higher motion instability than rigid metamorphic mechanism. How to select suitable flexible materials becomes a key issue in the practical application of flexible metamorphic mechanisms.

Shock phenomena are inevitable in metamorphic mechanisms during configuration change. The shock problem faced by flexible metamorphic bodies is more complex. How to optimize the structure to reduce the shock and vibration generated by the flexible metamorphic mechanism during configuration change and control it within the usable range is an essential part of the flexible metamorphic mechanism to be put into high-precision use scenarios.

The chaos phenomenon in flexible metamorphic mechanisms adds uncertainty to their practical engineering applications and affects the response and safety of the system, which is still less studied at present.

Flexible metamorphic mechanism now tends to simplify and lighten the structure, miniaturize, diversify the function, and convenient the control mode in the practical application design, which has a broad development prospect in a variety of fields.

6. Concusion

Metamorphic institutions, as a hotspot of institutional research, have achieved considerable research results after more than two decades of research. The flexible metamorphic mechanism, which is extended on the basis of the metamorphic mechanism, is still insufficient in all aspects of the research results, and a lot of theoretical research and structural design need to be further improved so that it can be put into practical application scenarios. This paper summarizes the development history of the related theories of flexible metamorphic mechanism in recent years, lists the representative application results, and puts forward the deficiencies and development trends in the research. Flexible metamorphic mechanism has the advantages of simple process, light weight and no friction. With the depth and perfection of the research, it will surely be used in more fields.

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