The Application and Development of Rigid Body Mechanics in Robotics Technology

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Abstract

As an important branch of classical mechanics, rigid body mechanics plays a core role in the development of robotics. This paper systematically reviews the theoretical basis and application of rigid body mechanics in robotics, and analyzes its key role in kinematics, dynamics and control systems. Studies have shown that rigid body mechanics provides theoretical support for high-precision motion control and structural optimization for industrial robots through kinematic and dynamic modeling; in flexible robots, the analysis method of rigid-flexible combination promotes breakthroughs in adaptability to complex environments; in control systems, rigid body mechanics supports the realization of trajectory tracking and force control strategies. The article also explores the development trend of rigid body mechanics in the design and intelligent control of new robots, and points out its potential for integration with artificial intelligence, real-time computing and interdisciplinary. In the future, rigid body mechanics will play a greater role in multi-robot collaboration, rigid-flexible hybrid systems and autonomous technology, and provide a solid foundation for the innovation of robotics.

Keywords: rigid body mechanics; robotics; kinematics; dynamics; control systems

1. Introduction

1.1 Research background and significance

A prominent section of classical mechanics, rigid body mechanics is about the law of motion of rigid body under the constraint of force and motion, and plays an extremely important role as a theoretical foundation of present engineering technology. As robot technology has emerged rapidly, its application of its own brand of rigid body mechanics to robot design, motion planning and motion control has increasingly gained foreground. Used today in various fields of industrial production, medical treatment, aerospace, etc., its core is achieving high-precision and high-efficiency motion and operation, and the study of rigid body mechanics has provided people with theoretical support for kinematics and dynamic modeling of robots [1]. For example, laws of rigid body mechanics are used to examine the forces and motion tracks of robot joints, optimizing the performance and stability of the robot arm correspondingly. In recent years, together with the development of intelligent manufacture and automation technology, the improvement of robot systems' dynamic performance as well as adaptability to diverse complex environments has continued to broaden. Rigid body mechanics has proved its irreplaceable value for the solution of multi-body system dynamic problems, collision detection, and force control, etc. [2].

The significance of this study is to systematically sort out the current application status of rigid body mechanics in robotics, explore its potential in the design and control of new robots, and provide theoretical reference and technical guidance for related fields. By analyzing the specific application of rigid body mechanics in robot motion modeling, structural optimization and control strategies, this paper aims to reveal its role in promoting the development of robotics technology and provide a new perspective for interdisciplinary research [3]. As robotics technology moves towards high precision and intelligence, the research and application of rigid body mechanics will be further deepened, laying the foundation for the breakthrough of the next generation of robotics technology.

1.2 Overview of rigid body mechanics and robotics technology

Rigid body mechanics is the study of motion laws and force of objects under conditions of non-deformation. Its main content is kinematics, analysis of dynamics and statics, which is an essential tool for the theory and application of robotics technology [4]. Rigid body mechanics is generally applied to the analysis and design of motion of robotic arms, mobile robots and humanoid robots in robotics technology. For instance, kinematics analysis of rigid body mechanics is employed to present the spatial relation of position and velocity between robot joints and end effectors, and dynamic analysis determines the force and motion relation of the whole system by Newton-Euler equation or Lagrange method, which forms the basis of robot control [5]. Moreover, rigid body mechanics is also fundamental to robot structural design. It can optimize the force distribution of rigid body parts and enhance the capacity of load and motion accuracy of the robot.

In recent years, with the development of robotics technology toward flexible robots and soft robots, integrated applications of rigid body mechanics and flexible mechanics have gained very extensive attention. Even for flexible robots that focus on the deformation characteristics of material, there still is an initial model and analysis framework of rigid body mechanics for hybrid systems [6]. For example, for medical robots, there is an analysis of surgical manipulator rigid part motion by way of rigid body mechanics, but there is an analysis of interactive behaviors of soft tissues by way of flexible mechanics. This paper would start from the theory of rigid body mechanics, systematically elaborate its application to robot kinematics, dynamics and control, and study its development directions and application difficulties for new robot systems.

2. Theoretical basis of rigid body mechanics in robotics

2.1 Basic principles of rigid body mechanics

Rigid body mechanics is a discipline that studies the movement of rigid bodies under the action of force and movement, and is a basic prerequisite for the theoretical research of robotics. Its core theories involve kinematics, dynamics and statics, such as translation and rotation of rigid bodies, and based on Newton's laws of mechanics and Euler's motion equations [7]. In robotics, rigid body mechanics accurately describes the movement relationship between robot arms and end effectors by establishing coordinate transformations and constraint equations, facilitating the study of multi-degree-of-freedom systems [8]. For example, the Lagrangian method and Newton-Euler method are pervasively used for dynamic analysis of robot systems and facilitating the design of effective motion control strategies. In the past decades, coupled with high-performance computing technology, rigid body mechanics provides dynamic analysis and real-time simulation of complex multi-body systems, for example, optimizing the motion trajectory and force distribution of robotic arm motion of industrial robots [9]. These theories not only provide robot motion planning with theoretical support, but also play an indispensable part in the mechanical interaction between robots and environment, for example, maintaining the operational safety and stability by researching contact forces and collision forces. As the basis of robotics theories, rigid body mechanics has promoted the relentless development of system design as well as performance optimization, and provided formal support for the development of intelligent robot systems.

2.2 Robot kinematics and dynamics analysis

Robot kinematics and dynamics analysis is the core application of rigid body mechanics in robotics. Kinematic analysis studies the relationship between the spatial position, velocity, and acceleration of each component in a robot system, and is achieved through forward kinematics and inverse kinematics methods. Forward kinematics calculates the position of the end effector based on joint parameters, while inverse kinematics solves the joint configuration for a given end position, usually using Denavit-Hartenberg parameters for modeling [10]. Dynamic analysis uses the Newton-Euler equations or Lagrangian method of rigid body mechanics to establish the relationship between the force and motion of the system, providing a theoretical basis for robot motion planning and control [11]. For example, in industrial robotic arms, dynamic analysis is used to optimize motion paths and reduce energy consumption and vibration. These methods of rigid body mechanics also support the analysis of multi-robot collaborative systems, optimizing task allocation and coordinated motion by modeling the dynamic coupling of multi-body systems. As robotics technology expands into complex scenarios, rigid body mechanics combined with modern control theory can achieve high-precision real-time control, such as optimizing gait stability in humanoid robots, which has promoted the widespread application of robotics technology in industry, medicine and other fields.

Figure 1 Rigid body motion and Euler angle representation

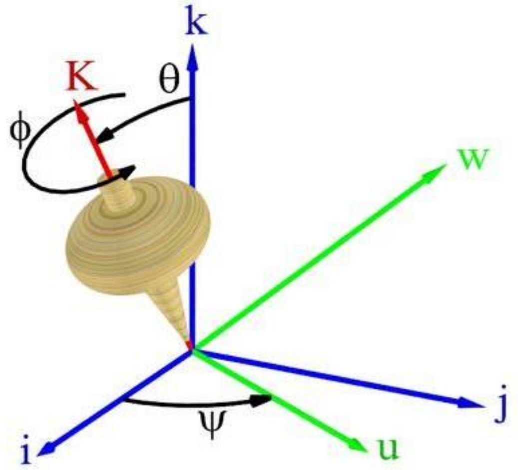

Figure 1 shows the rigid body motion of a gyroscope, including the three-dimensional coordinate system (i, j, k) and the angular velocity vector (w, u), with the Euler angles (φ, θ, ψ) marked. These parameters are particularly critical in robotics, specifically used to optimize the joint motion trajectory of industrial robot arms in welding tasks, and to accurately model the dynamic response of the rigid components of flexible grippers in medical surgical robots.

2.3 The role of rigid body mechanics in robot design

Rigid body mechanics is of great importance for robot design, including structural optimization, motion planning, and dynamic performance analysis. For structural design, rigid body mechanics can be used to study the force and motion characteristics of robot components for ensured stability of the system under high load or dynamic conditions. For example, through the combination of finite element analysis and laws of rigid body mechanics, design engineers can optimize the stiffness-to-weight ratio of robot joints and improve mechanical capability [7]. For motion planning, the path optimization theory is founded upon rigid body mechanics, and the effectiveness and smoothness of robot motion are ensured by studying motion restriction and mechanical characteristics [10]. Additionally, dynamic performance analysis is also where the significance of rigid body mechanics has been pronounced. Under the condition of dynamic motion simulation of multi-body systems, response characteristics of robots under complex working conditions can be predicted, providing reference for design optimization. For modular robot design, mechanical coupling analysis of modules can be assisted by means of rigid body mechanics for ensured stability and functionality of the entire system [11]. By bridging traditional rigid body mechanics and emerging design tools, robot design can optimize performance and costs and meet requirements of functionality, providing good impetus for innovation of next-generation robot technology.

3. Application of rigid body mechanics in robotics

3.1 Rigid body mechanics in industrial robots

The application of rigid body mechanics in the field of industrial robots is an important manifestation of its theoretical value, especially in improving motion accuracy and load capacity. Industrial robots, such as robotic arms, are widely used in welding, assembly, and material handling in the manufacturing industry. Their design and operation rely on rigid body mechanics analysis to ensure high efficiency and stability. Through the kinematic and dynamic models of rigid body mechanics, the motion trajectory and force distribution of the robotic arm joints can be accurately calculated, thereby optimizing operational efficiency [12]. For example, dynamic analysis based on the Newton-Euler equation can predict the vibration characteristics of the robotic arm in high-speed motion and reduce mechanical errors and fatigue by optimizing the structural design [13]. Rigid body mechanics also supports the mechanical analysis of industrial robots under complex working conditions. For example, in heavy-load tasks, the safety and reliability of the system can be ensured by calculating the joint torque and force distribution of the end effector [14]. With the advancement of intelligent manufacturing, rigid body mechanics combined with real-time simulation technology has significantly improved the adaptability of industrial robots to dynamic environments, such as realizing multi-robot collaborative operation and task optimization on automated production lines [15]. These applications of rigid body mechanics enable industrial robots to play a greater role in high-precision and high-efficiency manufacturing scenarios, providing key technical support for the development of Industry 4.0.

Figure 2 Schematic diagram of the structure of a four-axis industrial robotic arm

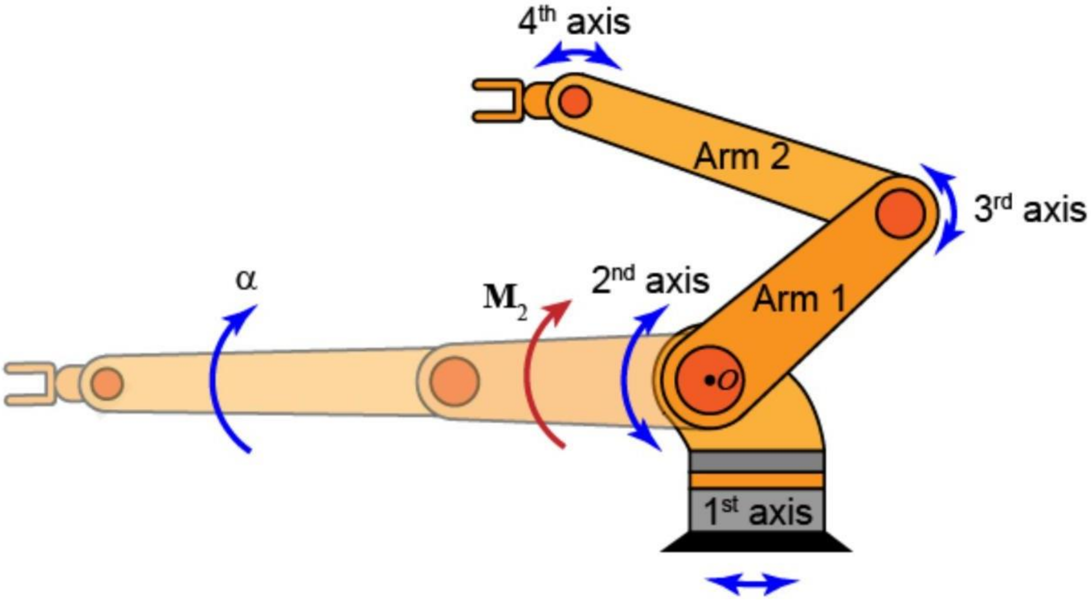

Figure 2 shows the structure of a four-axis industrial robot arm, showing the joint axes (1st axis, 2nd axis, 3rd axis, 4th axis) and their movement directions, including torque (M_2) and angle (α). The torque balance can be expressed by the dynamic equation:

$$M_2 = I\ddot{\theta}$$

Among them, I is the moment of inertia, and $\ddot{\theta}$ is the angular acceleration. Combined with the real-time control strategy, these parameters significantly improve the accuracy and stability of the robot in intelligent manufacturing.

3.2 Combination of flexible robots and rigid bodies

Flexible robots have attracted widespread attention due to their adaptability under complex conditions, and rigid body mechanics plays an indispensable role in the analysis and modeling of rigid-flexible hybrid systems. Flexible robots generally combine flexible components and stiff components, and rigid body mechanics can give the theory of analyzing motion and force of stiff components. For example, for medical robots, rigid body mechanics is used to model stiff joint motion of surgical robot hands, however, flexible material is used to handle contacting soft tissues [16]. From the analysis of multi-body dynamics of rigid body mechanics, the motion model of the rigid-flexible hybrid system could be established to optimize the stability and coordination of the whole system [12]. What is more, rigid body mechanics plays an indispensable role in the structural design of flexible robots. From the analysis of force allocation of stiff framework, the attachment strength of flexible component and stiff component is optimized for ensuring whole performance. During the recent years, the use of combined rigid body mechanics and flexible mechanics has inspired innovation for emerging robot systems. For example, for soft grippers, basis motion trajectory design has been carried out based on the use of rigid body mechanics for promoting grasping precision [15]. This analysis method of rigid flexibility not only optimizes flexible robot performance, but also presents new directions for applications under complex conditions such as rescue and medical treatment.

3.3 Application of rigid body mechanics in robot control

Rigid body mechanics is also extremely prominent for robot control systems and has theoretical basis for achieving dynamic response and high-precision control strategies. Based on the dynamic model of rigid body mechanics, the control system can compute the robot joint's torque and motion status for the purpose of achieving precise force control and precise tracking of the path of movement in real time. Taking servo control of industrial robot arm as an example, for example, the Newton-Euler method of rigid body mechanics is employed to set up dynamic equations and optimize motion performance as well as optimize feedback control algorithms [13]. Interactive environmental control is facilitated by rigid body mechanics in collaborative robots, and safety-ensuring force control strategies are designed by analyzing contact and collision forces [14]. Moreover, rigid body mechanics also plays an indispensable part in the real-time control of complex robot systems. Taking gait control of humanoid robots as an example, for example, joint torque distribution is optimized based on dynamic analysis for the purpose of ensuring stability and naturalness of movement [16]. As computing power is enhanced, combined with machine learning technology, however, rigid body mechanics has also driven the development of adaptive control strategies, such as adjusting robot movement based on dynamic modeling of dynamic environments in real time [15]. These applications of rigid body mechanics have greatly facilitated the accuracy and robustness of robot control, and have given key support for the autonomy and intelligence of intelligent robot systems.

4. Conclusion

4.1 Research Summary

A major limb of classical mechanics, the study of rigid body mechanics is of great significance for the development of robotics. This paper systematically discusses the theory foundation and application situation of the theory of rigid body mechanics for robotics, covering kinematics, dynamic analysis and its special application for industrial robots, flexible robots and control systems. Rigid body mechanics provides an elegant mathematical model of robot motion. By using Newton-Euler equations, Lagrange methods, etc., the optimization analysis of joint motion trajectory and force distribution is gained. In industrial robots, the study of rigid body mechanics greatly improves the accuracy and stability of robotic arm; in flexible robots, the analysis method of composite of the flexible body achieves the innovation of extending adaptability to complex environments; in control systems, the study of rigid body mechanics provides technical support for building high-precision strategies of trajectory tracking and force control. These applications not only upgrade the performance of robot systems, but also provide technical support for intelligent manufacturing, medical treatment and rescue. Research of the present paper shows that the theory of rigid body mechanics is not only the theory foundation of robotics, but also has great value of cross-field integration, providing a solid basis for innovation of design and control of robots.

4.2 Future Prospects

As robotics technology develops towards intelligence and autonomy, rigid body mechanics will show greater potential in the future. Future research can focus on the deep integration of rigid body mechanics and flexible mechanics, and further optimize the design and control of rigid-flexible hybrid systems to adapt to more complex dynamic environments. At the same time, rigid body mechanics combined with artificial intelligence and real-time computing technology is expected to achieve adaptive motion planning and control of robotic systems in unstructured environments, such as in complex tasks of humanoid robots or autonomous mobile robots. Interdisciplinary collaborative research will also be a focus, and new lightweight and high-strength robot structures will be developed by integrating materials science, control theory and rigid body mechanics. In addition, rigid body mechanics has broad application prospects in multi-robot collaborative systems, especially in the fields of distributed control and group coordination. The future challenge is how to further improve the real-time and accuracy of rigid body mechanics models through efficient algorithms and high-performance computing, and provide support for breakthroughs in the next generation of robotics technology.

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