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A Review of Hexapod Robot Research: From Structural Design to Intelligent Control

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ABSTRACT

Hexapod robots, their exceptional static stability, redundant limb structures, and strong terrain adaptability, demonstrate broad application prospects in fields such as interstellar exploration, disaster rescue, military reconnaissance, and complex environment operations. Based on a systematic review of multiple high-quality academic papers published in recent years, this paper provides an in-depth review of the current state of hexapod robot technology from key dimensions, including mechanical structure design and optimization, kinematics and dynamics modeling, gait planning and motion control, environmental perception and autonomous decision-making, and adaptability under special operating conditions. The analysis indicates that current research is shifting from traditional single-structure, regular gait, and model-dependent control toward lightweight/reconfigurable structures, adaptive gaits for complex terrains, and intelligent control based on deep reinforcement learning. In the future, integrating advanced sensing technologies and achieving higher autonomy and environmental robustness will be key breakthroughs in hexapod robot research.

KEYWORDS

Hexapod Robot; Structural Design; Gait Planning; Motion Control; Environmental Perception; Deep Reinforcement Learning.

1. INTRODUCTION

When exploring the unknown, performing hazardous tasks, or navigating complex terrain, mobile robots play an indispensable role. Compared with wheeled and tracked robots, legged robots, thanks to their discrete footholds, are better suited to rugged and uneven environments. Among them, hexapod robots, with their inherent static stability (with three legs always forming a stable support surface) and highly redundant limb configurations, demonstrate unique advantages in terms of load capacity, motion stability, and fault tolerance. For example, Ye Bin [1] designed a "wheel-leg-spoke" metamorphic robot, whose hexapod configuration enables stable locomotion over uneven terrain. In recent years, with the rapid advancement of bionics, materials science, control theory, and artificial intelligence, hexapod robotics has achieved unprecedented breakthroughs. Research focuses have shifted from merely mimicking biological motion toward systematic innovations that integrate structure, perception, and control. This paper aims to synthesize key research findings in this field, systematically review the core research topics, and discuss future development directions.

2. INNOVATIONS IN MECHANICAL STRUCTURE AND MECHANISM DESIGN

The mechanical structure serves as the physical foundation of a hexapod robot, and its design directly determines the robot’s locomotion capability, load efficiency, and environmental adaptability. Current research mainly focuses on three aspects: lightweight design, metamorphic/hybrid locomotion modes, and novel actuation mechanisms.

2.1. Solid-Lubricant Nanofillers and Hybrids

To enhance the robot's mobility and load capacity, lightweight design remains a perpetual focus. Lu Xiaoxu et al. [2] conducted a study on the legs of a large-scale hexapod robot, combining finite element static/dynamic analysis with the Six Sigma research method. Through topology optimization and variable cross-section perforation design, they successfully reduced the weight of the thigh structure by 47.00%, decreased the maximum stress by 47.24%, and reduced the maximum deformation by 84.61%, while also significantly improving the first four natural frequencies. This optimization provides an important reference for lightweight design in other engineering structures. Wang Pengyun [3], in the design of a four-wheel-legged robot, achieved a self-weight-to-load ratio of 2:1 through the use of integrated hollow joints, optimized leg topology, and finite element analysis of key components. Yin Zhipeng [4] designed a hexapod robot with fewer actuators and also reduced leg weight through structural optimization while maintaining strength. Yu Changjuan [5], in her research on a deformable hexapod robot, employed B-spline curves for joint-space trajectory planning and used the Kane method to establish a dynamic model, providing a theoretical basis for subsequent lightweight design. Similar optimization approaches have been widely applied in the design of other hexapod robots. For instance, Ye Bin conducted detailed finite element analysis on the toe parts, connecting rods, and mechanical legs of a "wheel-leg-spoke" metamorphic robot to ensure the strength of key load-bearing components.

2.2. Lightweight Design and Structural Optimization

To balance rapid movement on flat terrain with obstacle-crossing capability in complex environments, researchers have explored various metamorphic designs. Xu Kun et al. [6] designed a six-wheel-legged robot capable of switching between wheeled and legged locomotion modes by changing leg configurations (e.g., folding into wheels) without requiring additional actuators. Ye Bin proposed a more typical "wheel-leg-spoke" metamorphic robot, which features four configurations: hexapod, two-wheel, three-wheel, and wheel-spoke. The hexapod configuration is used for uneven terrain; the two-wheel configuration, combined with a robotic arm, enables task execution on flat surfaces; the three-wheel configuration achieves rapid and stable locomotion; and the wheel-spoke configuration can traverse large obstacles or deep ditches, realizing complementary advantages of legged and wheeled locomotion. Wang Xiaolei et al. [7] designed a metamorphic hexapod robot whose legs can switch between crawling and rolling modes through morphological changes (e.g., folding into a circle). Using workspace, dexterity, and stiffness as optimization indicators, they employed a particle swarm algorithm to optimize leg dimensional parameters, resulting in a 1.28% increase in workspace, a 22.50% improvement in dexterity, and a 42.80% enhancement in stiffness. Shou Xing et al. [8] developed a spherical hexapod robot for lunar exploration, capable of switching between spherical rolling and hexapod crawling modes to adapt to different exploration tasks and terrains. Yang Mingyuan [9], inspired by insects, designed a wheel-legged robot with an underactuated waist joint, utilizing mechanical intelligence to simplify control.

2.3. Innovations in Actuation Mechanisms

Traditional hexapod robots typically have three motors driving each leg (totaling 18 degrees of freedom), resulting in complex control systems and high costs. To simplify the design, Yang Mingyuan and Yin Zhipeng respectively developed hexapod robots with reduced actuation or even a single actuator. The Hlbot robot designed by Yang Mingyuan uses only one motor to drive six wheel-legs through a synchronous belt system, achieving underactuated control through mechanical intelligence. The robot's body is divided into front and rear sections connected by a passive waist joint, allowing it to passively lift the body when encountering obstacles and climb heights up to 2.8 times the wheel-leg radius. Yin Zhipeng, through an ingenious linkage mechanism design, achieved walking with only one actuator per side. Furthermore, by introducing a metamorphic mechanism, the robot can switch between "single-actuator + single stride" and "dual-actuator + variable stride" modes, increasing the maximum leg lifting height from 169.79 mm to 221.54 mm and improving single-step obstacle clearance height from 150 mm to 167 mm. Zhan Yuxin et al. [10] incorporated a clutch mechanism in the design of a wheel-leg hybrid robot to enable switching between wheeled and legged modes, placing the wheels at the connection between the thigh and shank to simplify the structure. These studies provide new approaches for developing hexapod robots that are low-cost, structurally simple, and easy to control.

3. KINEMATICS AND DYNAMICS MODELING

Accurate kinematics and dynamics models are the foundation for robot motion planning and control. Most studies employ the Denavit–Hartenberg (D-H) parameter method or screw theory for modeling.

3.1. Kinematics Analysis

Yu Changjuan utilized screw theory and the product of exponentials (POE) method to perform kinematics analysis on the legs of a hexapod robot with deformable joints, addressing the singularity issues that the D-H method may encounter in specific configurations. The inverse kinematics was solved using the Paden–Kahan subproblem approach, yielding explicit inverse solutions. Chen Mengqi [11] and Yang Dongkai [12] respectively established the kinematics models of their hexapod robots using the modified D-H method and the standard D-H method, and analyzed the foot-end workspace using the Monte Carlo method. Zhou Juanli et al. [13] employed the D-H model for kinematics modeling of a spider-inspired hexapod robot and established a dynamics model using the incidence matrix method from spatial structure theory. Liao Zifeng [14]focused on the swing leg and established a dynamics equation using the Lagrangian method, providing a basis for subsequent trajectory tracking control. Li Ruiwen [15] also used the D-H parameter method to construct a forward kinematics model and solved the inverse kinematics via a geometric approach, followed by an analysis of the foot-end motion workspace.

3.2. Dynamics Analysis

Yu Changjuan selected the Kane method for dynamic modeling of a single leg, avoiding the complexity of analyzing intermediate constraint forces inherent in the Newton–Euler method, as well as the complicated partial derivative calculations required by the Lagrangian method. She conducted a detailed analysis of the influence of joint angular velocity and acceleration on driving torque, as well as the proportions of inertia torque, centripetal torque, Coriolis torque, and gravitational torque in the driving torque of each joint, providing a basis for motor selection and structural optimization. Zhou Juanli et al.employed the incidence matrix method from spatial mechanism theory to establish a dynamic model for a spider-inspired hexapod robot, and further adopted a multiple-input multiple-output fuzzy control network for trajectory tracking control to mitigate the effects of uncertainties such as friction. Li Hui [16], in his research on control under weakened joint actuation capability, established a comprehensive dynamic model based on the Lagrangian method, laying the groundwork for subsequent adaptive control strategy design. These dynamic models provide theoretical support for the design of high-precision controllers in subsequent work.

4. GAIT PLANNING AND MOTION CONTROL

Gait planning and motion control are central to achieving stable and efficient locomotion in hexapod robots. Current research hotspots are shifting from classical regular gaits toward adaptive and intelligent control for complex terrains.

4.1. Gait Pattern Design

Classical gait patterns include tripod gait, quadruped gait, and quintuped gait. The tripod gait is widely used due to its high speed and simple control; for example, Yang Dongkai employed the tripod gait in his lunar exploration robot, and Wang Yizhe [17] adopted it in his linkage-type robot. Chen Mengqi further designed ramp gaits and obstacle-climbing gaits, and proposed a state machine-based gait switching strategy. In the ramp gait, the robot maintains a level body posture by adjusting leg lengths; in the obstacle-climbing gait, a pre-adjusted two-stage strategy (adjustment phase and crossing phase) is used to overcome obstacles. Li Hui, in his study on reduced joint actuation capability, conducted a detailed analysis of the degradation pattern of motion capability under a two-stage gait (i.e., tripod gait), finding that hip joint damage has the greatest impact on step length (reduction exceeding 50%), while knee joint damage significantly reduces step height (reduction of approximately 60%). Li Shiqi et al. [18] evaluated stability for tripod and quadruped gaits using static stability margin (SSM) and zero moment point (ZMP) methods.

4.2. Trajectory Planning

The smoothness of foot-end trajectory directly affects the motion stability of the robot. Traditional methods employ composite cycloid curves or polynomial interpolation. Xu Ziyang [19] proposed using an eleventh-order Bézier curve for foot-end trajectory planning and conducted comparative experiments with the traditional composite cycloid. The results showed that the Bézier curve effectively reduces impact during touchdown and liftoff, resulting in smoother motion, a smaller range of pitch and roll angle variations, and fewer abrupt changes in angular velocity. Yu Changjuan employed quintic B-spline curves for joint-space trajectory planning, ensuring continuity of velocity, acceleration, and jerk, and performed time-optimal optimization using a genetic algorithm. Chen Mengqi also adopted quintic polynomial interpolation to optimize leg joint motion trajectories to reduce impact forces. Liao Zifeng designed a trajectory planning method based on sixth-order polynomials and Bézier curves for the swing leg, and compared its performance with that of fourth-order curves through simulation.

4.3. Motion Control Methods

Model-based control: Classic methods such as virtual model control (VMC) [20] and computed torque control (CTC) are widely adopted. Yu Changjuan designed a composite controller combining computed torque control with a radial basis function (RBF) neural network to compensate for modeling errors and external disturbances. Simulation results showed that this controller achieved low tracking error and strong robustness. Wu Qiuhan introduced a force direction penalty term and foot–terrain mechanical constraints into the VMC framework for soft terrain scenarios, optimizing foot-end force distribution through quadratic programming. By improving the friction cone model, they reduced the pitch angle fluctuation of the robot body by approximately 33% and the Z-axis displacement fluctuation by about 50%. Li Shiqi et al. designed a central pattern generator (CPG) network based on Hopf oscillators and generated smooth joint trajectories using an improved mapping function.

Intelligent control: With the rise of artificial intelligence, deep reinforcement learning (DRL) has been increasingly applied to hexapod robot control. DRL enables robots to autonomously learn adaptive gait strategies in complex environments through trial and error, reducing the dependence on accurate modeling. Some studies have also employed fuzzy control and neural network methods to address challenges such as model uncertainties and nonlinearities, thereby enhancing the robot's adaptability and robustness in unstructured environments.

5. ENVIRONMENTAL PERCEPTION AND AUTONOMOUS DECISION-MAKING

Environmental perception is a prerequisite for robots to achieve autonomous locomotion. In addition to traditional vision and LiDAR, proprioception-based sensing strategies have become a research hotspot due to their robustness.

5.1. Environmental Perception Based on External Sensors

Liu Xiuqi [21] constructed a comprehensive environmental perception system that performs localization via visual-inertial SLAM (VINS-Mono) and builds 3D semantic maps and cost maps using an improved lightweight DeepLabv3+ semantic segmentation model and the YOLOv5s object detection algorithm, thereby providing information for path planning. The improved DeepLabv3+ model reduced the number of parameters from 54.74×10^6 in the original version to 4.85×10^6, while more than doubling the segmentation speed. Chen Mengqi also integrated attitude sensors and force sensors on a hexapod robot, enabling body state estimation and foot-end contact force feedback.

5.2. Environmental Adaptation Based on Proprioception

In environments where visual sensors are restricted (e.g., tall grass, dust, low light), utilizing the robot's own sensors (IMU, joint encoders, force sensors) for environmental perception becomes particularly important. The work of Li Ruiwen is based on this concept; using only proprioceptive signals, a high-level policy network was trained through reinforcement learning to achieve autonomous walking in flexible, highly occluded environments. Wu Qiuhan designed an intelligent foot end that integrates a six-axis force sensor and an IMU, enabling real-time perception of foot–terrain contact forces and terrain inclinations. This information was used to improve VMC control, reducing the pitch angle fluctuation of the robot body by approximately 33% and the Z-axis displacement fluctuation by about 50% in experiments on sloped sandy terrain. The research by Liu Xiuqi similarly relied on joint encoder and IMU information, combined with object detection and depth images for obstacle size measurement; the experimental errors in measured obstacle width and height relative to the actual values were within 2.6%. This closed-loop "perception–control" design enables the robot to better adapt to environmental changes.

6. CONCLUSION

This paper reviews the research progress in hexapod robots regarding structural design, kinematics/dynamics modeling, gait control, environmental perception, and responses to special working conditions. The analysis reveals the following trends in this field:

Integrated and intelligent structure: Development is shifting from simple serial joints toward lightweight design, metamorphic configurations, wheel–leg hybrids, and reduced actuation, aiming to simplify structure, reduce energy consumption, and enhance environmental adaptability. Examples such as Ye Bin's four-configuration switching, Yang Mingyuan's underactuated design, and Yin Zhipeng's metamorphic mechanism all demonstrate how structural innovation expands functionality.

Fusion of control algorithms: Single model-based control or bio-inspired control alone is insufficient for highly complex environments. Combining model-based classical control (e.g., VMC, CTC) with advanced learning-based algorithms (e.g., DRL) to form hierarchical, adaptive control architectures has become a mainstream trend. Representative examples include Li Ruiwen's CPG-DRL two-layer architecture and Li Hui's evolutionary strategy–reinforcement learning fusion framework.

Closed-loop perception–control: By utilizing proprioception (e.g., force, IMU) and vision/LiDAR information, a closed loop of "perception–decision–control" is constructed, enabling the robot to perceive its own state and external environmental changes in real time and respond optimally. This trend is reflected in Wu Qiuhan's integration of an intelligent foot end with VMC, as well as Liu Xiuqi's combination of semantic mapping with path planning.

Increasingly extreme research scenarios: Research is expanding from structured environments to unstructured and extreme settings (e.g., soft lunar soil, rugged terrain, post-disaster rubble, joint failures), imposing higher demands on robot mechanisms, control algorithms, and reliability. Shou Xing's lunar surface robot, Wu Qiuhan's soft-terrain robot, and Li Hui's fault-tolerant robot are all manifestations of this trend.

It can be anticipated that with continued breakthroughs in related technologies, hexapod robots will play increasingly irreplaceable roles across a wider range of fields, providing strong support for humanity's exploration of unknown worlds and response to complex challenges.

CONFLICTS OF INTEREST

The authors declare that they have no conflict of interest.

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