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| **Title** | テンセグリティ構造とその形態に基づく脚移動ロボットの制御系設計および安定性解析 |
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# Abstract

Inspired by biology, biomimetic robots imitate living organisms to enhance their adaptability and mobility. Designing robots based on their morphology can provide specific functions, but there is a lack of unified guidance and efficient research methods in this area. Therefore, an innovative theory of robot morphology is urgently needed. To establish this system, a representative minimal model is necessary to explore essential issues and provide a research platform. The first step in robot morphology is designing a minimal model that can serve as a platform for future academic research.

Rigid and soft robots are the two main types of robots, each with unique features and applications. Rigid robots offer higher precision, speed, and agility due to their mathematical models, especially their dynamic models. Soft robots, on the other hand, have high adaptability but struggle with high-precision mathematical models, resulting in slower speed and lower accuracy. However, the adaptability of soft robots cannot be replaced by rigid robots.

The significance of robot morphology lies in finding the optimal form for specific tasks. Variable soft robots are advantageous as a minimal model because their structures are more changeable compared to rigid robots. However, the study of soft robots often doesn't utilize high-precision mathematical models, which contradicts the requirements of the minimal model.

Tensegrity robots combine the precision and agility of rigid robots with the adaptability of soft robots, making them lighter, stiffer, and more versatile. They have gained attention in recent years, such as NASA's Super Ball Bot for planetary exploration. However, these robots face challenges, such as difficulties in building dynamic models, limiting their high-speed motion control. Despite this, tensegrity robots offer opportunities for dynamic modeling, making them ideal candidates for studying robot morphology.

This paper focuses on a minimal model called the rimless-wheel-like tensegrity walker (RWT), inspired by the widely studied rimless wheel (RW) model for legged locomotion. The dynamics model considers the internal coupling force from elasticity and the external constraint force from the environment. Different movement modes are discussed, providing guidance for dynamics modeling and bridging the gap between rigid and soft robots.

Considering practical applications, modifications to the minimal model are necessary. For instance, the SLIP model based on an inverted pendulum explains the motion of the center of gravity during human walking more effectively. Extensions to the RW model accommodate objective conditions like semicircular feet and frictional road surfaces, improving the model's accuracy. A MATLAB-based simulator is designed, demonstrating that the RW achieves periodic passive gaits and stability even when each rod is independent. Changes in the internal structure lead to discrete changes in the RW's characteristics, showcasing the importance of morphology. Morphological transitions based on the proposed morphology-based control (MBC) theory enable different gaits such as crawling, walking, and hopping. The MBC approach simulates morphological changes by controlling inputs, enhancing adaptability and stability of the control system. A simplified version of the model, the simplified rimless-wheel-like tensegrity walker (SRWT), achieves continuous morphological changes through MBC, resulting in locomotion on flat ground. Detailed analyses of gait, stability, and applications are provided. Physical experiments validate the minimal model of robot morphology. Verification experiments reveal drastic internal property changes in tensegrity robots with varying structures, confirming the necessity of the RW as the minimal model. Engineering experiments demonstrate flat walking of the SRWT based on the presented theory, highlighting the model's relevance in academic research and engineering applications.

In conclusion, this study introduces the minimal model for robot morphology, providing a theoretical method and advancing its implementation. Dynamic modeling of tensegrity robots offers insights for high-speed and high-precision movement and interaction with rigid and soft robots. The experiments demonstrate the positive impact of the proposed model in engineering applications.



**Keywords**: Robot morphology, Minimal model, Tensegrity robots, Rimless wheel, Dynamics modeling, Stability analysis