Abstract of Doctoral Thesis

Title：Locomotion Study of Passive-Spine Multi-Legged Robot

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In complex natural environments, multi-legged animals, such as centipedes, can adapt to different environments. Multi-legged animals typically move in varied environments, such as on soft land or rough terrain, with strong adaptability, fault tolerance, and high mobility. The trajectory of a multi-legged robot constitutes a series of discrete footprints, while wheeled and crawler robots are a series of continuous tracks. Rough terrains often contain obstacles, such as rocks, mud, sand, and even cliffs and steep slopes, which means that wheeled and crawler robots are no longer suitable for this type of terrain. While legged robots only need discrete points to touch the ground, they possess strong adaptability to this kind of terrain. Consequently, legged robots tend cause less damage to the environment. Although multi-legged robots have many advantages, numerous disadvantages remain. For example, in order to make the legs coordinate with each other and stabilize movement, the mechanical structural design and the control system are more complicated than those of other types of robots. As a result, compared with natural arthropods, the performance of bionic leg robots needs to be improved.

In order to overcome these challenges, a new methodology for designing a multi-legged robot with a simple structure and a small number of actuators has been proposed. A traditional multi-legged robot with 2n-legs requires three motors per leg and necessitates a total of 6n actuators. In this thesis, we have proposed a legged robot with only one actuator per leg that controls the lateral swing of the legs to achieve leg lifting and landing. Such a 2n-legged robot requires just 2n actuators, and thus not only the number of the actuators, but also body weight, are greatly reduced compared to the conventional design. This multi-legged robot comprises n body segments and $n-1$ passive body segment joints between the body segments.

Determination of precisely how to design this robot, which can abduct and adduct its legs with the same motion ability as a traditional legged-robot, constitutes the focus and challenge of our research. To model the mobility of this kind of robot with a simple design, the candidate configurations are first selected by a mobility analysis based on screw theory. By analyzing these configurations, omni-directional locomotive performance which is generated by a different order of configuration transitions has been deduced.

Our research also needs to solve the problem of how to better combine motion of the active leg joints with the passive body segment joints to form the motion of the entire robot. Considering the results of the mobility analysis, we have obtained the locomotion principle of omni-directional

motion based on a geometric analysis. The contribution of the duration of the supporting phase of various configurations to the direction of rotation between configuration transitions has been determined. These different gaits and gait transitions have been also achieved to complete an obstacle avoidance task.

Our research also provides a method to design multi-legged robots based on the internal motion mechanism of centipedes. Indeed, the movement method of passive-spine can be extended to a 2n-legged robot to perform undulatory motion by abducting and adducting in the frontal plane of their active legs.

We have utilized the Open Dynamics Engine (ODE) environment to obtain the simulation results of the robot design, mobility and the different gait patterns, which verified the correctness of our robot model and the above analysis. Finally, the results of the analysis that are demonstrated in this thesis have been confirmed by experiments of a six-legged and a 10-legged robot. The experimental results show that the proposed design and analysis methodology effectively decrease the numbers of actuators installed on the multi-legged robot.

［様式－学 5］

博士論文要旨

論文題名：受動体節構造を有する多脚ロボットの歩行研究

立命館大学大学院理工学研究科
機械システム専攻博士課程後期課程

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ムカデなどに代表される多脚生物は，様々な環境に適応して，移動することが可能である．柔軟な土壌や起伏の激しい地形などの環境において，多脚の生物は高い移動適応性，耐故障性，高い移動性能が発揮する．多脚生物に似た多脚ロボットには多くの利点がある一方で，欠点も存在する．例えば，機構の設計および制御方法が６脚以下のロボットより複雑になる．これらの問題を軽減するために，本研究はまず水平面環境において，単純な構造及び最少アクチュエータを有しながら基本的な機能を持つ多脚ロボットを設計するための新しい方法論を提案する．

従来の多脚ロボットでは，各脚に 3 個のアクチュエータを必要としている．本論文では，各脚に１つのアクチュエータのみを用いた多脚ロボット構造を提案し，その制御方法をも検討する．この多脚ロボットが 2n 本の脚を有する場合，必要とされるアクチュエータ数は合計で 2n 個のみである．そのために従来の多脚ロボットと比較して，アクチュエータの数だけでなく，ロボットの重量も大幅に削減することができる．この多脚ロボットは n 個の体節と体節間に設置される n-1 個の受動関節で構成される．提案する多脚ロボットに従来の多脚ロボットと同程度の移動能力を持たすため，本ロボットをモデル化し，スクリュー理論に基づく解析方法でロボットが取りうる各姿勢を解析した．その結果を用いて，それぞれの姿勢で発揮される全方向への移動性能を検証した．また，能動的な脚関節の動作と受動的な体節関節を適切に組み合わせ，移動量の解析結果を基準に幾何学的な解析により全方向への移動原理を導出した．なお，歩容遷移の際の回転方向に関する様々な姿勢の支持状態の持続期間も検討し，障害物回避も実現できる新たな歩容および歩容遷移を得た．

計算機シミュレーションを用いて多脚ロボットの移動性能及び各歩容を検証した．また 6 本脚および 10 本脚の多脚ロボットの実機モデルを用いた実機実験より解析結果を検証した．実験結果より，提案した設計方法および解析方法が多脚ロボットのアクチュエータ数を効果的に削減するだけではなく，全方向への移動を可能にすることをも検証した．

本研究で得られた結果と知見は実用的な多脚ロボットの基本設計方法を提供し，体節間の受動関節を用いた移動方法は様々な環境に適応移動できる 2n 本の多脚ロボットの設計と制御の基礎になる．