Title	間接励起を用いた劣駆動リミットサイクル移動ロボットの運動解析と制御系設計
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論文の内容の要旨

Nowadays, locomotion robots have been considered to play more and more important roles in industrial and agricultural production, disaster rescue, as well as space exploration. Consequently, achieving stable and efficient locomotion on complex terrains becomes the most important property for locomotion robots. Slippery road surface, which induces a changeable grounding point, is one of the most difficult terrains for locomotion robots to overcome. Many remarkable locomotion robots have been proposed and developed to address this issue. Despite the success they achieved, however, the efficiency of their robots are not well guaranteed and they are difficult to be applied to real tasks due to the complicated sensing and control systems. Moreover, most of these robots have to walk very carefully in such a condition.

With the consideration of achieving stable locomotion on slippery ground with natural and simple gait as well as avoiding intricate sensing and control systems, a novel seed-like robot has been proposed and developed recently. Unlike walking robots stepping with legs, this legless robot generates sliding locomotion on slippery downhill by means of body rotation. A substantial advantage of this robot is that it positively utilizes the sliding locomotion, which is generally considered to be harmful to the walking robot. In contrast, a fundamental issue is that such locomotion can only be generated on the slippery downhill.

Towards achieving high-speed and energy-efficient sliding locomotion on the slippery level ground, indirectly controlling mechanism is applied to this robot due to the underactuation at the grounding point. Inspired by the vibration of viscera and carrying loads in biological systems, indirectly controlling mechanism has been proposed based on entrainment effect recently. Instead of manipulating any link of the robot, an active wobbling mass is attached to a limit cycle walker. The wobbling mass is forced to oscillate periodically, the robot locomotion system is, therefore, entrained to it. The implementation of this control method is easy, however, the resultant dynamics is complicated due to the high nonlinearity of it.

To better understand this control method, investigation on nonlinear properties, *e.g.*, entrainment, chaos and

hysteresis phenomenon, ought to be performed. Using a combined rimless wheel with an active wobbling mass (CRW) as a simple example, the detailed entrainment properties of such indirectly controlled limit cycle locomotion robots are characterized by Arnold tongue, where the size of it gives the range of entrained locomotion. The entrainability of the wobbling mass, therefore, can be measured by it. To observe various patterns of locomotion, quasi-periodic and chaotic gaits are observed by means of plotting the phase difference between the walker and the wobbling mass in one cycle. The sensitivity to initial conditions is analyzed by means of hysteresis phenomenon. Moreover, the basin of attraction, which estimates the stable range of the dynamics, is used to count the number of initial conditions leading to individual attractor. In view of these investigations, nonlinear properties of this indirectly controlled limit cycle walker are clarified.

To guarantee the rigorousness of this research, experimentally study is necessary to be conducted to verify the overall entrainment effect. An experimental machine is designed and produced to conduct real experiment. A tilted convey belt guarantees long time walking and the wobbling mass is controlled by EPOS2 controller for Maxon motor. The up-and-down oscillation of the wobbling mass is mapped to the rotation of motor by means of a piston crank mechanism. Most importantly, the walking period is obtained between adjacent ground collisions of one walking trial, which is measured via an accelerometer

MPU6050, inspired by the collision equation. Clean-cut Arnold tongue is obtained and the experiment results are highly consistent with numerical simulations.

Since the dynamics of the system is highly nonlinear, the equation of motion of this indirectly controlled limit cycle walker is approximated by a scalar phase equation for pursuing an optimal entrainment waveform to reduce the forcing energy. Here, the "optimal" is defined by maximizing the entrainment range with fixed energy. Since the step length of the rimless wheel is a constant, a larger entrainment range potentially leads to a higher frequency the walker could be entrained to, which consequently results in higher walking speed. To utilize the phase equation, phase response curve, which tabulates the sensitivity of the walker with respect to external disturbances, is numerically obtained by applying slight perturbations at different phases of the whole limit cycle. Afterwards, the cost function is obtained by maximizing the entrainment range with fixed forcing power. By applying calculus of variations on the cost function, the optimal entrainment waveform is analytically derived. As an ecological extension, an example of m : 1 entrainment waveform, which means during m cycles walking, the wobbling mass is required to make only one cycle, is numerically obtained. The analytical results are further confirmed by numerical simulations by comparing the sizes of Arnold tongues. The results show that the entrainment ranges are able to be magnified by utilizing a phase sensitive forcing function, where the specific Arnold tongue is able to be maximized accordingly.

Based on the processes above, this indirectly controlling mechanism has been well understood and can be applied to the seed-like robot to generate sliding locomotion on slippery level ground. Rather than serving as a rhythm generator only, the wobbling mass should also be able to generate enough propulsive force at the underactuated grounding point appropriately for inducing high-speed and energy-efficient sliding locomotion on level ground. The original rotatory wobbling mass is removed and an oscillatory wobbling mass is attached

to a point away from the center of the body to increase the asymmetry. This indirectly controlled locomotion robot slides backward and/or forward by means of the propulsive force at the grounding point induced by the oscillation of the wobbling mass and the periodicity of the locomotion is guaranteed by the body rotation entrained to the wobbling motion. Stable and efficient sliding locomotion on slippery level ground can be generated by this underactuated robot. Nonlinear analysis shows the dependency of efficiency on the entrainment effect. Moreover, the reason for inducing the entrained, however, inefficient locomotion is analyzed through mechanical energy consumption point of view. The results show that it is due to the unconcentrated sliding direction.

To further enhance the sliding velocity, three aspects are considered: 1. To concentrate the instantaneous sliding direction instead of wandering backward and forward. 2. To strengthen the propulsive force at the grounding point for increasing the sliding distance in one rotation cycle. 3. To maximize the entrainment range with an optimal trajectory for wobbling motion to exclude inefficient locomotion. Therefore, the robot is modified into an arc-shaped base with an elastic body, which is modeled by spring and damper, indirectly controlled by the active wobbling mass. The sliding velocity is dramatically in- creased benefited from the facts observed from analysis on nonlinear properties and energy consumption:

1. The instantaneous sliding direction is concentrated by damping force, since part of the redundant energy that leads to backward sliding can be consumed by it. 2. The sliding distance in one rotation cycle around the grounding point is increased by the anti-phase oscillation between the wobbling mass and the spring. 3. The entrainment range is enlarged, benefited from the elasticity of the body. In this case, sine wave is the optimal entrainment waveform since the spring’s oscillation is sinusoidal.

Keywords: Underactuated systems, Limit cycle walking, Entrainment, Stability, Efficiency

論文審査の結果の要旨

床面に固定されない移動ロボットは本質的に劣駆動な機械システムであり、その安定な運動生成においては一般に高度な制御技術が必要となる。特に低摩擦路面上の移動等、床面に対する力を印加することが困難な状況においては、身体形状や環境を含めた統合的なロバスト制御系設計法が求められる。また悪路に屈しない頑健な定常運動生成の実現においては、厳密な数学モデルや状態フィードバックを利用した精密な実時間制御よりも、不確定性を吸収できる内部発振器依存の運動制御が有利となる場合が多い。以上を踏まえ本論文は、身体内部に取り付けられた揺動質量の高周波振動が生む間接励起の効果に着目した頑健かつ効率的な劣駆動ロボットの前進運動生成理論、および移動機能の拡張と運動性能の向上に資する制御技術に関する基礎的考察を行ったものである。

第一に、上下方向に振動する能動的な揺動質量を取り付けた胴体フレームで 2 台の同一の受動リムレスホイールを繋いだ準受動歩行ロボットに関して、以下の成果を得た。吸引領域の評価指標としてアーノルドの舌を導入し、その面積を揺動の周波数と振幅をパラメ

ータとして最大化する最適制御入力を位相応答曲線に基づき決定する手法を提案した。また数値シミュレーションによる徹底した運動解析を通して、n:m 引き込み・分岐・ヒステリシス・移動効率等の自明でない歩行特性や非線形現象の変化傾向を明らかにした。更には、自ら開発した連結型リムレスホイールの実験機を用いて実機検証を行い、上記の理論的結果の妥当性を確認した。これらの結果は、身体構造の変更が困難な完成済みの移動ロボットの運動機能拡張を、簡明で汎用な機械要素の追加とその適切な制御により実現するという着想を具現化したものと評価できる。

第二に、円弧形状をした本体フレームとその内部に取り付けられた能動的な揺動質量から構成される匍匐型移動ロボットの運動生成問題に関して、以下の成果を得た。低摩擦な水平面上の匍匐運動生成に関して、単純ではあるが前後非対称な揺動を用いることで従来よりも高速な前進運動の実現に成功した。更に運動解析を通して得た接地点の摺動や本体の回転運動の特性に関する知見も考慮して、揺動の間接励起の効果を最大化すべく身体内部に粘弾性要素を追加した新しいモデルを提案し、期待された高速前進運動生成が実際に可能となること、特に自然周波数以上で 1:1 引き込みが達成される条件下において安定した高性能運動が実現されることを数値的に確認した。

以上、本論文は、劣駆動ロボットの移動制御技術に関する革新的かつ実用的な基礎理論および現実的応用手法を提案し、それらの有効性を示したものであり、学術的に貢献するところが大きい。よって博士（情報科学）の学位論文として十分価値あるものと認めた。