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学 位 論 文 題 目	Gait stabilization of a three-dimensional quasi-passive walker based on energy balance （エネルギー収支バランスに基づく三次元準受動歩行機の歩容安定化）
論 文 審 査 委 員	主査 教 授　鈴 木　聡一郎 教 授　柴 野　純 一 教 授　榮 坂　俊 雄 教 授　三 波　篤 郎 准教授　渡 辺　美知子

学位論文内容の要旨

A passive walker can walk down a gentle slope powered only by gravity without any actuator and control. Its similarity to human gait implies that human walking may sufficiently utilize passive dynamics, and passive walkers have high energy efficiency. Therefore, study of passive walking contributes to an understanding of the mechanism of biped walking and to design and control of biped robots.

Stable passive walking can be realized under the condition of appropriate design, appropriate initial state and appropriate slope angle. However, it is difficult to stabilize passive walkers in variable environments, such as a variable slope with different slope angles and elastic coefficient. Therefore, addition of some stabilization control is necessary to stabilize the walking gait of passive walkers. Some researchers have focused on actuation of the hip, ankle and knee. However, most of these quasi-passive walkers can only walk on flat ground. In the previous study, it has been experimentally demonstrated that synchronization of the period of lateral motion T_L with the period of swing leg motion T_S is a necessary condition for stable 3D passive walking, which is used as a necessary stabilization condition and is named period stabilization condition in this research. In the next step, a mechanical oscillator actuated by a stepping motor has been mounted on a 3D passive walker with spherical feet, and can roll in the frontal plane to control T_L and to synchronize T_L into T_S. The movement of the mechanical oscillator is always entrained into the lateral motion of the quasi-passive walker based on forced entrainment realized by Van der Pol oscillator, and the quasi-passive walker can be stabilized on flat ground.

However, the problems of excess or deficiency of input energy from the mechanical oscillator exist under uncertain ground conditions due to the determination method of the amplitude of the mechanical oscillator based on period stabilization condition. In order to solve the problem, This research proposes a gait stabilization method based on energy balance and examines the method numerically and experimentally under uncertain ground condition. In this stabilization method, the target path of the mechanical oscillator is determined based on energy balance and forced entrainment. The energy balance means that the input energy in periodic stable walking is transformed to the dissipation energy and the change in potential energy of the quasi-passive walker during one step. If energy balance is satisfied, the change in kinetic energy during one step is equal to 0, which means that the quasi-passive walker can keep periodic stable walking. The stabilization method based on energy balance has two advantages. First, since energy balance can be satisfied in different ground conditions such as downward and upward slopes, the proposed method based on energy balance can stabilize the gait of the quasi-passive walker under complex and even uncertain ground conditions. Second, the control method does not rely on a specific parameter of gait, so the quasi-passive walker under the control based on energy balance is robust to the sudden change of the gait caused by the change of ground condition. Moreover, the energy transformation and the energy transfer of walking are investigated, and it is found that the input energy is transformed into the mechanical energy consumption and the change in potential energy during periodic stable walking.

In chapter 1, the background of the research is introduced. In chapter 2, simulation model and experimental quasi-passive walker are introduced, and uphill-, level-waking and turn control methods based on stabilization control are proposed. The proposed methods are examined numerically and experimentally, and the results are indicated. In chapter 3, energy efficiency of downhill-, uphill- and level-walking are investigated numerically and compared with other biped robots and human walking. Energy transformation and energy transfer of walking are investigated to show the importance of energy balance for stable walking by using Open Dynamics Engine simulation. In chapter 4, a stabilization algorithm based on energy balance is proposed and examined numerically and experimentally under uncertain ground condition, and a direct method and an indirect method are proposed to calculate the input energy based on energy balance. Moreover, the dynamics of lateral motion of the quasi-passive walker is introduced, and the relation between the amplitude of the mechanical oscillator and mechanical work performed by the quasi-passive walker is investigated analytically based on the dynamics of the lateral motion of the quasi-passive walker. In chapter 5, the proposed methods including direct method and indirect method are examined under uncertain ground conditions. In chapter 6, some conclusions and findings of the research and future work are summarized.

論文審査結果の要旨

受動歩行の安定性に関する研究は、安定な二足歩行の原理解明のみならず、歩行ロボットの環境適応性の向上や省エネルギー化を目的としており、人間との共存・協調が可能なヒューマノイドロボットの実用化に大きく貢献するものとして近年注目されている。

本論文は、受動歩行の安定化を図る基本的方策として、生物の歩容生成に密接な関係があるといわれる神経振動子の機能を模擬し、歩行中の脚部の運動周期に引き込まれた、機械的振動子の往復運動で発生する力学的制御入力を利用する。とくに環境適応性の向上に主眼を置き、生物の感覚フィードバックを規範として、内界センサ情報から求まる歩行中のエネルギー収支に着目した受動歩行の安定化手法について、数値シミュレーションと実験の両面から検討した。その結果、本体の加速度変化と歩幅の情報からエネルギー収支を直接計算するDirect Method、ならびに振動子の振幅と前額面内の脚部の傾斜角からエネルギー収支を推定するIndirect Methodを提案し、歩行路の反発係数の変化に適応できることを示した。さらに未知の性状をもつ複合的歩行路に対してIndirect Methodの環境適応性が優位となることを明らかにした。これを要するに、申請者は受動歩行の安定化について、高い環境適応性をもつ生物の歩容生成メカニズムを規範とした新たな制御手法を提案しており、歩行ロボットの実用化に大きく貢献するものである。よって申請者は、北見工業大学博士（工学）の学位を授与される資格があるものと認める。