Title	早戻りリンク機構を利用した劣駆動移動ロボットの低摩擦路面上における前進運動生成と解析
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Motion Genelation and Analysis of Underactuated Locomotion Robot with Quick-Return Linkage on Slippery Road Surface

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Extended Abstract

Generally, adaptation to environment is an important ability for practical locomotion robots, moreover a slippery road surface is one of the most difficult environments for locomotion control. On the low friction road, it is difficult to generate stable locomotion with a direct propulsion applying system that obtains thrust by friction. In order to achieve a stable locomotion on slippery road surface, several underactuated locomotion systems utilizing the effect of indirectly controlled wobbling mass have been investigated. As a basic research on the underactuated-locomotion system, walking robots indirectly controlled by the inner wobbling mass oscillation were proposed, and the possibility of stationary motion generation was numerically and experimentally confirmed. Several limit cycle walkers do not have high adaptability to environment, hence they fall down when walking on the slippery road surface. With the consideration of preventing from falling down on slippery road surface, a sliding or crawling robot is a candidate for achieving stable locomotion.

As the fundamental research, a simple underactuated locomotion robot which consists of semicircular body frames and an inner wobbling mass was proposed, and it was shown that a motion generation and the moving speed control is possible on a downhill. The results showed a feasibility of a new locomotion robot using sliding effect at the grounding point and that generates stable forward motion using the inner wobbling.

Based on these observations, in this research, I deepen understanding a motion on a low friction road surface, and also aim to expand the operational scope of a new locomotion robot skillfully utilizing the sliding effect of the grounding point. A proposed robot is composed of semicircular body frame and quick-return linkage which is attached in the body frame, and it is achieved to generate forward motion on slippery level surface by using the asymmetric wobbling effect generated by the linkage.

Additionally, based on the analytical results, I clarify the dominant relationship of the dynamics among the force generated by the wobbling mass, the rotation motion of the body and the sliding on the grounding point, and also verify the validity of the numerical result utilizing an experimental machine. In addition, I designed an underactuated control system which is advantageous to increase the transfer efficiency.

First, I decided the specification of the robot about the body shape and the parameters, and derived the equation of motion of the robot model. Then, a motion generation is performed with the robot model to confirm the sliding and rotating motion changing by setting the parameters. Additionally, in order to confirm the effect of some parameters, I perform parametric analyses about the wobbling frequency, ω [rad/s], and the wobbling mass, m_5 [kg]. In the analyses, I confirmed some characteristics on the transformation of the moving speed when changing the wobbling frequency, and it is confirmed that the wobbling mass has little effect for increasing the moving speed in the hight frequency.

Second, I developed an experimental machine and environment which meets the specifications of the robot model with a purpose of verifying the analytical results. The experimental machine is composed of two identical bow-like frames, some connection frames and two quick-return linkages. Each quick-return linkage is driven by a direct current (DC) motor whose rotation speed is controlled by a control circuit. The rotation speed is controlled by using pulse width modulation (PWM) control, and the pulse width is calculated by a PID control. In the verification, I verified the validity of the numerical result, but the magnitude of the moving speed has a slight difference. This is caused by significant gap between experimental and numerical results on the friction model and the position of center of mass (CoM).

Third, I examined the following reasons of two characteristics in common between experimental and numerical results.

- The moving speed becomes unstable in a certain range near the resonance frequency.
- There is a positive correlation between moving speed and wobbling frequency in certain ranges, but the moving speed exhibits little change at enough high frequency.

In order to confirm the reason of the first characteristic, a model of an underactuated locomotion robot utilizing a flywheel was considered. The flywheel just affect the robot body as a torque. The numerical simulation shows, however, that the forward motion is generated according to the effect of the controlled flywheel motion. Therefore, it is considered that the first characteristic is caused by that the rotating motion becomes large near the resonance frequency. Then, to confirm the reason of the second characteristic, frequency analyses were performed on the numerical result. In these analyses, I considered two ways of the analysis which are bifurcation of the rotating motion and discrete Fourier transform (DFT). It is confirmed that the rotating motion has bifurcation in the low frequency band, thereby it is inferred that the natural frequency of the body and wobbling frequency coexist. On the other hand, the bifurcation became disappearing when the wobbling frequency approaches the high frequency band. To analyze the power spectrum of the rotating motion with DFT, it is confirmed that the natural frequency appears between the low frequency band and the middle frequency band. On the contrary, the natural frequency disappears in the high frequency band. It is inferred that the rotating motion is drawn to the wobbling motion and the natural frequency of the robot body becomes disappearing. Thus, it is considered that the second characteristic reason is that the forward motion is generated by wobbling effect in high frequency band.

In conclusion, the findings obtained are stated as follows.

- I decided the specifications of the underactuated locomotion robot with quick-return linkage, and then derived the mathematical model and the equation of motion.
- I performed numerical simulation and confirmed the changing tendency of the moving speed with respect to each parameter.
- I developed a prototype experimental machine which reproduced the specifications of the mathematical model.
- I performed an experimental verification with the prototype machine and confirmed that the changing tendency of the moving speed is consistent with the simulation results.
- It was confirmed that the rotating motion of the robot body produces a sufficient driving force in the forward direction.
- I confirmed that the change in the changing tendency of the moving speed is caused by the transition of the dominant dynamics.

By the findings, the following is necessary to generate an efficient forward motion.

- Mechanisms or control law to control the ground reaction force.
- Inner wobbling motion using a resonance phenomenon to excite the rotating motion.
- Control law of those timing.

In the future, I will develop a systematic design method for increasing the transfer energy efficiency, and reconsider the mathematical model of the friction to fill the gap between the numerical and experimental results obtained. In addition, I will investigate some extensions of the basic results obtained in this thesis to development of more versatile locomotion robots that can slide skillfully and efficiently by introducing novel techniques such as combination of multiple robots or cooperation with different type locomotion robots.