

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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Abstract

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 increased 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 springs oscillation is sinusoidal.

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