Title	時間対称な制御入力信号と引き込み効果に基づく2脚ロボットの高効率かつ頑健な歩容生成
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Abstract

Bipedal robots can operate in more restricted environments than multi-legged and wheeled robots, and most conventional bipedal robots are driven by actuators at each joint with precise joint angle control to follow a target trajectory for walking motion. In typical motion control methods for bipedal robots, the ZMP (zero moment point), the point at which the combined forces of gravity and inertia are projected onto the road, is the standard for stable walking, but it is commonly noted that this control method does not make excellent use of its own EI (embodied intelligence) to improve walking efficiency and to obtain a natural gait. Moreover, the robot requires precise real-time feedback control to achieve stable walking in a fully-actuated manner, which results in huge energy loss and cannot be sustained for long periods of time in real-world environments. Therefore, in recent years, numerous researchers have focused on how to use body dynamics to control robots to maintain efficient motion. The most significant challenge in this research direction is to improve walking efficiency while having available robustness.

By exploiting the dynamics dictated by the robot's body structure, the robot can not only considerably improve the efficiency of its motion but also considerably reduce its computational effort and thus the difficulty of control. Nonetheless, the fundamental problem with this approach is that the expected behavior of the system is highly dependent on environmental conditions, which leads to a lack of robustness. For example, a passive walking robot could use its body dynamics to walk down a slope in a deep natural way without any input. However, it can only function under the constraints of a suitable slope angle and ground friction. Another example is the CPG (central pattern generator), a local oscillatory network composed of neurons, which generates stable phase-locking relationships through mutual inhibition between neurons and produces rhythmic movements at relevant parts of the soma through self-excited oscillations. The CPG-based approach to motion control simulates the temporal sequencing of animal walking, which is a more natural approach for robotic motion control problems. However, an extremely large number of term conditions typically require attention when constructing CPG models, resulting in control methods that are still not concise enough.

In this paper, the author aims to explore more underlying mechanisms of walking and achieve a more simple and more efficient method of motion control for bipedal robots. We can draw on two signal systems acquired by humans during evolution, namely the first and the second signal system. A similar classification of signal systems can be made for the generation of robotic motion. The former is used to reliably generate and maintain elementary motions, while the latter is used to adapt flexibly to complex environments where each system operates in a shared and coordinated manner. First, a minimalist compass-like bipedal robot where only the hip torque can be applied, so the robot is an underactuated system. Here the bipedal robot can be made to walk efficiently and stably on downhill as well as horizontal surfaces by means of entrainment effects, using a reasonable feedforward input waveform (e.g., a sine wave). It can be regarded as the motion generation of the control signal (first signal system) generated at the level of human reflexes without any feedback control, which greatly reduces the cost of control. At the same time, step length, walking frequency, and walking speed, which are important indicators of walking within the entrainment range, can be simply tuned by controlling the parameters.

To ensure the practical feasibility of the proposed method, it is necessary to conduct an experimental study to verify whether entrainment effects can successfully control a robot to generate dynamic walking in a realistic environment. A bipedal walker was designed and fabricated to allow for practical experiments. The control method is consistent with that used in the simulation, where a designed planetary gear mechanism is used to complete gait generation on a horizontal road surface by feeding a preset feed-forward waveform through a hip-only servo motor. It should be noted that in order to avoid gait failure due to foot scuffing while swinging the leg, the rotator foot is designed to circumvent it. Although the 1:1 entrainment between the input waveform frequency and the actual

walk frequency is only achieved due to hardware conditions, the experimental results are in good agreement with the numerical simulations.

In order to pursue higher walking performance, such as high-speed walking, and to obtain the highest energy utilization while limiting the walking speed, the author performs a global optimization of the control parameters, as well as the physical parameters of the robot itself, by means of Bayesian optimization. The results show that the fastest walking speed occurs in a 2:1 entrainment waveform when only the control parameters are changed, while the fastest walking speed can be achieved in a 1:1 entrainment waveform after optimizing the foot shape, which indicates that the structural design of the robot itself, such as the foot shape and the overall center of gravity distribution, is also important. The results for walking efficiency show that while maintaining a walking speed of 0.5 [m/s] or more, SR can be as low as 0.007 (lower values indicate higher walking efficiency) by the proposed control method, which is much lower than the current robots by conventional control methods and even better than humans.

In bipedal dynamic walking, one also usually expects the gait to converge to a limit cycle gait. From another point of view, the most basic requirement for achieving stable bipedal walking is not to fall, which requires a large BOA (basin of attraction) to tolerate disturbances. Chaotic oscillators tend to have larger basins of attraction compared to the limit cycle. Correspondingly, it is hypothesized in this paper that a properly generated chaotic bipedal gait due to entrainment effects may be more robust to perturbations such as walking on uneven ground. Based on this consideration, a chaotic gait is generated by employing a typical chaotic oscillator Rössler attractor. It was shown that the chaotic bipedal gait has a larger BOA than the limiting periodic walk with the same input strength, and the domain of stable walking was further explored by varying the control parameters of the chaotic bipedal gait.

Work so far has focused on exploring the robot's walking conditions under the first signal system and generating relatively stable and efficient gaits. The judgment of more complex road conditions requires advanced signal processing capabilities corresponding to a second signaling system. The present work lays the groundwork for further research, not only by enabling bipedal walking on uneven ground with extremely simple control methods but also by showing the positive side of chaos in dynamic walking and providing a new perspective on the stability of bipedal gait.

Keywords: Bipedal robot, Passive walking, Entrainment, Rimless wheel, Semicircular feet, Chaotic gait, Stability, Efficiency