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| Title | 粘弾性脚を持つ歩行ロボットの歩容生成と不整地適応に関する研究 |
| Author(s) | 河本，隼治 |
| Citation | |
| Issue Date | 2012-03 |
| Type | Thesis or Dissertation |
| Text version | author |
| URL | http://hdl.handle.net/10119/10400 |
| Rights | |
| Description | Supervisor:浅野文彦，情報科学研究科，修士 |

# Gait Generation and Adaptation to Irregular Terrain of Viscoelastic-legged Walking Robots

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February 6, 2012

**Keywords:** Limit cycle walking, Gait generation, Double-limb support, Viscoelasticity, Irregular ground.

Limit cycle walking including passive dynamic walking originally studied by McGeer is a novel approach to gait generation and has attracted attention as an effective strategy to energy-efficient walking. Passive dynamic walking is a phenomenon that a simple legged robot without any actuators can walk down a gentle slope only by using the gravity effect. The generated gait is natural, energy-efficient, and human-like. This suggests that a walking gait emerges naturally and passively by utilizing the inherent dynamics of human body, and that a stable gait can be easily generated without any control torques for stabilization. The stability of the generated gait is, however, not robust and sensitive to the initial conditions, physical parameters, and disturbances. Achieving stable walking on bad surface conditions such as sand area, mud lake, and snowy road is necessary for robotic dynamic walkers from a practical application standpoint.

Limit cycle walking is generally modeled as a nonlinear hybrid dynamical system including state jumps; which consists of the robot equation of motion and transition equations at impacts. The equation of collision is traditionally developed as a perfectly inelastic collision model on the assumption that the previous stance-leg (rear leg) leaves the ground just after landing of the next stance-leg (fore leg). In this case, the stance-leg exchange is completed in zero time. The period of double-limb support

(DLS) then vanishes and the continuous motion consists only of the period of single-limb support (SLS). In the case that limit-cycle walkers with rigid leg-frames walk on the rigid road, the validity of this model has been confirmed in many studies of experimental walkers.

The mathematical model of rigid-legged walkers has also been criticized from a biological standpoint. In human walking, the period of DLS accounts for more than 10% of one cycle. In contrast, the period of DLS does not exist in limit-cycle walking. The properties of DLS must have great effects on the creation of natural, efficient, flexible motion in human walking. Also in robot walking, DLS would play important roles in enhancing and improving the gait efficiency and stability.

Based on the observations, in this paper we investigated modeling, analysis, and control of limit cycle walking including DLS. As the model for limit cycle walking that emerges DLS, we introduce rimless wheel and biped models with viscoelastic legs. First, we observe an experimental passive dynamic walking on a treadmill and confirm that there is a period of DLS during motion. We then reconsider the traditional collision model and develop a new one which is modeled on the assumption that the rear leg does not leave the ground even if the fore leg hits the ground. We numerically show that this model generates stable passive gaits including DLS on a gentle slope and analyze the basic motion properties. Second, we attempt level dynamic walking by adding an upper body and control torque that exerts between the fore leg and upper body. We numerically show that this model can generate stable gaits by applying an output following control for maintaining the upper body upright. Third, we consider an extension to a bipedal model with an upper body. We numerically show that the model can also achieve level dynamic walking by applying the motion control of the swing leg together with the upper body control. Furthermore, we investigate the adaptability of viscoelastic-legged walkers to irregular ground such as steps and flexible surfaces. The models of flexible surfaces are represented by simple linear spring-damper systems. It is numerically shown that the viscoelastic-legged model has an advantage in overcoming steps and adaptation to flexible surfaces over the rigid-legged model. The validity is also confirmed by experiments.