Title	遊脚着地時の運動エネルギー損失の低減化を考慮した劣駆動2脚ロボットの歩容生成と制御
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Gait Generation and Control by Underactuated Biped Robot with the Consideration of Reducing Energy Lost at Landing Moment of Swing Leg

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At the moment of ground landing of the swing-leg during the robot locomotion, ideally, if the relative velocity between the swing foot and road surface is zero, the collisionless walking will be achieved. Since collisionless motion can avoid kinetic energy loss at ground landing moment in each step, the total mechanical energy of the system is conserved. Therefore forward locomotion can be generated even without any input theoretically. Moreover, stable walking can be expected where no external disturbance caused by collision exsists. However, for an underactuated biped robot, such kind of locomotion is hard to be achieved due to the increased DOF (degrees of freedom), which led it remain a crucial problem since last century. In the field of collisionless walking, few studies on bipedal robots exsist. Moreover, studies on dynamic analysis of collisionless walking leaks either. Ignoring the achievement of the group of M.W. Gomes which enabled collisionless walking without any constraint by introducing a rimless wheel with an internal energy conservation mechanism, the general solution for generating collisionless walking has not been solved until now.

The most important issue for generating continuous collisionless walking is to make the relative velocity between swing foot and ground surface at landing moment in each step zero, *i.e.*, the velocity accelerates from zero and decelerates to zero again. Therefore, the energy efficiency is inherently low. In addition, the resultant state of zero dynamics must be return to the initial state after finishing each step, otherwise the robot has a risk to fall down due to the accumulate error. Therefore, advanced methods and theoretical analysis from mathematical point of view is necessary.

Based on these considerations, in this research, we used the model without feet which means there is only one contact point between swing leg and the ground. Without ankle-joint torque, the robot will be more underactuated. This research also establishes the control methods from system dynamics analysis point of view via derivation of mathematical equations. We formulated the problems from a simple 2-DOF rimless wheel with a torso to a 7-DOF underactuated biped robot, the analysis goes over from gait generation to control mechanism and discusses the maximization of energy utilization.

The research starts from mathematical modeling of a 2-DOF rimless wheel with a torso. First, we establish the equation of motion and consider the constraint force. Second, we set the absolute angular acceleration of rimless wheel as the target to be tracked, and obtain the linear relationship between the control input and the output. Third, we propose the control methods from both discrete and continuous points of view for the system dynamics. In order to get the target trajectory, the system dynamics is discretized, and the second order derivative of the target trajectory is calculated by the state-space equation. Fourth, we proved the stability of the collisionless walking gait generated by this simple underactuated system. By calculating the equation of motion, we can figure out all the motion states after one step mathematically, and find the corresponding conditions to generate the collisionless walking. Through the analysis of the motion state, we verify that the stability of the robot without collision at landing moment was low, and proves that without specified initial conditions, the robot is not able to return to the initial ones after one step. Fifth, the model was extended to more complicated high DOF underactuated biped robot model. In the bipedal robot model, we utilized the results obtained from the rimless wheel model and focused on the control method of achieving clearance between the swing-leg end and ground during the stance phase. In this control method, we refer to the asymmetrical function F_d to control the angular acceleration of swing leg during motion. By changing the parameters of F_d, we can well control the swing-foot clearance. Sixth, we applied the results to a bipedal robot with an upper body. The general problems are discussed and solved mathematically, such as the necessary clearance between the swing foot and road surface during motion, and the relationship between achieving collisionless walking and the upper body are analyzed via numerical simulations. The results imply that the stability is reduced by adding the upper body to the biped robot.

To find the effects of the upper body on the collisionless walking, the solution of generating collisionless walking is based on the linearization methods of a 2-DOF rimless wheel with a torso. Therefore, the equation of motion is linearized, the linear relationship between the target trajectory and all the motion states is obtained, and the necessary conditions for the steady walking is sought. By means of the obtained motion, the numerical solution of the necessary conditions for steady walking in nonlinear systems is determined. The necessary conditions are explored from mathematical and physical points of view. To relate the linear and nonlinear systems, double support control method is proposed, which enables the system to become fully actuated to eliminate the error. Here, the legs are mainly fixed, on the basis of standing, and control the torso alone to return to initial states. Finally, all of the above results are extended to a human-like underactuated robot with torso and knees, to realize some specific gaits, *e.g.*, overcoming the obstacle by adjusting the knee angles. In this case, with the increasement of DOF, the stability of the robot decreases dramatically. In control mechanism, the target trajectories of the active joints are designed specifically to achieve collisionless walking, as well as overcoming the obstacle. However, some uncontrollable DOFs like the torso, can not be as stable as before. Therefore, double support control method is necessary in the case of low stable condition.

This research established the systematic model of collisionless walking from 2-DOF to high DOF underactuated biped robots. The system dynamics and specific locomotion are analyzed. An ideal solution for maximum utilization the consumed energy are achieved and the stability of collisionless walking is proved, which makes a contribution to further analysis of collisionless walking by establishing a mathematical framework.