Title	床面との滑り接触を考慮したリミットサイクル規範型脚移動ロボットの歩行運動生成と解析
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Gait Generation and Analysis of Limit Cycle Walking Robot on Slippery Road Surface

Tetsuro Fujimoto (1310063)

School of Information Science,
Japan Advanced Institute of Science and Technology

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Passive dynamic walkers can walk on a gentle downhill without any external energy souses and the generated walking gaits are natural and energy-efficient. Robotic walkers that walk on level ground by using small control inputs, so-called "limit cycle walkers", also generate energy-efficient gaits as a stable limit cycle by exploiting inherent passive dynamics. Such walkers, however, cannot adapt to various surface conditions such as mud and snowy road in return for the high efficiency. It is generally difficult to achieve both high efficiency and high adaptability in limit cycle walking depending in large part on the robot natural dynamics. Recently, however, the effects of a passive wobbling mass have been attracted as a novel passive mechanism that can improve the gait adaptability without decreasing the gait efficiency and naturalness. Tanaka studied the gait properties of a passive combined rimless wheel (CRW) that has a passive wobbling mass in the body frame, and clarified that the effect of the wobbling mass incorporating spring and damper improves the walking speed and gait robustness. Akutsu also studied passive bipedal walking with the effect of a passive wobbling mass connected in parallel to the leg frame, and showed that the wobbling mass can improve the gait properties.

First, I introduce the model of a CRW for analysis of passive dynamic gaits generated on a slippery downhill. The CRW consists of two identical

RWs and a rigid torso link. The two RWs are connected by the torso and rod, and they rotate in synchronization during motion. Developing the numerical model, I solved the equation of motion and collision equation. Since a passive dynamic gait of the RW always becomes asymptotically stable and period-1, the CRW also behaves in the same manner as the single RW. I then add a passive wobbling mass to the torso link with the spring and damper and investigate how the gait properties change according to the dynamical effects by checking the numerical simulation result of walking speed. I conduct numerical simulations to observe the fundamental properties of the generated passive dynamic gaits of the CRW with the wobbling mass. I numerically show that the effect of the wobbling mass improves the gait efficiency.

Second, I introduce the model of an underactuated biped robot with an upper body that achieves constraint on impact posture by strict output following control. The most different feature of this model is existence of a swing leg motion. It is known, however, that biped walkers with a swing leg can behave similarly to the passive RW if they can fall down in the same posture immediately before every impact. I show that the underactuated bipedal walker can walk on a slippery downhill by achieving constraint on impact posture by the numerical simulation. I also analyze the change tendency in the gait properties with respect to the system parameters. Furthermore,

This paper contains three parts of study topics. First is investigation of the gait of CRWM(Combined rimless wheel with wobbling mass) on enough static friction slope. Second is investigation of the gait of CRWM on slippery slope. Third is investigation of the gait of the biped robot with upper body.

In the first topic, I simulated the walking gait of CRWM on the enough static friction surface. Leg exchange is modeled for inelastic collision. The result says that the wobbling mass increases walking speed, which is corresponds with previous research. It is also shown that wobbling mass makes the robot able to generate a gait more gentle slope. In other words, wobbling mass makes the robot generating the gait with more lower energy, because step length of RW is constant. The wobbling mass has been thought that the mechanics of getting faster with wobbling mass are two cases.

One is flattening of the COM. The wobbling mass move as the path of the COM would be flattened. The other is getting the COM shaking harder. In the both case, we can consider that the wobbling mass helps the robot to overcome the potential barrier. To check them, I defined TOD (total oscillation distance of COM) which is able us to check how hardly COM is shaking with the quantification. By comparing the value of TOD through numerical simulation, I got the result that the wobbling mass getting the robot two cases, and this result is correspond with previous consideration. I checked the two cases of contribution of the wobbling mass. In the both case, the wobbling mass generally increases the walking speed.

In the second topic, the walking gait of CRWM on the slippery road was simulated. In this paper, the slippery road is defined for the condition which includes only dynamic friction. Leg exchange is modeled for inelastic collision. I conduct the numerical model to getting numerical simulation. In the result where $\mu_0 = 0.50$, the sliding distance during one step is much more smaller than a step length. Then I get the result that robot could generate the gait to moving forward even if it is on the slippery road. I discussed through comparing with locked condition which is the case that the wobbling mass is fastened to torso to avoid wobbling mass from shaking. The condition which is the case that the wobbling mass can shake up and down (wobbling condition) is more faster than locked condition. Furthermore, I get the result that two cases which are the cases of the contribution of the wobbling mass are there in common with non-slip condition. I also checked limit cycle walking gait.The result revealed that the wobbling mass makes the robot faster than the locked one. I also checked the two cases. One is getting the path of COM more shaking. The other is getting path of COM more lower.

In the third topic, the walking gait of the biped robot with upper body on the slippery road was simulated. By using following output control, I found that two types of gait would be generated by choosing the speed of swinging of legs. It is skipping gait. The skipping gait of the based on passive dynamic robot is reported by Asano et al. by using RW. They found RW generate the skipping gait with the fast rotation of torso. My result is revealed that same situation make the other based on passive dynamic robot generating skipping gait. The result of limit cycle walking or skipping gait revealed the three tendencies. First, the step period has the consistent tendency to go on with swing speed of legs more slower even if they include the skipping gait. Second, the step length doesn't have the consistent tendency while walking and skipping gaits. Thirds, the walking speed has the consistent tendency while two types of gait. The walking speed get more faster with more fast speed of swinging legs while two conditions.

Finally, I revealed them that the CRWM and biped robot can generate the walking gait on on the condition of the the slippery road, the equipping wobbling mass is efficient way for CRW even if on such the condition, and biped robot can generate two types of gait, which characteristic has been founded for RW.