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# Motion Analysis and Control of Underactuated Locomotion Robot Utilizing Effects of Sliding and Wobbling

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Recently, some fundamental investigations on the possibility and stability of passive-dynamic walking have been conducted. By using simple Coulomb friction model, it was rimless wheels and compass biped robots can generate stable passive locomotion on slippery downhill. The holonomic constraint conditions in these models is only 1-DOF constraint in both the single-support and collision phases. In addition, it was revealed that within a certain range of the dynamic friction coefficient, the system demonstrates the same dynamic characteristics as the case without sliding contact when slipping for a short period immediately after replacement of the support leg. These research results indicate that it is possible to achieve walking motion more naturally than general passive walking. Furthermore, in some similar previous researches, the control law incorporate with sliding motion at ground contact points achieved the desired pose. They, however, cannot be applied to all kinds of friction due to using only a parameter demanded experimentally.

Based on these researches, I achieved a deeper understanding about the motion when the body of the robot makes a contact with the slippery downhill. Then, in this research, I explored feasibility of a new mobile robot, which can take advantage of the sliding at the contact point. The proposed robot is composed of two identical arc-shaped body frames and a wobbling mass of a single-link attached inside the body frame. This achieves downward motion on the downhill via using the dynamic characteristics generated by the high frequency oscillation of the wobbling mass. In this research, using this simple model, I clarified the basic changing tendency of robot motion characteristics with respect to system parameters.

Furthermore, based on the analysis result, I also clarified the dominant relationship among the three dynamics of oscillation of wobbling mass, rotation of body frame and sliding at ground contact point. Last, I verified the validity of the theoretical results by using the developed machine.

First, I specified the physical parameters of the underactuated locomotion robot and derived the mathematical model. Based on these, to investigate the main relationship between the rotational motion of the robot and the oscillation of the wobbling mass, I verified that the motion can be generated by numerical simulation at first. Next, I numerically analyzed the change of the moving speed of the robot with the increasing of $\omega$. As a result, it was confirmed that moving speed is increased with the growth of $\omega$. Next, I numerically analyzed the change of the moving speed when changing the robot's frame radius $R$ and the centering angle $y_0$ of the wobbling motion. The result of this is that there was fairly any change in moving speed when changing $R$. And, it was confirmed that the movement speed changes with respect to $y_0$. This change tended to occur periodically, and peaks of moving speed were observed around $0.25\pi$ and $1.25\pi$. I then numerically analyzed the change of the moving speed with respect to the length of the wobbling mass, $b$. The result demonstrates that the moving speed has a positive correlation with $b$.

To verify the validity of these analysis results, I developed an actual machine. Preliminary experiments were carried out using this actual machine. However, as contacting with the edge of the rail caused frictional resistance more than expected, unexpected oscillation and some other phenomena occurred. Therefore, the frictional resistance increased, and it was impossible to achieve the ideal operation of the machine. Based on this, I added the following specifications and designed the parts of the machine.

- Variability of center of mass (CoM) position
- Simple adjustment of weight and length of wobbling mass

- Suppress the motor vibration
- Improve maintainability of machine

To satisfy these specifications, it is possible to adjust the CoM with a frame that allows parts to slide above it. Furthermore, by arranging the wobbling mass on both sides out of the frame, the bias of CoM is eliminated. This change makes it easier to adjust the weight and length of the wobbling mass. In addition, by changing the direction in which the slider crank mechanism operates, the wobbling effect can be obtained better than the conventional mechanism. Although I checked the operation using this, a phenomenon causing the operation becomes unstable was observed. The first reason may be a load applied to the slider crank mechanism. The part mainly performed unstable motion is the slider section of the slider crank mechanism. To achieve light weight and simple mechanism, a holding method by one side support was adopted, ignoring the fact that it is easy to deform with high load. As the mass wobbles, the acceleration changes instantaneously, so a large force is generated. Furthermore, the slider crank mechanism has points, such as top dead center and bottom dead center, where the greatest load is applied. Since the direction of the mass oscillation is changed at these points, it can be inferred that a large force is generated by a change in the acceleration. Also, since deformation occurs, a phenomenon is also observed in which the rack gear does not transmit its motion away from the fair lock gear. The second reason is the lack of lubricity for smooth operation of the mechanism. Therefore, reinforcement of slider crank mechanism and mounting of new parts were carried out. Finally, it was possible to generate motion similar to simulation, and change of each parameter became easy.

Above, I confirmed the stopping operation problem of the robot due to the experimental environment, so I improved the environment. It was the problem that some things like the height of the rail and the frictional resistance were not uniform. The reasons are the errors of parts themselves, the placement of parts, and differences in the states of the material surface. Therefore, solution was carried out by adjusting the height of the rail and installing square rods. As a result, it enabled experiments in this environment similar to simulation. For the machine, its natural frequency and natural angular frequency were clarified, and it was confirmed that the possibility of destruction by sympathetic vibration is low.

Experiments were carried out on the machine, and it was confirmed that the peaks of moving speed appeared in the same place as simulation, but other places are different. The reason is considered to be the ground reaction force generated by the acceleration of the slider crank mechanism. It is necessary to measure the floor reaction force generated in the machine and apply it on the mathematical model. Moreover, from the experimental result, it was confirmed that the moving speed changes when changing the wobbling mass. In the end, I considered about the control of the robot, and speculated that speeding up by tuning several parameters such as wobbling frequency and ground reaction force. It is possible to control the moving speed by using those parameters.

If this control is completed, it can be expected that the development of mobile robots which can utilize slipping effectively, and walking aid machine which can reduce slipping in the future.