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Generation of Sliding-resistant Stealth Walking Gait on Descending Stairs Based on Angular Momentum Constraint Control

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Adaptability in various environments is an essential ability for locomotion robots to work in the real environment. In particular, a slippery road surface is one of the most difficult environments to generate stable locomotion. In general, a limit-cycle gait consists of continuous single-support motion and discontinuous state jump at an instant of stance-leg exchange. Since the overall motion is essentially stable, and it can be generated only by setting the initial state and restoring mechanical energy appropriately. In return for the easy control, however, the adaptability to irregular terrains such as a slippery road surface is low. In order to solve this problem, a different approach considering the surface condition is required.

Aiming at adaptation to various environments, Asano proposed a novel method of stealth walking (SW) that can generate an underactuated gait completing in one step and can reduce the loss of kinetic energy caused by fore-foot landing to zero. He also extended the basic method to strict stealth walking (SSW) for achieving stable SW on a frictionless road surface. He proposed the method of angular momentum constraint control (AMCC) to maintain the horizontal ground reaction force to zero during motion. SSW achieves both SW and AMCC simultaneously which is an ultimately careful walking motion opposite to limit-cycle walking which is an ultimately careless walking motion. In addition, SSW is an elaborate walking motion humans and animals cannot achieve because it is generated by precise control without any uncertainties only. Therefore, SSW is essentially unstable, and the motion of zero dynamics such as the upper body, which is not explicitly controlled, is determined resultantly.

In previous research, the underactuated robot with 2 degrees of freedom (2-DOF) which consists of a rimless wheel and an upper body has an ability to avoid sliding on the frictionless level surface utilizing SSW. On uneven terrain, however, this control problem has not been discussed. In an actual environment, it is necessary to adapt not only to the horizontal surface but also to the road surface with height difference such as frozen stairs. In order to achieve SSW on any road, it is necessary to satisfy the following three conditions.

1. The relative velocity between the forefoot and the ground must be controlled to zero at the instant of landing in each step.

2. The horizontal speed of the whole center of mass position of the robot must be maintained to constant during the single-support phase.

3. The resultant state of zero dynamics must become identical to the initial state.

In particular, since the resultant state of zero dynamics is greatly affected by the nonlinearity, achieving SSW on the uneven terrain is more difficult than on a level surface.

In this research, in order to increase the adaptability of walking robots, I aim to achieve SSW on the frictionless descending stairs. In the previous studies of SSW, an underactuated robot that consists of a rimless wheel and upper body was considered. In this thesis, I propose a new robot with a reaction wheel added to the previous robot.

First, I investigate the influence of nonlinear factors when descending the high friction stairs through simulation utilizing the 2-DOF model. Since the resultant terminal state of the upper body becomes different from the target initial state in the nonlinear model, I proposed a method for correcting the gap during the double support phase (DSP) while maintaining double support.

Second, I extended the mathematical model to the frictionless descending stairs. Based on the linearized 2-DOF model, I attempted to achieve SSW without including DSP by setting the initial state of the upper body appropriately. A SSW gait, however, could not be achieved. This is considered that there is no trajectory of the upper body which simultaneously satisfies both the above conditions (1) and (2) which are required by SSW. The upper body controls the whole center of mass of the robot, but regarding the rimless wheel, the difference between the angular velocity and the velocity of the center of mass increases with the tilt angle. In addition, I considered that the gap appears between the initial state and the terminal state by the asymmetry of the robot motion. Therefore, I finally concluded that it is impossible to achieve the SSW on the frictionless descending stairs with the 2-DOF model.

Third, I considered increasing the degree of freedom of the robot to achieve AMCC and control of the support leg simultaneously. Then, I introduced a 3-DOF model that added a reaction wheel to the 2-DOF model. Based on the linearized 3-DOF model, I conducted searching the initial states of the upper body and reaction wheel by using a bisection method. Although the reaction wheel does assist the upper body, its initial angular velocity does not affect the dynamics of the upper body, and hence it is possible to search the initial state. The reaction wheel successfully supports the trajectory-tracking control of the rimless wheel while achieving AMCC. After achieving the generation of SSW by searching the initial state, I investigated the relationship between the mass of the upper body and the tilt angle of descending stairs.

In this research, I performed the following matters.

- I derived the equation of motion of the 2-DOF model.
- On the high friction descending stairs, I confirmed that SSW can be achieved by including DSP with attention to ZMP.
- I extended the method of SSW to the frictionless descending stairs and confirmed that a SSW gait cannot be generated even if the DSP motion is included.
- I added a reaction wheel to the 2-DOF model and derived the equation of motion.
- The initial states of the upper body and reaction wheel could be successfully identified by using the bisection method.
- I investigated the relationship between the mass of the robot and the tilt angle of descending stairs.

In conclusion, I obtained the findings described as follows.

- In the 2-DOF model, SSW could not be achieved on the descending stairs.
- By increasing the mass ratio of the upper body in order to suppress its movement, it was possible to adapt to the descending stairs having a more inclined angle.
- Although SSW is highly adaptable to the environment, zero dynamics diverge when it deviates slightly from the appropriate initial state.

At present, only numerical analysis is performed and it is not verified whether the robot can achieve SSW in the real environment. In the future, the proposed 3-DOF robot is expected to be used in the real environment. As can be seen from limit-cycle walking and SSW, stability and adaptability are a trade-off. In order to put the SSW into practical use, it is necessary to further improve the stability. For example, by increasing the degree of freedom of the upper body, it is expected that the robot can achieve a gait motion on the stairs with a different inclination for each step. I believe improving the stability of SSW is the most important task to improve availability in the real environment.