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Generation of Strict Stealth Walking Gait for Biped Robot and Improvement of Walking Performance

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Adaptation to various terrains is an important issue for a walking robot to work in the real environment. In particular, stable walking on slippery road surface is one of the most difficult tasks for walking robots and has been discussed many times. The famous gaits currently being studied include passive dynamic walking and limit cycle walking. These walking achieve high-efficiency gait with simple control and mechanical energy. However, it only provides simple control and it cannot adapt to irregular terrain such as slippery road surface and fall over quickly. Therefore, walking on irregular terrain requires a different approach.

Asano has proposed stealth walking (SW) to achieve walking on irregular terrain. SW is a form of legged locomotion that is completed in one step and does not include collision. Since this walk does not include a collision, there is no energy loss due to landing on the foot, and it is expected to be applied to walking on uneven terrain. Furthermore, Asano has proposed strict stealth walking (SSW) by extending SW. He proposed angular momentum constraint control (AMCC) based on the relationship between angular momentum and horizontal ground reaction force, and achieved on low friction road surface. These locomotion are very careful walking, as opposed to relaxed walks like limit cycle walking.

In previous studies, SSW gait was achieved by an underactuated rimless wheel (URW) with an upper body. Using SSW gait, it achieved a smooth walking on a frictionless road surface. In addition, by using the reaction wheel as well as the upper body, SSW on the downstairs is achieved. However, all studies to date have been performed using rimless wheels, and studies using on bipedal robots have not been fully discussed. In order to apply SSW gait to real walking robots, it is essential to study SSW gait for biped robot. In addition, SW is inefficient due to careful walking, and there has not been enough discussion to solve these problems. In this paper, I realize SSW gait for biped robot and explain how to increase the efficiency of the generated SSW gait.

First, I analyze a biped robot with an upper body and apply AMCC to enable walking on a frictionless road surface. To generate SSW gait with a biped robot, the following conditions must be satisfied.

- The speed of the swing foot must be zero at the moment of landing.
- The horizontal ground reaction force generated at the stance leg must always kept at zero.

- The state of zero dynamics must match the initial state at landing.

In URW, it was not necessary to consider swing leg motion, but bipedal robot cannot generate forward motion without careful consideration of swing leg motion. So the problem of zero dynamics is more complicated than URW. Therefore, in order to satisfy all of the above conditions and realize SSW gait in a biped robot, stricter and more complicated control than URW is required. In this study, the above conditions were satisfied by designing a control system that keeps the the horizontal ground reaction force to zero while strictly controlling the hip joint angle of the robot. In addition, the linearized model was used to solve the problem of zero dynamics, and the parameters obtained from the linearized model were used to match the state of the zero dynamics after walking was completed with the initial state. The generated gait satisfies all the necessary conditions for SSW gait, and the biped robot successfully generated SSW gait.

In this study, I also analyzed the efficiency of SSW gait. As mentioned earlier, SSW gait has very strict control and is inefficient. I suggested changing physical factors, such as adding elastic force or changing the shape of the foot, to increase the efficiency of SSW. I succeeded in increasing the efficiency of SSW gait by changing physical factors such as adding elastic force and changing the shape of the feet. For a robot with semicircular feet, the grounding point of the stance leg always moves due to the rolling of the semicircular feet, so the relationship between the angular momentum and the floor reaction force as in the past did not hold. Therefore, a control system was designed using the relationship between the ground reaction force and the position of the center of mass of the robot. The new robot's SSW gait was successful with the resulting control system and analysis solution. As a result, analysis of the semicircular feet showed that a control system designed by linearizing the horizontal ground reaction force's equation yielded an analytical solution equivalent to AMCC. However, it was difficult to find a symbolic analytical solution due to the influence of the semicircular feet, and it was extremely difficult to analyze both linearized and nonlinear models.

This research has clarified the following.

- SSW gait was generated in a biped robot with an upper body.
- An approximate solution was derived using a linearized model, and based on the solution, a binary search was successfully performed using a nonlinear model.
- The relationship between elastic force and SSW gait was analyzed.

- The numerical solution equivalent to AMCC was found to be obtained by linearizing the relational expression between the ground reaction force and the position of the center of mass.
- The effects of the semicircular feet made it difficult to analytically analyze both linearized and nonlinear models.
- It was analyzed that elastic force and semicircular feet are effective in improving the efficiency of SSW gait.
- The 3-DOF model achieves SSW walking with two inputs, but because of the large impact of zero dynamics, analysis becomes difficult when the mathematical load is large.

Future work is to be achieved by a real robot. There have been several studies on SW gait, including this paper, but experiments and discussions with actual robots have not been performed sufficiently yet. In addition, I discussed how to improve the efficiency of SSW gait, but it is also important to discuss how to improve stability. The SSW gait has a very strict condition that the horizontal ground reaction force at the ground contact point of the stance leg must be kept at zero, and If this condition could be mitigated slightly, the load on the control input would be reduced. Another task is to achieve SSW on irregular terrain using this robot. To generate a stable SSW gait in various terrains and conditions, it may be necessary to increase the input as in previous studies. To find the right analytic solution for the nonlinear model, improving search algorithms is also important.