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High-speed Stealth Walking Gait Generation of Biped Robot Based on Vertical Ground Reaction Control and its Application

2010229 Runyu Liu

In recent years, there has been a lot of research in the field of robotics on the development of walking robots that are more adaptable to uneven terrain and rough surfaces. Compared to normal biped robots, the compass-like robot with point foot was noted to have higher stability and efficiency in walking. Such an underactuated bipedal robot can achieve highly stable limit-cycle walking with simple input, but it is deeply dependent on the initial state, making it difficult to stop walking at any given moment and to control the walking period. It is also pointed out that the simple control makes the robot have less adaptability to rough surfaces. In response to this, a new walking method called stealth walking was proposed. In normal walking, the collision between the robot's swing leg and the ground causes a discontinuity in the motion state before and after the impact, which leads to instability. Stealth walking, however, can avoid the collision by controlling the vertical velocity of the tip of the swing leg to be zero when it touches the ground. This increases the stability of the robot and makes it easier to stop the motion. By avoiding collision with the ground, the robot is capable to overcome unstable footholds such as rubble. I have also shown that stable walking can be achieved by controlling the ground reaction force and the angular momentum on both vibrating and low-friction surfaces. Furthermore, to control the angular momentum, the robot's posture should be strictly controlled, which can be easily achieved by adding an upper body and flywheel.

Based on the above, this study addresses the realization and analysis of high-speed stealth walking on low-friction or oscillatory low-friction surfaces by controlling the ground reaction force in the vertical direction to improve the adaptability to adverse environments. Conversely, through the control of the ground reaction force, it is possible to control the robot walking on vibrating ground. When a normal robot walks on an oscillatory surface, its gait is greatly affected by the ground vibration. For example, it was pointed out that places such as a walking bridge can cause the bridge to sway and collapse due to the vibration of the road surface, causing a synchronization of the walking period of the group. We believe that stealth walking can also be achieved by a gait that maintains a constant gait period. And by controlling the ground reaction force, it could synchronize the step period of other passive and easily controlled robots. This model can also be used to prevent the collapse of a bridge by controlling the frequency of the synchronized motion to a different frequency than the inherent frequency of the bridge through stealth walking and ground reaction force control when the synchronization phenomenon occurs on the bridge. In this study, we also explore how to control the synchronization of a swarm of robots on a vibrating road surface through stealth walking.

In my research, I extend an upper body with telescopic joints and a flywheel to a bipedal robot, aiming at high-speed stealth walking on general, low-friction, and oscillating surfaces. First, we control the ground reaction forces in the vertical direction to avoid the robot jumping from the surface. Second, we apply a control law that maintains the horizontal ground reaction force at zero to improve the robot's adaptability to low-friction surfaces. We also explore the adaptability to oscillating surfaces. In addition, we perform a fundamental study on the synchronization control of a passive swarm robot on an oscillating surface using the model as the driving source.

To begin the study, a 7 degree of freedom(DOF) bipedal robot model with a telescopically jointed upper body and the flywheel was established on a non-slippery surface. First, we have generated the dynamics and collision equations for the model. Second, we have designed a time orbit to control the angular velocities of the robot's support and swing feet to be zero when the feet contact the ground. Third, we control the acceleration of the robot's center of mass(COM) in the vertical direction to be positive so that the robot cannot jump from the ground when walking at high speed. Fourth, I have designed a sinusoidal time track for the upper body of the robot, averaged the horizontal ground reaction force as the evaluation function, and minimized the evaluation function by finding the optimum value of the amplitude of the sinusoidal function through the algorithm. Fifth, for the flywheel as zero dynamics, it could suitable initial angular velocity by using the binary search method to stabilize the flywheel's motion. Sixth, numerical simulations were carried out to verify that the robot was capable to perform stable stealth walking at any period.

Then I have changed the control of the upper body to the acceleration of the horizontal COM to enable the model to achieve stable, high-speed stealth walking on low-friction surfaces, which made both the upper body and the flywheel behavior like zero-dynamic. First, I have maintained the robot's horizontal ground reaction force at zero by controlling the horizontal acceleration of COM to be zero so that the robot will not slide on any hard ground with any coefficient of friction. Second, the initial angular velocity of the upper body was found by the condition that the velocity of the robot's COM in the horizontal direction is always constant, and the initial angular velocity of the flywheel was found by using the previous binary search method. Third, we verified this result through simulation and found the relationship between the initial angular velocity of the zero-dynamics part and the walking period. As the walking period decreases, the absolute value of the initial angular velocity of the zero-dynamics part increases. Fourth, I have evaluated the walking efficiency of the robot in terms of the energy costs per unit distance of walking and found that the walking efficiency decreases as the walking period decreases. Fifth, I have used this control method to analyze the robot's when it walking on a vibrating low-friction ground. I have modeled the dynamics of the ground by using a spring-damped-mass model. Through numerical simulations, I found that although the ground reaction forces in the horizontal and vertical directions maintain from before, the flywheel could not be stabilized due to the ground vibrations.

Finally, I try to extend the application of the model. I have used the robot as a drive source for the simultaneous control of other passive robots through the vibrating ground. First, as a basis for this study, I have built a model of two identical compass-like robots on a vibrating slope. Second, I have generated the equation of dynamics and collisions of this model and added a simple sine wave input between the legs of one of the robots. Third, through numerical simulation, we found that when the viscosity coefficient was greater than a certain value it caused the ground to behave like a hard surface, which made simultaneous control unsuccessful. I have obtained the maximum range of simultaneous frequencies for both robots by adjusting the amplitude of the sinusoidal input signal. Fourth, I have replaced one of the active compass robots with the input with a previous 7-DOF bipedal robot model with a telescopic upper body and flywheel to make the two robots ' walking period simultaneous by controlling the active robot's vertical ground reaction force. Through numerical simulations, I have achieved simultaneous control of the two robots and obtained the relationship between the range of the two robots' simultaneous period and the vertical ground reaction forces.

In this paper, a mathematical model of a bipedal robot with a telescopic upper body and a flywheel has been generated. The stealthy walking of the robot on non-slippery, low friction, and oscillating low friction surfaces is analyzed through numerical simulations. By keeping the vertical ground reaction force constant, the robot can achieve stealth walking with constant step length and arbitrary period, enabling ultrahigh-speed stealth walking. By controlling the horizontal ground reaction force to zero, the robot can achieve ultrahigh-speed stealth walking on low-friction surfaces and oscillating low-friction surfaces. It was found that the robot ' s walking efficiency increased with decreasing walking period. In addition, synchronous control of two compass robots on an oscillating ramp was performed by using the sine wave input at one compass robot as the drive source and the effect of the viscosity coefficient of the surface as well as the period and amplitude of the input on the synchronous control was analyzed. Finally, it has shown that synchronous control with a compass-type robot can be achieved by using a bipedal robot with a telescopic upper body and a flywheel as the drive source to control vertical ground reaction forces on the slope in a sinusoidal manner. Compared to a simple input to a compass robot, this 7-DOF robot proposed in this paper using vertical ground reaction force control can synchronize the two robots faster and extend the synchronization range.

A new control method should be considered for oscillating surfaces, where the flywheel, which acts as the robot's zero-dynamics, cannot be stabilized even when a suitable initial state is set. Another important issue is to improve the efficiency of the robot's high-speed stealth walking. Also, only one robot is used as a drive source, synchronously controlled with another passive robot. In the future, we will increase the number of passive robots to two or more and try to synchronize the control of swarm robots. We believe that it is important to construct a control law that stabilizes the zero-dynamics in any initial states, considering the applications to real robots.