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Asymptotically stable running gait generation for X-shaped bipedal robot with elastic legs based on adaptive updating of control variables

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The compass-shaped robot, in which two leg frames are connected at the hip joint's rotational axis, behaves similarly to human walking: the supporting leg rotates forward around the contact point, while the swing leg rotates in the opposite direction around the hip joint. On the other hand, when walking with both leg frames of equal length, a problem arises in ensuring sufficient clearance for the swing leg above the floor surface. Kiefer and Ramesh introduced a three-degree-of-freedom X-shaped bipedal robot to address this issue, placing a reaction wheel between the two leg frames and enabling stable wheel gait generation on both horizontal and inclined planes. A wheel gait refers to a type of gait where both leg frames rotate in the same direction, which eliminates the need to consider clearance with the floor surface. Additionally, when the leg frames are connected at their center points to form an X-shape, the resulting equations of motion are simple, with few nonlinear terms. This configuration exhibits unique characteristics, such as the unchanged angular velocity of the rear leg at the instant of stance-leg exchange and the time integral of the control input for one step becoming zero in the steady gait. Despite these advantages, because there is no rotational moment around the hip joint, natural leg swing motion does not occur, and a driving force is always necessary to generate the wheel gait. Moreover, stabilizing the system, including the zero dynamics, is theoretically difficult, and the construction of realistic models and control laws was not fully developed in earlier studies. In response, subsequent research introduced an X-shaped bipedal robot with telescopic legs instead of reaction wheels. This model successfully generated wheel gait on a horizontal plane. Furthermore, the optimal elasticity coefficients and natural length were derived in a model equipped with elastic elements parallel to the telescopic legs, leading to improved energy efficiency and reduced control loads. When the telescopic joints are driven, both ends of the leg frame undergo symmetric stretching and compressing motions. This property allows for control of the relative lengths of the legs in a way that the rear leg is relatively more extended and the front leg shorter at the moment of stance-leg exchange, causing the center of mass to approach the contact point of the front leg and easily overcoming the next potential barrier that appears mid-stance phase. While this feature is an advantage that facilitates wheel gait, geometrical constraints under conditions where the stance leg is in constant contact with the floor surface require a smaller relative hip-joint angle and stride length at the instant of stance-leg exchange to increase walking speed. Although forward acceleration can be achieved by extending the stance leg so that it becomes an asymmetric impact posture in the anteroposterior direction, the stride length must be reduced accordingly to prevent the center of mass from moving away from the front leg's contact point. One potential solution is introducing jumping motion into the wheel gait to overcome stride constraints and increase walking speed. Starting with Matsuoka's work, various studies have been conducted on hopping robots and bipedal running gaits that leverage jumping. Additionally, hopping and bipedal running gait stability analyses have been carried out. While previous studies enabled high mobility with fewer actuators through the introduction of jumping, they faced problems in realizing running gait. This was due to unrealistic control inputs or special assumptions that neglected leg mass, which diminished the feasibility of implementation. In contrast, McGeer's research demonstrated higher feasibility and inherent stability in certain parameter sets, although the motion was limited to slopes. Additionally, an Asano and Suguro model, which, like the research presented in this paper, incorporated telescopic joints into a rimless wheel, demonstrated high-speed running but was limited by structural difficulties and inadequate analysis of the control inputs necessary for running gait. In order to solve this problem, this paper proposes running gait generation on a horizontal plane using an X-shaped bipedal robot with elastic legs and analyzes its stability through numerical simulation. In addition, although previous studies have reported the verification of a wheel gait, the successful generation of a stable wheel gait has not been reported. Therefore, we also propose an experimental X-shaped bipedal robot, which we have developed. In Chapter 2, an X-shaped bipedal robot with telescopic legs is analyzed through numerical simulations with and without restraining the telescopic legs during an inelastic collision with the floor surface, and the gait characteristics are compared for each. We generated wheel gait by considering whether mechanical constraints were applied to the telescopic joints during each collision. The results indicated that when mechanical constraints were applied to the telescopic joints, an increase in the relative hip-joint angle during each collision led to a monotonically increasing walking cycle, with walking speed and stride rate decreasing monotonically. In contrast, in the absence of mechanical restraints, the support legs have the property of first contracting and then extending to the terminal value, which was shown to be advantageous for larger strides than in the presence of mechanical restraints. In Chapter 3, the assumption that the telescopic legs are driven linearly symmetric was removed, and we propose to extend the X-shaped bipedal robot with telescopic legs to an eight-degree-of-freedom redundant model. It also compared the translational driving force of a three-input model under holonomic constraints with the control input of a five-input model, which included assumptions about control inputs. This comparison revealed that the translational driving force reflects the potential input-output relationship of telescopic legs. In Chapter 4, we analyzed the wheel gait of the X-shaped bipedal robot with elastic legs, where elastic elements were added to the telescopic legs. We evaluated its performance from the perspectives of energy efficiency and the control load. Furthermore, the optimal physical parameters for the elastic elements were derived by analyzing the time variation of the total mechanical energy. In Chapter 5, Using the X-shaped bipedal robot with elastic legs, a new wheel mixed gait, and a wheel running gait were generated, and it was demonstrated that the generated wheel running gait is asymptotically stable using the Poincaré map method. Adaptive updating of control variables was used for the running gait, where the stance leg was contracted at the moment of transitioning to the flight phase, enabling the realization of the running gait. Stability was evaluated based on the eigenvalues and singular values of the nonlinear discrete functions, revealing that while the system is asymptotically stable, the convergence is not strong. Chapter 6 describes the outline of the experimental machine for the novel X-shaped bipedal robot we developed based on the theoretical knowledge of previous studies, reports the basic experimental results of wheel gait generation using this machine, and discusses the robot's feasibility. The structure and control method for realizing a wheel gait near the theoretical knowledge are described. Then, the experimental results are reported, and the problems and improvement measures are discussed. In Chapter 7, conclusions and future works are described.