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Whole-Body Balance Control of Wheeled-Bipedal Robots for Perception-less Terrain Adatation

Abstract— **In** ***this paper, we present a whole-body control framework that allows a wheeled-bipedal robot to achieve robust locomotion across diverse environments without relying on terrain perception. The proposed approach consists of a whole-body motion planner and an optimization-based torque computation module. By considering the floating-base dynamics of the robot, the motion planner produces terrain-adaptive behaviors using the zero moment point (ZMP) to preserve balance without prior knowledge of the terrain. In addition, the torque computation module combines a linear quadratic regulator (LQR) with a quadratic programming (QP)-based controller. The LQR computes wheel torques to regulate the body angle while addressing the inherent non-minimum phase characteristics. Using these wheel torques, the QP-based controller allocates optimal joint torques to achieve the desired motion and maintain stable balance. The proposed framework is validated on a wheeled-bipedal robot, demonstrating locomotion over various terrains, including slopes, stairs, as well as robustness against external disturbances.***

Keywords—wheeled-bipedal robot, optimal control, whole-body control

I. INTRODUCTION

Owing to rapid progress in mobile robotics, robot deployment has extended beyond flat ground to complex terrains commonly encountered in everyday environments, such as stairs and slopes. This shift places greater emphasis on achieving robust mobility across diverse terrains. Accordingly, a wide range of mobile robot platforms capable of operating on unstructured terrain have been actively studied. In particular, wheeled-bipedal robots achieve high-speed locomotion on flat surfaces using wheels, while utilizing their legs to traverse uneven and complex environments.

To realize stable balance control for wheel‑legged robots, predictive control methods such as model predictive control (MPC) and the linear quadratic regulator (LQR) have been used. Specifically, an MPC-based wheel slip ratio adjustment method is proposed [1], and an MPC controller that enforces wheel position constraints while computing the robot's contact forces and torques is implemented on a wheeled-bipedal robot [2]. However, MPC controllers typically operate at relatively low update rates and require additional strategies to address the inherent non-minimum phase characteristics of wheel‑legged robots. LQR-based controllers have been widely employed for wheeled‑bipedal robots because their linear structure enables high-rate control updates when regulating low-dimensional core dynamics such as robot balance [3]. Nevertheless, because LQR controllers cannot explicitly handle constraints when computing control inputs, they are often combined with QP in practical implementations. The balancing capability against external pushes is demonstrated using a hierarchical whole-body controller that takes the desired pitch acceleration generated by an LQR method [4]. An LQR controller computes the torso's acceleration reference based on the horizontal offset, and a QP controller then uses this reference to generate torque commands while enforcing a control Lyapunov function constraint[5].

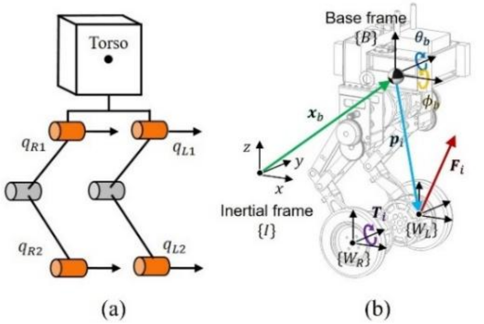

Fig. 1. Schematic drawing of (a) Mechanical structure including motor distribution and (b) literal notations.

In this paper, we present a whole-body control framework for a wheeled-bipedal robot that achieves robust locomotion over slopes, stairs, and uneven terrain without the use of terrain perception. The proposed framework is composed of two primary modules: a whole-body motion planner and an optimization-based torque controller. The motion planner generates desired robot motions based on the zero moment point (ZMP) while accounting for the floating-base dynamics. Furthermore, by reflecting the dynamic characteristics of wheeled-bipedal systems, the torque controller combines LQR with quadratic programming (QP) to produce joint torques that ensure stable balance. The performance of the proposed approach is demonstrated through experiments conducted on a wheeled-bipedal robot.

II. WHOLE-BODY BALANCE CONTROL

To realize the stable balancing ability, the torso dynamics with 6 DoFs must be regulated. Because the wheeled-bipedal robot is represented as a floating base system detached from the

Fig. 2. Locomotive abilities on (a) a 2-step stair and (b) slope with a 10° inclinetaion.

ground, regulating the torso to its desired state enables the robot to maintain balance stably. The dynamics of the robot' s torso can be rewritten as

$$\begin{cases} m(\ddot{\boldsymbol{x}}_b + \boldsymbol{g}_b) = \boldsymbol{F}_r + \boldsymbol{F}_r \\ \boldsymbol{I}_b \dot{\boldsymbol{\omega}}_b = \quad \left(\boldsymbol{x}_{b,i} \times \boldsymbol{F}_i\right) + \boldsymbol{T}_i. \end{cases} \tag{1}$$

Using Eq. (1), we can formulate the state space equation of the robot can be given by

$$\dot{\boldsymbol{x}}(t) = \boldsymbol{A}(t)\boldsymbol{x}(t) + \boldsymbol{B}(t)\boldsymbol{u}(t). \tag{2}$$

Based on Eq. (2), the LQR controller that minimizes the cost function $\boldsymbol{J} \in \mathbb{R}$ is defined as follows:

$$\boldsymbol{J} = \int_0^\infty (\boldsymbol{x}^T \boldsymbol{Q} \boldsymbol{x} + \boldsymbol{u}^T \boldsymbol{R} \boldsymbol{u}) dt. \tag{3}$$

The optimal wheel torque generated by the LQR controller is included in the QP-based whole-body controller with considering the floating base-related tasks as

$$min \ \sum_{\boldsymbol{i=1}}^{\boldsymbol{k}} \boldsymbol{w_i} \|\boldsymbol{A_i f} - \boldsymbol{B_i}\|^{\boldsymbol{2}}. \tag{4}$$

Here, we employ the ZMP-based torso's motion planning, which enables the robot to maintain the stable balance, and its equation is expressed as follows:

$$p_{ZMP}^x = \frac{F_l^z p_l^y + F_r^z p_r^y}{F_l^z + F_r^z} \tag{5}$$

$$p_{ZMP}^y = \frac{F_l^z p_l^x + F_r^z F_r^x}{F_l^z + F_r^z}. \tag{6}$$

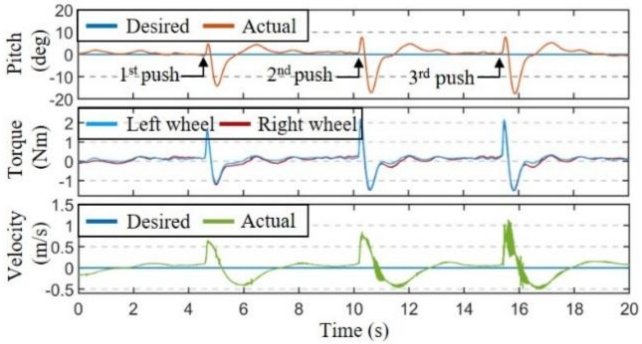

Fig. 3. The desired and actual states of the CoM and actual torques of the two wheels during the balance recovery test for x-axis

III. EXPERIMENTS

To evaluate the proposed whole-body controller, wheeled-bipedal locomotion is conducted on a 2-step stair and a slope with a 10° inclinetaion, as shown in Fig. 2. In addition, three disturbances were imposed to the wheeled- bipedal robot, as shown in Fig. 3. By the applied pushes, several CoM states were changed and wheel torques were generated to recover the robot's balance.

IV. CONCLUSION

In this paper, we present a whole-body balance control approach for a wheeled-bipedal robot that achieves robust locomotion over diverse terrains without terrain perception. The motion planner generates the CoM motion using the ZMP, while the torque generator computes joint torques to ensure stable balance during locomotion. The approach is test on a real through simulations on slopes, stairs, and uneven terrain, as well as an external push test. The results demonstrate stable balance and robust locomotion across various terrains.

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