CDM-MPC: An Integrated Dynamic Planning and Control Framework for Bipedal Robots Jumping

Zhicheng He, Jiayang Wu, Jingwen Zhang, Shibowen Zhang, Yapeng Shi, Lining Sun, Yao Su, *Member, IEEE*, and Xiaokun Leng

***Abstract*—Performing acrobatic maneuvers like dynamic jumping in bipedal robots presents significant challenges in terms of actuation, motion planning, and control. Traditional approaches to these tasks often simplify dynamics to enhance computational efficiency, potentially overlooking critical factors such as the control of centroidal angular momentum (CAM) and the variability of centroidal composite rigid body inertia (CCRBI). This paper introduces a novel integrated dynamic planning and control framework, termed centroidal dynamics model-based model predictive control (CDM-MPC), designed for robust jumping control that fully considers centroidal momentum and non-constant CCRBI. The framework comprises an optimization-based kinodynamic motion planner and an MPC controller for real-time trajectory tracking and replanning. Additionally, a centroidal momentum-based inverse kinematics (IK) solver and a landing heuristic controller are developed to ensure stability during high-impact landings. The efficacy of the CDM-MPC framework is validated through extensive testing on the full-sized humanoid robot KUAVO in both simulations and experiments.**

***Index Terms*—Jumping control, model predictive control, bipedal robot, optimization, acrobatic motion planning**

I. Introduction

Achieving acrobatic motions, a significant challenge in bipedal robotics, requires not only powerful robot actuators but also sophisticated motion planning and control algorithms. Unlike the control of walking or running—where the **centroidal angular momentum (CAM)** is typically overlooked to simplify the highly nonlinear multi-body dynamics using models like linear inverted pendulum model (LIPM), spring-loaded inverted pendulum model (SLIPM), or single rigid body model (SRBM) for computational efficiency, CAM plays a key role in the jumping control of bipedal robots. This introduces unique challenges and necessitates additional considerations in the control strategy to accurately manage CAM throughout the entire process.

To enhance the generation of dynamic motions for legged robots across various speeds and magnitudes, the **centroidal dynamics model (CDM)** was integrated into trajectory optimization formulations. Specifically, Budhiraja *et al*. introduced a formulation to reconcile the CDM with the complete dynamics model; Ponton *et al*. employed the CDM for efficient walking pattern generation; Kwon *et al*. utilized the CDM for footstep planning, integrating a momentum-mapped Inverse Kinematics (IK) solver to design whole-body motion.

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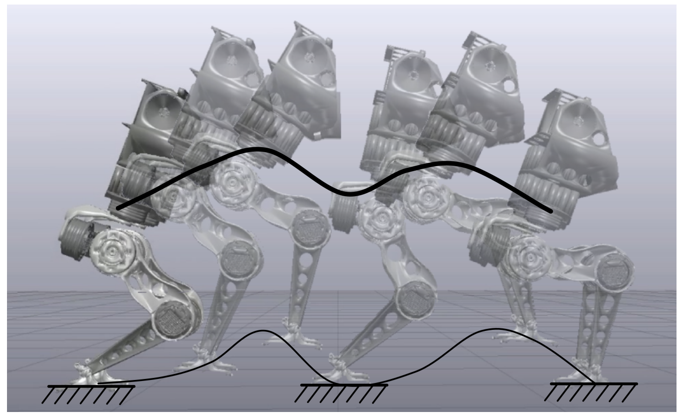


Fig. 1: **The proposed integrated dynamic planning and control framework endows bipedal robots capable of continuously forward jumping.** The trajectories of the foot and the torso links are plotted in thin and bold black lines, respectively.

Moreover, the CDM-based real-time model predictive control (MPC) frameworks have been successfully implemented on agile maneuver control of quadruped robots, considering the constant centroidal composite rigid body inertia (CCRBI) of the robot. In this study, we concentrate on the jumping control of biped robots while accounting for non-constant CCRBI. We first derive the relationship between CCRBI and robot leg length as a constraint, then incorporate it into a real-time MPC framework to accurately regulate the body posture of a biped robot during the jumping process.

II. Platform Model

A. Hardware Introduction

The hardware platform depicted in Fig. 2 is developed to evaluate the performance of the proposed CDM-MPC framework. The KUAVO bipedal robot platform stands $1.2\ m$ in height and weighs $34.5\ kg$. It incorporates 18 motors: each leg is equipped with 5 DoFs and each arm with 4 DoFs. For a comprehensive overview of the hardware platform's specifications, please refer to Tab. I.

TABLE I: **Main Physical Parameters of KUAVO Robot**

Dimension Parameters				
Total mass	Pelvis width	Thigh length	Calf length	Foot length
34.5 [kg]	0.22 [m]	0.23 [m]	0.26 [m]	0.15 [m]
Motion Range & Joint Peak Torque				
Hip Yaw	Hip Roll	Hip Pitch	Knee Pitch	Ankle Pitch
$-90^\circ \sim 60^\circ$	$-30^\circ \sim 75^\circ$	$-30^\circ \sim 120^\circ$	$-120^\circ \sim 10^\circ$	$-30^\circ \sim 80^\circ$
48 [Nm]	110 [Nm]	110 [Nm]	110 [Nm]	48 [Nm]

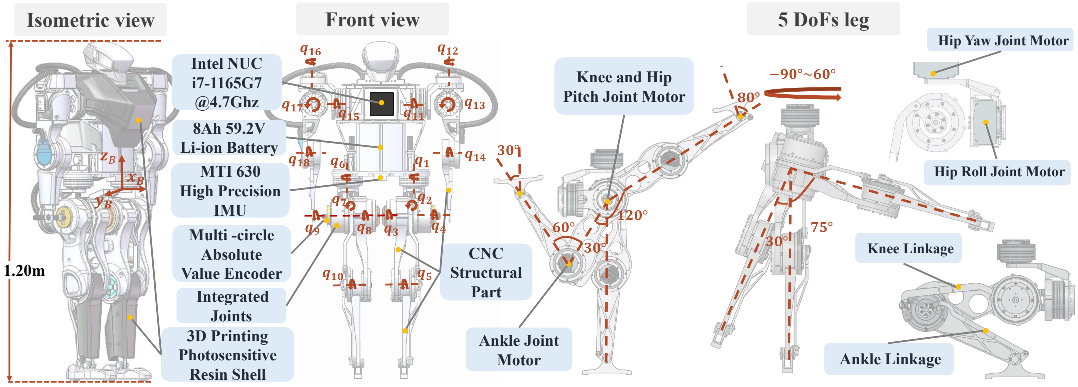


Fig. 2: **Hardware design and configuration of the bipedal humanoid robot KUAVO.** Each leg contains 5 Degree of Freedoms (DoFs): 3 DoFs for the hip joint, 1 DoF for the knee joint and 1 DoF for the ankle joint.

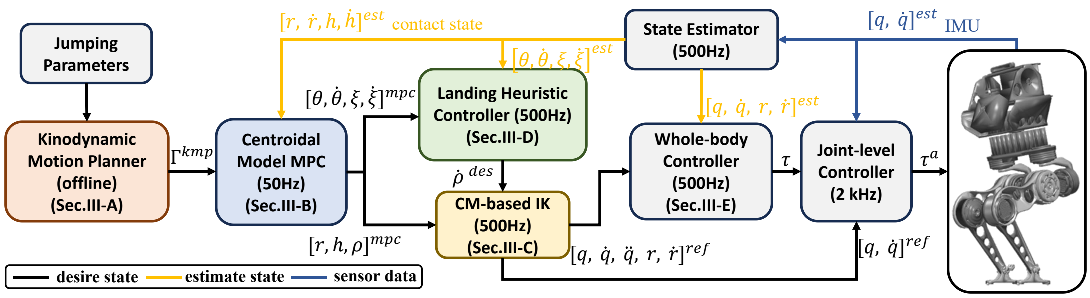


Fig. 3: **The CDM-MPC dynamic planning and control framework.** (i) The CDM-based kinodynamic motion planner produces the centroidal momentum reference trajectory. (ii) The real-time MPC controller provides accurate trajectory tracking and fast replanning under disturbances. (iii) The centroidal moment-based IK solves whole-body trajectory without simplifying leg dynamics. (iv) The landing heuristic controller guarantees robust landing stabilization.

III. Dynamic Planning & Control Framework

Building upon the CDM, we develop the CDM-MPC framework to address the complexities encountered during bipedal robot jumping in the launching, flight, and landing phases, as introduced in Sec. I. Our framework consists of four primary components: (i) an optimization-based kinodynamic motion planner to produce the CDM trajectory, contact force, and contact position; (ii) a real-time MPC controller with CDM for trajectory tracking and fast replanning; (iii) an IK solver based on centroidal momentum that calculates whole-body trajectories; (iv) a landing heuristic controller for robust stabilization. The overall framework is summarized in Fig. 3.

IV. Verification

To rigorously evaluate the efficacy of the proposed CDM-MPC framework, simulations and experiments were executed using the KUAVO bipedal robot platform. Physical validation trials were carried out on the physical KUAVO platform. Four test cases were designed as follows: (i) **Case 1:** we compared the disturbance rejection performance of the proposed CDM-MPC method with a baseline SRBM-MPC method during in-place jumping; (ii) **Case 2:** we studied the robustness of proposed landing controller with variable forward jumping velocities; (iii) **Case 3:** we validated the proposed framework on the physical KUAVO robot in a jumping experiment; and (iv) **Case 4:** we explored the versatility of the framework by applying it to walking locomotion.

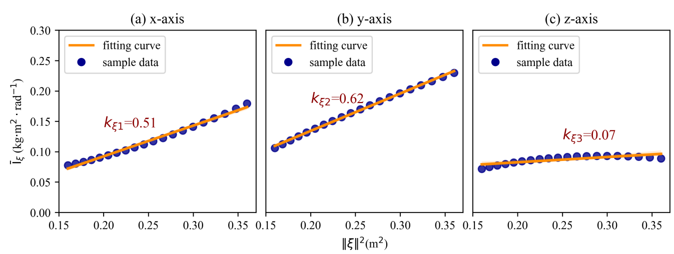


Fig. 4: **Inertia parameter calibration results.** The x and y axes components of $\bar{\boldsymbol{I}}_\xi$ has linear relationship with $\|\xi\|^2$, while the z axis component of $\bar{\boldsymbol{I}}_\xi$ is invariant.

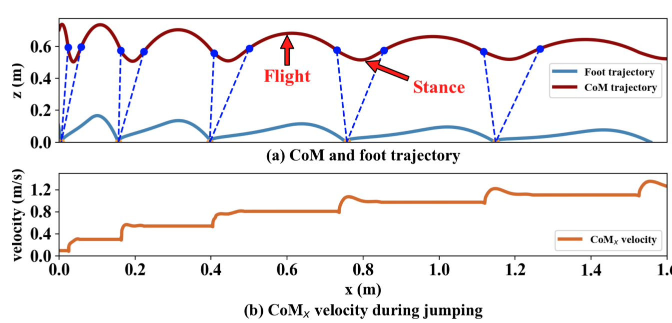
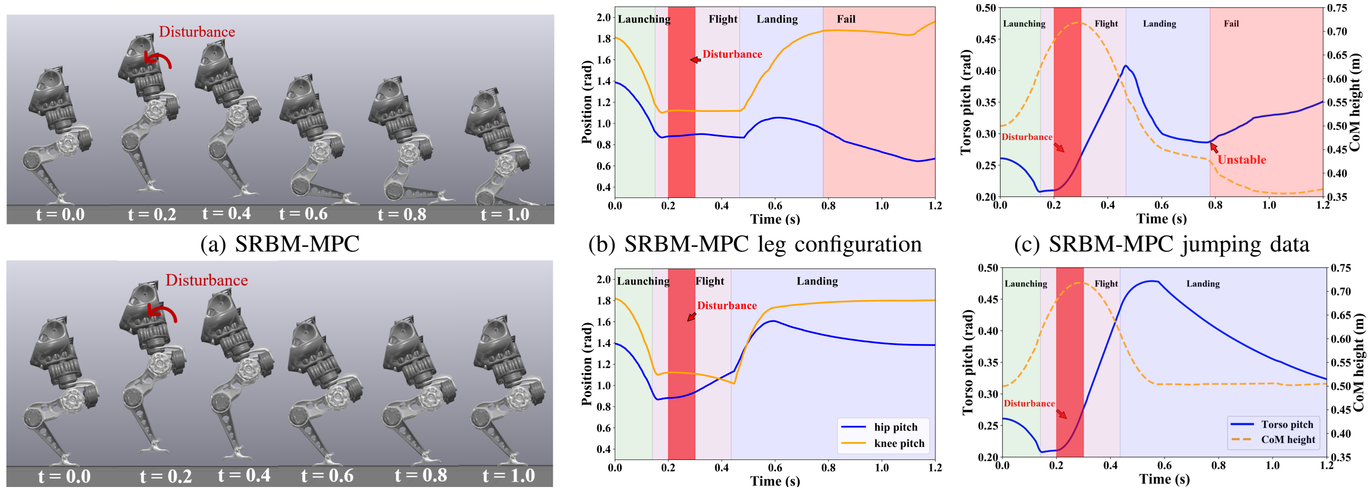


Fig. 5: **Case2 (Simulation): Continuous forward jumping with increasing jumping velocities.** (a) CoM and foot trajectory of the robot during the process. (b) Corresponding estimated velocity.



(a) SRBM-MPC (b) SRBM-MPC leg configuration (c) SRBM-MPC jumping data

(d) CDM-MPC (e) CDM-MPC leg configuration (f) CDM-MPC jumping data

Fig. 6: **Case1 (Simulation): Disturbance rejection performance study during in-place jumping.** (a) The SRBM-MPC method cannot maintain the robot's stability when subjected to disturbance torque, leading to its collapse. (c) Conversely, the CDM-MPC method preserves the robot's stability throughout the entire flight phase, culminating in a successful landing. (b)(e) depict the joint configuration of hip pitch and knee pitch joints while (c)(f) depict the pitch angle of the torso and the CoM height for both methods, respectively.

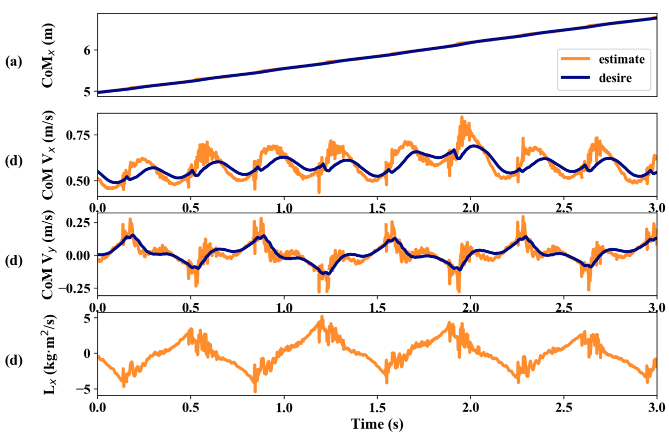
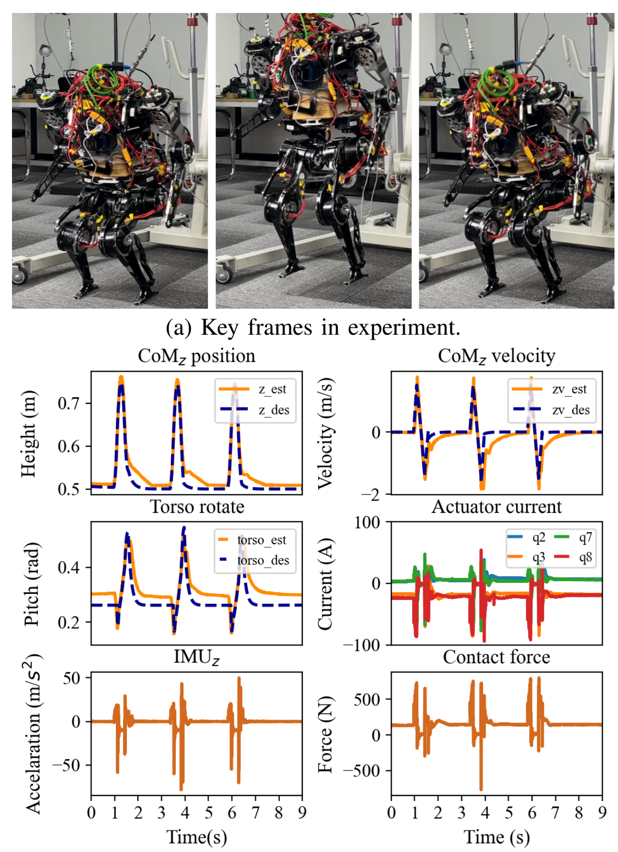


Fig. 7: **Case4 (Experiment): Apply the proposed framework for walking control.** The KUAVO robot achieves stable walking performance with a speed of 0.6 m/s.

V. Conclusion

In this paper, we have presented an integrated dynamic planning and control framework (CDM-MPC) for the jumping motion of bipedal robots. This framework considers centroidal momentum in both dynamics planning of the launching phase and online tracking control of the flight phase, and it integrates a robust landing to ensure stability. Altogether, the proposed framework enables agile and continuous jumping motions on full-sized bipedal robots. We validated the effectiveness of this framework based on a novel full-sized bipedal robot KUAVO in both realistic simulations and real-world experiments and confirmed its applicability to other locomotion modes, such as walking. Future directions include generalizing the framework for unified walking, running, and jumping control with smooth transitional behavior and integrating reinforcement learning-based methods for performance and robustness improvement.



(b) Experiment results

Fig. 8: **Case3 (Experiment): Continuous in-place jumping on physical KUAVO robot.** The KUAVO robot executes three vertical jumps of approximately 0.28 m and lands stably with the proposed jump control framework.