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EXPLOITING PASSIVE DYNAMICS FOR STEADY-STATE WALKING ON LEVEL AND INCLINED TERRAIN

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1. INTRODUCTION

In passive dynamic walking, stable and energy-efficient bipedal gait is performed through the exploitation of the inherent dynamics of appropriately designed mechanical systems. However, purely passive bipeds are necessarily restricted to downhill walks, where gravity compensates for impacts and other losses. Extending such motions to level and uphill terrain while preserving the desirable characteristics of passive gait remains a significant challenge. Here, an under-actuated biped robot, designed to rely on and exploit its passive dynamics while in active locomotion, is studied for its ability to generate stable and energy-efficient locomotion on level and positively sloped ground.

2. FROM PASSIVE TO UNDERACTUATED BIPED

The base passive biped [1] has been incrementally augmented with biomechanically-inspired design elements that improve the robustness of its passive gait: a biomimetic footshape is incorporated [2] to facilitate rollover, and a four-bar mechanism is employed at the knees to decrease impact propagation [3]. The base passive biped is shown schematically in Fig. 1(a). Repetitive gait is enabled as potential energy gains balance dissipative losses, whilst gait stability solely depends on the system's mechanical design. It is intuitive that repetitive walking on level or positively inclined terrain cannot be achieved without external energy input. Direct actuation of all joints, as needed in a feedback linearization scheme, is impractical in legged systems. To preserve passive dynamics while in underactuation, a counterweight (CW) link is introduced [4], shown in Fig. 1 (b). This additional link acts similarly to a torso and allows the generation and balancing of the motor torques required to replicate the passive gait.
The model-based Underactuated Virtual Gravity (UVG) controller [4] is utilized to control actively the gait. The UVG computes the gravitational torques experienced by the passive biped during gait on negative sloped terrain and imposes them on the underactuated active biped. The result is an active gait on level ground that emulates the passive gait on a downward slope, called the *passivity angle* of the UVG. In the present study, the walkable domain of the robot is extended to positively inclined terrain through systematic variation of the active biped's walking slope and controller passivity angles.

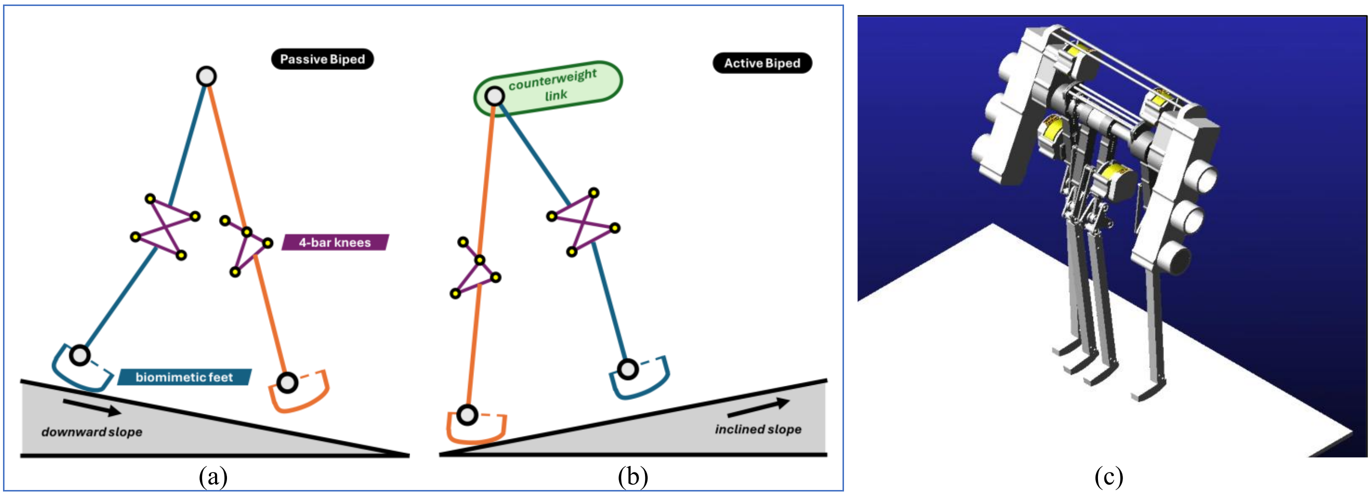

Figure 1. (a) Passive biped model. (b) The resulting active biped model with the addition of a counterweight link ascends an inclined slope. (c) The active biped model simulated in MSC Adams.

3. RESULTS & DISCUSSION

Two independent dynamic models were developed to evaluate the developed biped design: an analytical model implemented in MATLAB and a CAD-based multibody dynamics model constructed in SolidWorks and simulated in MSC Adams. The computationally efficient MATLAB formulation enabled systematic investigation of the system dynamics and controller behavior.

The computationally intensive MSC Adams environment, interfacing with Simulink to implement control feedback, provided a high-fidelity representation of the 3D dynamics and was used for validation.

Stable periodic gaits were obtained for level and uphill terrain across a range of the UVG controller's passivity angles, corresponding to downhill slopes that the UVG controller attempts to emulate. Performance was evaluated using the non-dimensional Cost of Transport (COT), providing a measure of energetic efficiency. In Fig. 2 (a-e), the resulting COT is depicted as a function of the controller's passivity angle for different ground slopes. For level ground, the COT values closely matched those of the corresponding passive downhill gait, which is theoretically equal to the sine of the passive gait's slope angle [4]. As the active ground slope increased, the COT also diverged from the passive prediction, and the range of UVG passivity angles leading to stable locomotion progressively narrowed, reflecting the higher energetic demands of uphill walking.

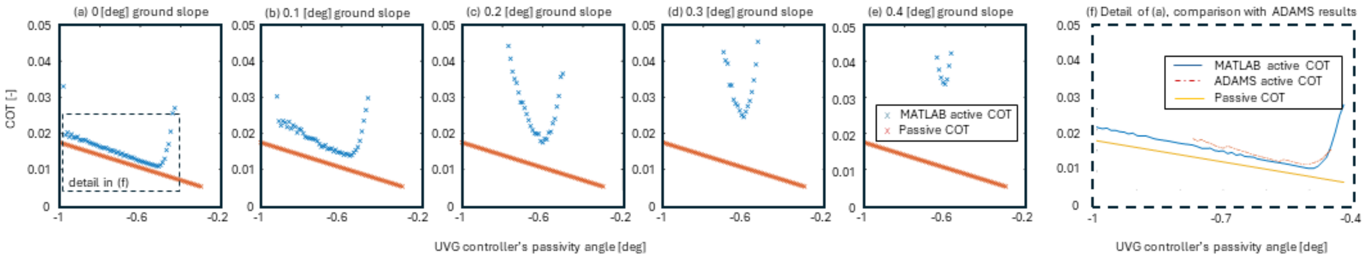

Figure 2. (a-e) COT as a function of the UVG controller's passivity angle for various ground slope configurations (f) Detail of (a), comparison of MATLAB's and MSC Adams active COT as a function of the controller's passivity angle for level ground slope.

Extremely small and large passivity angles produced sharp increases in COT. Notably, the passive biped was originally designed for a nominal slope of −0.6 [deg], and the minimum COT across all active configurations consistently occurred at this emulated passivity angle. This indicates that robustness of the underlying passive template directly translates to its active counterpart.

Finally, Fig. 1(f) presents a comparison between the MATLAB and MSC Adams models for level ground locomotion. Despite the differences in model fidelity, a close quantitative agreement between the predicted COT values is demonstrated. However, a reduction in the range of stable passive angles is observed for the ADAMS, as a result of non-modeled dynamics that are fully simulated in the ADAMS model while absent in MATLAB's analytical simulations and Simulink's UVG controller calculations.

4. CONCLUSION

This work demonstrates the generation of stable active gait for an underactuated biped on level and positively sloped terrain, through the emulation of passive downhill gait by a model-based controller. By introducing a counterweight joint on the biped and by applying the analytical Underactuated Virtual Gravity (UVG) controller, the system preserves the fundamental characteristics of passive dynamic via gravitationally inspired energy injection. The proposed control scheme is validated through comparison between an analytical dynamics model and a multibody co-simulation environment, displaying close agreement between the models as quantified by various results including the non-dimensional Cost of Transport.

Planned next steps of this work will focus in experimental validation. It is necessary that real-world applications of the developed method, and of similar model-informed approaches, must ensure backdrivability in the actuation system, in order to preserve the system dynamics that are exploited by the control and design scheme.

The results of this study highlight the potential of exploiting passive dynamic templates to achieve energy-efficient locomotion beyond descending terrain conditions. Mechanical design of the control system can be manipulated to promote specific desirable passive tendencies, which increase robustness around particular locomotion modes, enabling the efficient emulation of these motions beyond nominal conditions through morphologically-aware model-based controllers such as the UVG.

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