# Velocity Decomposition-Enhanced Control of Underactuated Bipeds

Martin Fevre†, Bill Goodwine, and James P. Schmiedeler

***Abstract*— This workshop contribution extends the use of the velocity decomposition metric for underactuated mechanical systems to the design of an enhanced hybrid zero dynamics (HZD)-based controller for biped robots. Here, an offset to the biped's desired torso angle is applied in proportion to the error in the unactuated velocity, as determined through the decomposition. This offset aids in rejecting acceleration and deceleration disturbances to the unactuated velocity and in traversing uneven terrains without ground perception. Simulation results with a point-foot, three-link planar biped show that the velocity decomposition-enhanced controller has nearly identical performance to transverse linearization feedback control and outperforms conventional HZD-based control in rejecting both velocity disturbances and stochastic perturbations on rough terrains. Experimental results with the planar, point-foot, five-link biped ERNIE confirm these same trends.**

## I. Problem Statement

The broad class of biped robots can be divided into two categories: 1) flat-footed, ankle-actuated bipeds that typically rely to some extent on the Zero-Moment Point criterion for stability [1], [2], and 2) underactuated dynamic walkers [3], like the highly efficient Cornell Ranger that walked over 65 km on a single battery pack [4]. While underactuated bipeds offer the promise of energetic efficiency, they face complex control challenges when trying to reject large disturbances in the unactuated degrees of freedom (DOFs). For robots to operate in a fully autonomous manner in human-designed environments, however, they must be both robust to disturbances and energetically efficient.

Disturbances can be added to the system in two forms: vanishing perturbations and non-vanishing perturbations. Velocity disturbances that accelerate or decelerate the robot for a finite amount of time belong to the first category. Stochastic perturbations that arise from walking on uneven terrain are part of the second category, since the perturbations do not die out with time and have infinite energy in the time domain. In practice, humans often encounter both types of disturbance, sometimes at the same time, and biped robots that aim to become fully autonomous must be able to reject both. A performance metric for uneven terrain should quantify how well a robot avoids falling in the presence of persistent disturbances.

The HZD-based control framework has been widely used but does not employ any feedback mechanism to change joint trajectories when the robot deviates from the zero dynamics trajectory [5]. Transverse linearization feedback control guarantees exponential orbital stability of the periodic orbit and forms a basis for fast time-scale control to improve robustness in blind walking by measuring the distance from the zero dynamics trajectory and adding a feedback on the unactuated velocity [6]. Despite recent advances on the topic of transverse linearization, the approach remains difficult to implement in real-time and has only been used to control a point-foot three-link biped in simulation and a two-link walker in experiment.

For an underactuated biped with a massive, human-like torso, the functionality of transverse linearization feedback control can be approximated using simple heuristic rules that can be layered on top of a conventional HZD-based controller. The work in [7] extends the use of velocity decomposition to the design of an enhanced HZD-based controller that captures the features of transverse linearization feedback control and can be implemented on higher dimensional, realistic bipeds. The heuristics implement torso and leg offsets that are proportional to the error in the unactuated velocity, as seen through the decomposition. Simulation results with a point-foot, three-link planar biped show that the proposed method has nearly identical performance to transverse linearization feedback control and outperforms conventional HZD-based control when rejecting velocity disturbances. The formulation was validated in experiment on the five-link biped ERNIE where it improved both steady-state performance and robustness to velocity disturbances. This approach has since been extended to walking on uneven terrain, which is the focus of this workshop contribution.

## II. Comparing Control Strategies

The velocity decomposition-enhanced controller is compared to HZD-based control and transverse linearization feedback control for baseline performance. HZD-based control employs high gain PD feedback to track the desired trajectories of each actuated DOF. Transverse linearization feedback control measures the distance from the zero dynamics trajectory in the presence of disturbances and modeling errors in experiment. The two control approaches are believed to span the spectrum of fast time-scale control systems in terms of robustness to disturbances in the absence of terrain preview.

The complexity of transverse linearization feedback control makes it difficult to implement on higher dimensional system, which motivates a simpler approach that can mimic the method and achieve similar performance. The heuristics used to design the velocity decomposition-enhanced controller sought to retain HZD-based control's simplicity yet enhance disturbance rejection. The focus was on capturing the dominant responses of transverse linearization feedback

The auhors are with the department of Aerospace and Mechanical Engineering, University of Notre Dame, IN USA.

† Corresponding author, e-mail: mfevre@nd.edu

control and implementing control actions extracted from transverse linearization feedback control in a feasible way for a physical robot.

The three control strategies were implemented on a point-foot, three-link model in simulation and extended to the five-link biped ERNIE in experiment. The velocity decomposition-enhanced controller was also implemented on a three-link model with curved feet and tested across different walking speeds.

## III. Overview of Results

### A. Velocity Disturbance Rejection

The performance of each controller was assessed by

- the magnitude of the disturbance they can reject,
- the speed of return to nominal step velocity following a disturbance,
- the energetic efficiency.

Overall, the performance of the velocity decomposition-enhanced controller was nearly identical to the performance of transverse linearization feedback control, both in terms of robustness and energetic efficiency.

### B. Uneven Terrain Walking

The control method was extended to underactuated walking on uneven terrain and experiments were conducted to validate the approach. The workshop contribution presents unpublished simulation and experimental results where velocity decomposition-enhanced control was used for traversing uneven terrain walking without ground perception.

For this work, rough terrains were modeled using stairs of varying heights. Another possible choice that is equally complex is to model the terrain using varying slopes. Both methods are valid to test stochastic performance of dynamic walkers. Here, a new change in height $\Delta h$ is randomly generated from a bounded Gaussian distribution $\{\Delta h \in \mathbb{R} \mid -c \leq \Delta h \leq c\}$. Because the height of a step a robot can clear is inherently related to its leg length, the step heights should be reported as percentages of the biped's leg length. The value for $c$ represents the maximum change in height, which was kept in the range of $2-3\%$ of the biped's leg length in simulation, and up to $6\%$ of ERNIE's leg length in experiment.

The same three controllers are compared to assess stochastic performance based on:

- the average number of steps taken before failure for different levels of terrain noise,
- the controller's ability to maintain walking around the designed gait profile, which is measured by the normal distribution of step velocity,
- the maximum change in height (biggest stair) that the robot can clear.

Simulation results indicate that the velocity decomposition-enhanced controller returns similar performance to transverse linearization feedback control when considering the average number of steps taken before failure. Both outperformed HZD-based control. In experiment, the proposed method was able to maintain the desired walking speed better than HZD-based control, as seen through a narrower distribution of step velocity around the designed gait. Velocity decomposition-enhanced control was also able to clear stairs that were $6.2\%$ of the robot's leg length, whereas HZD-based control only cleared stairs up to $4\%$.

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