

# Bridging Discrete and Continuous Interfaces to Generate Adaptive Gait Synthesis for Humanoid Robots

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**Abstract**—This paper presents a dynamic, omni-directional walking controller for the DARwIn-OP humanoid robot, implemented in the Webots simulation environment. The controller accepts both discrete (keyboard) and continuous (joystick) user inputs to generate momentum-aware gait transitions across forward, lateral, and rotational motion. Unlike traditional state-based or pre-scripted controllers, this system allows smooth, real-time blending of walking directions, resulting in more lifelike and adaptive locomotion.

**Index Terms**—Humanoid, Teleoperation, Dynamic Walking, Robotics, Darwin-OP

## I. INTRODUCTION

Humanoid robots have seen remarkable growth in both research and emerging commercial applications. While they have traditionally remained within the realms of academic labs and industrial R&D, there is a growing movement—spearheaded by startups and major robotics companies—to bring humanoid robots into real-world environments, including domestic settings. This vision, reminiscent of depictions in science fiction such as the film *I, Robot*, aims to create autonomous robotic assistants capable of supporting human life through versatile, lifelike behaviors [1], [2].

However, many modern approaches to humanoid locomotion rely heavily on advanced artificial intelligence techniques such as deep reinforcement learning, imitation learning, and complex control paradigms like model predictive control (MPC) or real-time feedback optimization [8], [9]. These methods often demand substantial computational resources, high-end sensors, and well-calibrated physical platforms, which limit accessibility and generalizability [3].

In contrast, the work presented here proposes a lightweight, accessible alternative. Using the older DARwIn-OP humanoid robot platform—simulated in the Webots environment [4]—we develop a novel dynamic walking controller that enables expressive, adaptive, and omnidirectional locomotion without requiring deep learning models, expensive hardware, or high computational overhead. This controller accepts either binary (keyboard) or analog (joystick) user inputs to generate smooth, momentum-aware gait transitions. By blending user intent with low-level gait shaping, the system achieves stability-aware omni-directional movement, something rarely seen in legacy humanoid platforms [5], [6].

The novelty of this work lies in its minimalist yet expressive design: the system dynamically adapts to varying

levels of user input, generating alternating gait cycles that resemble real-world locomotion. Unlike the standard DARwIn-OP walking modules [4], which use fixed gait parameters and exhibit slow, statically stable movement, our controller enables dynamic transitions and omni-directional locomotion that respond continuously to user intent. Compared to the robust but largely state-driven gait systems used by NimbRo in RoboCup [5], [6], which prioritize reliability over adaptability, our approach achieves smoother transitions and more lifelike motion blending using real-time amplitude modulation. Furthermore, it challenges the assumption that only high-end platforms with advanced actuators—like those from Unitree or Boston Dynamics [1], [3]—can perform lifelike walking. Our findings show that even older, affordable humanoid robots can demonstrate natural dynamic behaviors when driven by thoughtfully designed control architectures.

## II. RELATED WORK

Enabling dynamic walking in humanoid robots has long been one of the central challenges in robotics. Over the past few decades, a wide range of approaches have been proposed to address this, ranging from classical control strategies to modern learning-based techniques. Early solutions often relied on **trajectory optimization** or **model predictive control (MPC)**, both of which require detailed models of the robot’s kinematics and dynamics, as well as precisely tuned sensor feedback systems. These methods often depend on tightly calibrated environments and can be computationally demanding, making them more suited for controlled laboratory conditions than real-world deployment. In more recent years, particularly within the last two to three years, there has been a surge in the use of deep reinforcement learning (DRL) and imitation learning to train policies for complex bipedal locomotion. These approaches have enabled robots like Boston Dynamics’ Atlas [1], Agility Robotics’ Digit [2], and various models from Unitree Robotics [3] to perform robust, agile, and visually impressive walking behaviors. However, these systems typically rely on high-performance onboard or offboard computation, expensive sensors, and long training periods involving large-scale data collection [9]. As a result, they are inaccessible to most research institutions and universities, limiting reproducibility and practical experimentation.

Furthermore, while many humanoid robots can be teleoperated or guided using simple user interfaces, their walking

controllers are often built on predefined state machines or fixed gait sequences with limited adaptability. These controllers may include basic user input mechanisms but typically lack smooth transitions or responsiveness to dynamic user intent. In some cases, input recognition is limited to symbolic gesture detection or command mapping, which fails to reflect the nuanced motion control required for expressive locomotion [6], [7].

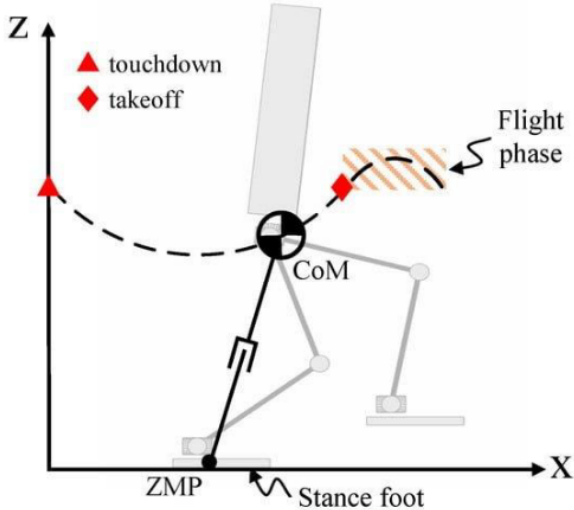


Fig. 1: The **zero-moment point (ZMP)** follows a planned trajectory within the support polygon to ensure dynamic stability as the robot transitions through single and double support phases during walking.

This work positions itself as a lightweight, accessible alternative. It bridges the gap between simplistic finite-state gait controllers—such as those used in DARwIn-OP’s default Webots simulation [4]—and complex machine-learned policies deployed on robots like Atlas and Digit [1], [2]. By enabling adaptive omni-directional dynamic walking through real-time binary (keyboard) or continuous (joystick) inputs, the controller offers greater expressiveness than static gait libraries [5], [6] and greater accessibility than reinforcement learning-based systems [8], [9]. Crucially, this approach does not rely on deep learning, external feedback loops, or high-cost actuators. Instead, it demonstrates that effective, naturalistic walking behaviors can be achieved on legacy platforms using a thoughtfully designed and smoothly modulated control architecture.

### III. SYSTEM ARCHITECTURE

#### A. Simulation Environment

The Darwin OP model in Webots features 20 degrees of freedom, each represented by individually controlled servo motors. These are accompanied by a suite of virtual sensors, including accelerometers, gyroscopes, foot-ground contact sensors, and joint position sensors. Webots simulates accurate foot-ground interaction and supports real-time visualization of motion dynamics, making it ideal for testing balance, trajectory, and walking behavior under different control inputs.

#### B. Controller Design

The architecture of the proposed controller is modular, lightweight, and highly responsive. It is designed to operate in real-time, utilizing either **discrete binary inputs** (via keyboard) or **continuous analog inputs** (via joystick) to drive the walking behavior. Both interfaces share a common low-level control structure, ensuring consistent behavior regardless of the input modality. Input data is processed at each simulation time step, triggering appropriate gait modulation functions based on the user’s commands.

#### C. Hardware Abstraction and Robot Interface

The Webots environment provides an abstracted hardware layer where motor control and sensor feedback are accessed via prebuilt API calls. The Darwin OP’s motors are interfaced using Motor and PositionSensor objects, while inertial data (from virtual IMUs) is read using Accelerometer and Gyro modules. This abstraction enables seamless controller deployment and simplifies integration between control logic and hardware behavior.

#### D. User Input Handling

The controller supports both binary keyboard input and analog joystick input through dedicated interface modules. In both modes, a deadzone filter is applied to prevent unintentional movements caused by noise or small signal fluctuations. Input values are mapped to three primary gait amplitudes:

$$A_x, A_y, A_\theta$$

These amplitudes are updated in real time using ramp functions:

$$A_{t+1} = A_t + \Delta a - \delta A_t$$

Where  $\Delta a$  is the user-driven acceleration component and  $\delta$  represents natural decay when no input is active.

#### E. Gait Modulation and Execution

At each simulation step, the gait amplitudes are passed to the Webots-integrated **GaitManager**, which translates them into lower-level motor commands. This modulation process occurs continuously, allowing the robot to smoothly accelerate and decelerate its walking motions in any direction. The use of ramp-based amplitude updates enables more lifelike motion transitions, avoiding the abrupt start/stop behavior typical in traditional gait state machines.

### IV. EXPERIMENTS AND RESULTS

To evaluate the effectiveness and responsiveness of the proposed walking controller, a series of exploratory walking trials were conducted in the Webots simulation environment using the Darwin-OP humanoid robot model. The controller was implemented using C++ within Webots’ native control interface, utilizing the built-in Darwin OP model provided by

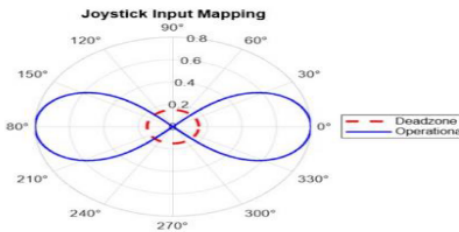


Fig. 2: This polar plot illustrates how the controller interprets user joystick input. The **red dashed circle** represents the deadzone threshold, a region near the centre where small inputs are ignored to prevent unintentional drift due to hardware noise or idle hand motion. The **blue operational curve** outlines the range of joystick input values that are mapped to gait amplitude commands. Once the input exceeds the dead zone, amplitude scaling begins using a nonlinear function to ensure smooth, controllable motion transitions. This mapping supports precise low-speed movement and full-speed dynamic walking as input pressure increases.

the simulator. The controller accessed the robot’s motors and sensors through Webots’ API and updated gait parameters at each simulation step based on real-time user input. The walking behaviour was modulated through amplitude adjustments passed to the Gait Manager, with different input sources—keyboard or joystick—processed through the same motion control logic.

The experiments involved manually teleoperating the robot using both the keyboard-based controller and the joystick-based controller, observing its gait transitions, stability, and ability to respond to directional inputs over time. The robot was walked in multiple directions — forward, backward, laterally, and rotationally — with emphasis on transitions between these motions. In the keyboard mode, discrete keys were held and released to observe the smooth ramp-up and decay of walking amplitude. In joystick mode, analog stick movements were varied in magnitude and direction to examine continuous gait modulation and the impact of the dead zone filter.

The robot demonstrated consistent dynamic behavior across all motion axes, with no sudden jolts or unstable transitions. It maintained balance without explicit feedback-based corrections, indicating that the controller’s amplitude ramping and natural deceleration contributed to a stable walking cycle. The omni-directional movement capabilities were fully operational, enabling fluid blending between walking directions in real time.

No reinforcement learning models, external feedback loops, or dynamic rebalancing algorithms were used, yet the robot was able to produce lifelike and expressive walking motions throughout the trials. These results confirm that the proposed architecture, even when deployed on a legacy platform like Darwin OP, can achieve reliable and adaptive locomotion using simple user-driven input mechanisms.

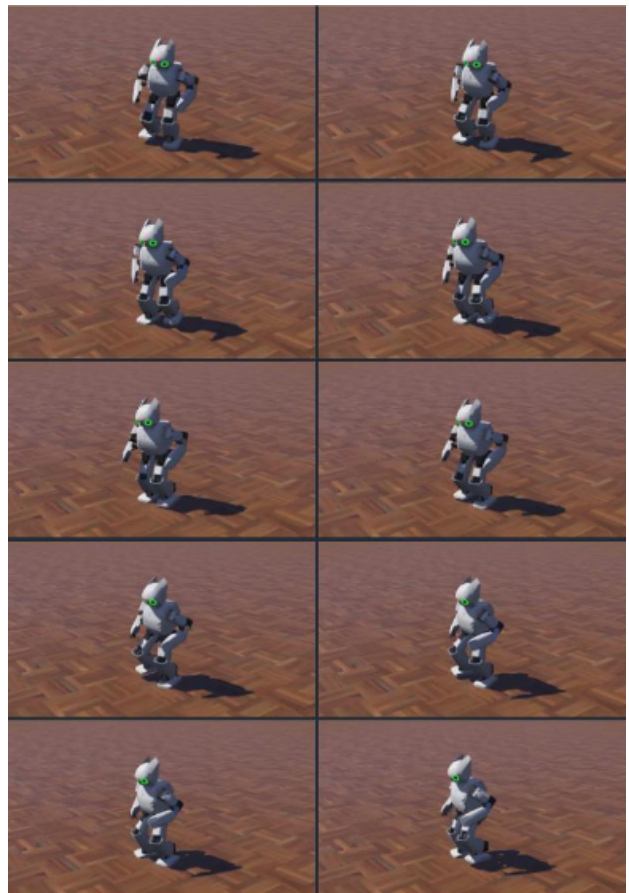


Fig. 3: The controllers developed in this project influence the robot’s dynamic stability margins during locomotion. Unlike static walking, where the center of mass (CoM) stays within the support polygon, dynamic walking introduces shifts in stability based on motion amplitude and velocity. As gait amplitudes increase—especially with joystick inputs—the center of pressure (CoP) moves more aggressively but remains controlled. The system maintains stability through smooth acceleration and deceleration, without relying on complex balance algorithms. This results in robust, stable locomotion driven by natural momentum and directional gait shaping.

## V. CONCLUSION

This work presents a lightweight, modular, and expressive dynamic walking controller for the DARwIn-OP humanoid robot, implemented within the Webots simulation environment [4]. By leveraging both discrete (keyboard) and continuous (joystick) input modes, the controller enables smooth, omni-directional locomotion without reliance on complex machine learning models [9], real-time feedback controllers, or expensive hardware [1], [2]. Through the use of amplitude ramping, deadzone filtering, and directional gait modulation, the system produces lifelike and adaptive walking patterns that remain stable across a variety of user-driven inputs.

The key novelty of this controller lies in its ability to translate user intent—whether binary or analog—into continuous, momentum-aware, omni-directional walking behavior. Unlike traditional controllers based on finite-state transitions or fixed

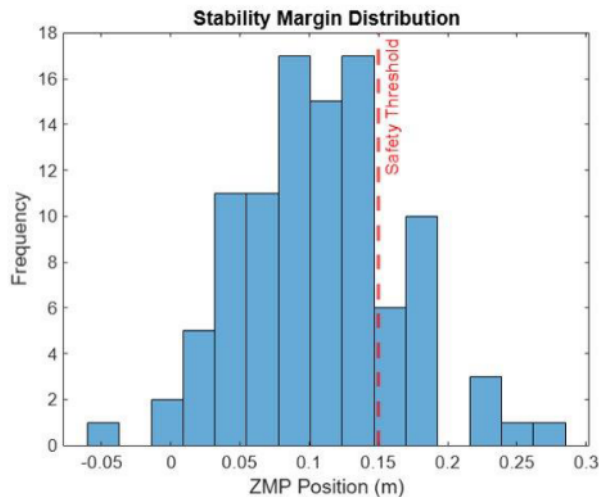


Fig. 4: In this figure it showcases the novelty of these controllers lies in transforming simple user inputs into smooth, adaptive dynamic walking without relying on machine learning or heavy computation. They enable realistic momentum and continuous gait modulation—features rarely seen in small humanoid teleoperation

trajectories [5], [6], this system enables seamless motion blending across multiple axes (forward, lateral, rotational), resulting in fluid and human-like transitions. It supports dynamic response to varying input magnitudes, allowing for expressive gait shaping that reflects walking speed, direction, and intent—all without requiring model-based optimization or reinforcement learning policies [8].

This work also uniquely demonstrates that expressive and dynamic locomotion can be achieved even on legacy humanoid platforms, such as DARwIn-OP with Dynamixel actuators [4], using minimal computational resources. The controller extends the expressive potential of these systems beyond their original, limited gait frameworks and toward more adaptable motion control.

Future work will explore extending this controller to handle terrain adaptation, multi-step planning, and integration with lightweight learning mechanisms for semi-autonomous gait refinement. Real-hardware deployment will also be a critical step in validating this approach and potentially expanding its application beyond simulation, toward real-world human-robot interaction scenarios.

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