Dynamic Multi-Contact Bipedal Robotic Walking

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1 Motivation

With thousands of years evolution, human walking developed continuously to an extent that it exhibits amazingly robust properties, and therefore, is one of the factors why human walking serves as a good example for bipedal robotic research. During the course of a step, humans undergo changes in phase [3], i.e., a change in contact points with the environment, including a heel-lift and toe strike, which is the main reason that awards human locomotion the advantages such as various terrain adaptivity and energy efficiency. Our approach starts with the understanding of multi-contact behaviors of human locomotion, then incorporates these intrinsic features into robotic walking through the design of the human-inspired controllers and optimization. Utilizing the essential formal elements of the controllers and optimization which generated these gaits, the results can be successfully implemented on to different physical robots.

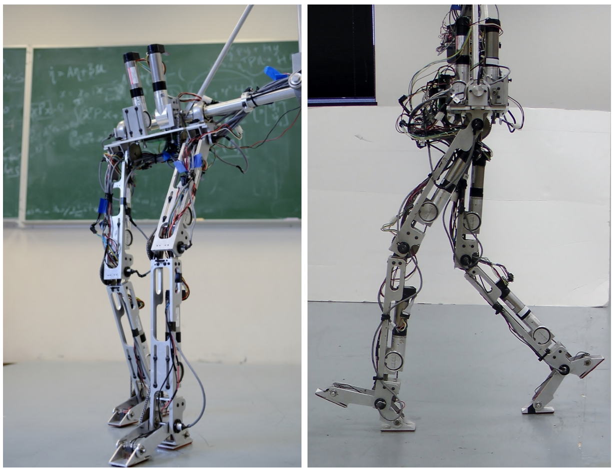


Figure 1: The bipedal robot AMBER2 (left) is constructed with the specific goal of multi-contact locomotion as indicated by the design of the feet (right).

2 State of the Art

Robotic walking has been studied from a variety of viewpoints, most of which are aimed at the ultimate goal of achieving human-like locomotion on bipedal robots. The vast majority of these approaches attempt to reduce the complexity of the problem through simplifying assumptions revolving around the ZMP point [8], [10]; yet, by the nature of the fact that these methods require the center of pressure to lie within the foot, i.e., the feet are required to remain flat while walking. As a result, these assumptions tend to preclude the human-like behavior of multi-contact locomotion. On the other end of the spectrum, formal methods for achieving bipedal locomotion have been presented in the case of underactuated walking robots with point feet through the use of hybrid zero dynamics [7, 6], some of which have been adopted to multi-contact walking in simulation [4]. Finally, recent work from the coauthors has looked toward human-locomotion for inspiration for the synthesis of walking controllers, both in the case of under [9] and full actuation [5]. Noticeably lacking from existing methods from any of these perspectives is a formal way to generate multi-contact locomotion in a manner that is both formally correct as well as physically realizable.

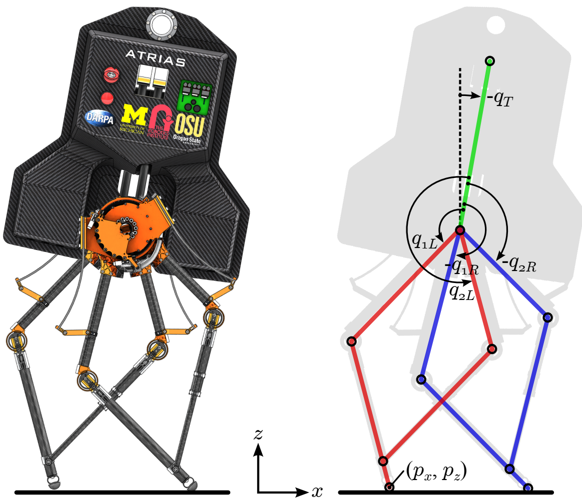


Figure 2: The coordinate configuration of the robot.

3 Own Approach

Our approach starts by noting that the multi-phase behavior of human locomotion can be represented as a multi-domain hybrid system. In this fashion, we create a hybrid system for a bipedal robot consisting of different actuation types of domain with transitions occurring at heel-strike, toe-strike and heel lift. Further motivated by human walking, we then introduce human-inspired controllers for the continuous dynamics in each of these discrete domains. To account for the hybrid nature of the system, a novel multi-domain optimization is proposed to ensure invariance of the zero dynamics surfaces. The end result is the generated controllers that yield human-like multi-contact locomotion as verified in simulation. This

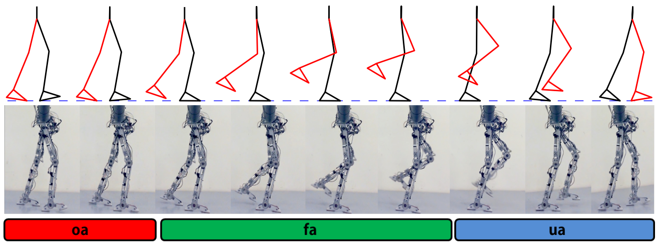
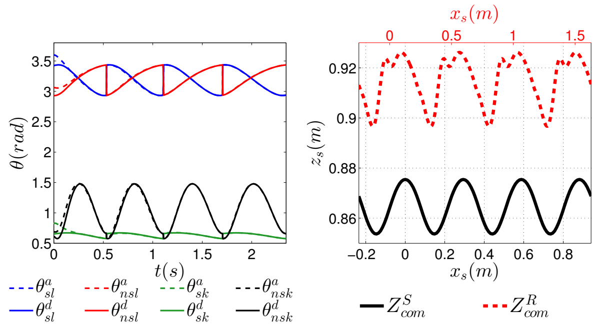


Figure 3: Comparison of walking tiles of simulated and experimental walking with PD control.



(a) Outputs (b) Center of Mass Position

Figure 4: Simulation results: (a) Desired versus actual outputs starting from a perturbed point. (b) A comparison of the center of mass trajectory between the ideal SLIP gait and the full-order robotic model.

formal result is first translated to the robot AMBER2 (**A&M** **B**ipedal **E**xperimental **R**obot 2). Followed by the formal construction, a novel trajectory reconstruction and the essential implementation similar to the process that generates the walking gait are implemented on the hardware to achieve robust human-like multi-contact walking.

Inspired but not limited to human-like multi-contact locomotion, this methodology is then extended to another underactuated compliant robot ATRIAS (**A**ssume **T**he **R**obot **I**s **A** **S**phere) to achieve bipedal walking by formally emulating gaits produced by the Spring Loaded Inverted Pendulum (SLIP). The formal framework of multi-domain hybrid system is specifically formulated that faithfully represents the full-order dynamics of ATRIAS. The SLIP model is used as a basis for constructing SLIP-inspired controllers that yield a dimension reduction through the use of hybrid zero dynamics. This allows for the formulation of an optimization problem that produces a stable SLIP-like periodic gait. Finally, similar hardware implementation strategy will be realized on the physical robot ATRAIS.

4 Current Results

Utilizing the methodology discussed above, AMBER2 displays qualitatively human-like walking with distinct multi-contact behaviors in a dynamic fashion. In comparison with the simulated walking with synchronized speed, the experimental walking gesture (i.e., walking pattern, as shown in Fig. 3) matches up exceptionally well with the simulated walking, which can be seen in the video [1]. On the other hand, the experimental result of ATRIAS shows a dynamically stable walking gait that exhibits multiple discrete phases of walking consisting of double and single support [2]. The comparison of the center of mass trajectory of the walking against SLIP walking gait shows very similar behavior, as shown in Fig. 4. Note that, the walkings of both AMBER2 and ATRAIS also show remarkably robustness with ability to overcome big obstacles and endure instantaneously push, the details of which can be referred to the attached videos.

Acknowledgment

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