Human-Inspired Bipedal Robotic Walking: From Theory to Experimental Implementation on AMBER

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1 Introduction

In this work, an approach towards experimental realization of underactuated bipedal robotic walking using human data is presented. Specifically, by studying experimental human walking data, we find that specific outputs of the human, i.e., functions of the kinematics, appear to be canonical to walking and are all characterized by a single function of time, termed a human walking function. Using the human outputs and walking function, we design a human-inspired controller that drives the output of the robot to the output of the human as represented by the walking function. The main result of this work is synthesis of a voltage based control law for rigid link electrically driven underactuated 2D bipedal robot. This result is demonstrated through the simulation and experimental implementation on a physical biped -AMBER. A state-based parameterization is introduced to remove time dependence and "Proportional feedback" control is used to track these functions. This leads to an autonomous feedback control law which results in stable, humanlike walking in two dimensions.

Keywords: Underactuated Walking, Bipedal Walking, Human-Inspired Control.

2 Motivation

The main idea behind this work is that, to achieve truly human-like robotic walking, one should first look to human walking. The simplicity that humans display when walking motivates the construction of a human-inspired controller for bipedal robots, especially in the case of underactuation where dynamic stability is necessary. For simple walking behaviors, such as walking on flat ground, locomotion appears to be controlled, or at least largely influenced, by central pattern generators in the spinal cord, resulting in very little cognitive load. This seems to imply that there are simple patterns present in human walking which, if they can be identified, can be exploited through robotic control to achieve human-like robotic walking. Design of controllers which are computationally tractable and therefore more realizable on physical robots is also one of the key objectives of this work. We have also drawn inspiration from the work on dynamic robotic walking, including but not limited to: passive walking, controlled symmetries, and hybrid zero dynamics.

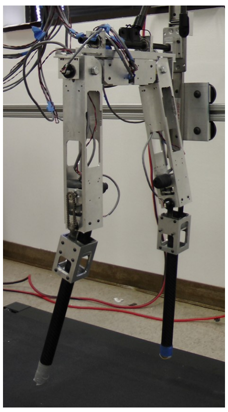

Figure 1: Picture of AMBER with Boom

3 State of the art

Bipedal Robotic Walking was still in its nascent stages until Marc Raibert came up with the idea of using inverted pendulums with hoppers and Tad Mcgeer introduced the concept of passive walking.Tad Mcgeer's concept of passive walking had a significant impact in changing the way people thought about walking. In fact, he was the one who showed that it is possible to make a 4 link biped walk down a slope without the use of any actuators, i.e., by completely using its potential energy. Collins biped came into the purview which used the concept of passive walking and developed new control strategies based on passivity based control ([3]). In fact, his biped came out to have least specific cost of transport, the standard method used to compute the cost to take one step normalised by the dimension of the robot. As the years went by, more and more people continued with the idea of using passive walking like Mark Spong, and Ambarish Goswami, Martijn Wisse and Andy Ruina [3].

Later on, Jessy Grizzle made significant strides in making underactuated bipeds (no feet) walk with the idea of hybrid zero dynamics [4]. He made the links follow a certain set of desired trajectories obtained from the Bézier polynomials. These Bézier polynomials were constructed in such a way that the biped was still tracking the polynomials despite the impacts (when the swinging foot hits ground). It basically means that the biped was not getting thrown away from the desired trajectories due to the impacts.

Coming to human walking, it has been studied extensively in the field of biomechanics, typically being analyzed by decoding its inner kinematics and kinetics, such as muscle functionality, ground reaction force, and energy expenditure in the design of prostheses and hip replacements. The complexity of the human muscle and nervous system prevents the direct application of the results from biomechanics to robot design. Some research had been attempted to bring down this gap by determining the inverse kinematics and forward kinematics of human walking, but the complexity of these methods prevent their direct application to robotic control.

4 Our own approach to this question

This paper attempts to bridge the gap by providing insight from the viewpoints of both control and biomechanics by using the kinematics data from a human walking experiment for controller design [2]. We begin by looking at human walking data, i.e., angles over time, achieved through motion capture of subjects walking on flat ground. Viewing this data as the samples from a highly complex system, we seek output functions of this data that appear to characterize the system- these should be mutually exclusive, thus providing a low dimensional representation of the system's behavior. After collecting the outputs of this form, we find that these human outputs, as computed from the data, appear to be described by a very simple function: the time solution to a linear spring-mass-damper system. Thus, humans appear to act like linear spring-mass-damper systems when walking on flat ground.

Then, by using input/output linearization, we can construct a torque based underactuated control law that drives the output of the robot to the output of the human, as represented by the canonical walking functions. We characterize the zero dynamics associated with the human-inspired controller and obtain conditions on the parameters of this controller that guarantee hybrid zero dynamics. The problem of finding a stable walking gait is thus reduced to a 2-dimensional system and, through energy methods, the existence of a stable periodic orbit can be determined through simple inequalities. Utilizing these conditions as constraints on an optimization problem, where the cost is the least squares fit of the human walking functions to the human walking data, we obtain parameters for the human-inspired controller that result in stable underactuated robotic walking that is as close as possible to human walking. The formal results of this paper are demonstrated on the model of a 2D underactuated bipedal robot AMBER (shown in Fig. 1). In particular, we construct a hybrid model of this system and utilize human-inspired control to obtain stable robotic walking for this biped as demonstrated through simulation.

Since the biped has nonlinear dynamics, implementing a linearizing controller is very computationally intensive and is sensitive to the changes in robot parameters, hence a linear control law is used to track the canonical walking functions derived from the torque control based optimization problem discussed above. Since the actuators have voltage as input, a simple feedback proportional control law on the output functions is used, which produces the required voltages to the actuators, thereby resulting in AMBER walking. The stability of this voltage based control scheme is verified numerically through simulation studies by adding motor model to the hybrid model of the robot and it is found to be very robust to terrain changes. While maintaining an experimental walking gait that is very close to the natural human walking gait as seen in Fig. 2, it is observed that the robot can handle changes in terrain of up to 4cm and disturbances from experimenter on various links including stance knee, and hip.

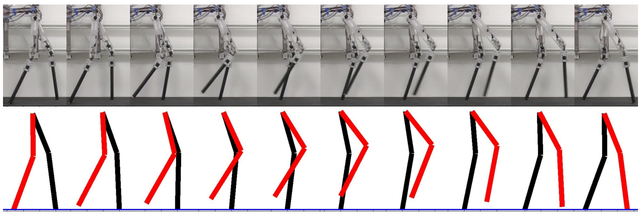

Figure 2: Walking tiles: AMBER Walking Vs Simulated Walking. See [1] for the video of AMBER walking.

5 Discussion Outline

The following sections will be covered in detail during the full presentation:

- AMBER model and the experimental setup.
- Human walking experiment and the canonical walking functions used to fit with the data.
- Human-Inspired torque control, which involves linearizing the dynamics and making the outputs of the robot track the canonical walking functions in simulation.
- Human-Inspired voltage control, which involves study and application of P control with voltage as the control input.
- Experiment results, which involves comparing the walking obtained in the simulation and that obtained with AMBER.
- Performing robustness tests on AMBER like disturbances on various joints and walking over wooden planks.

6 Format

We would like to present our work for a talk.

References

[1] Amber walking on the treadmill and undergoing robustness tests. `http://www.youtube.com/watch?v=SYXWoNU8QUE`.

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[4] E. R. Westervelt, J. W. Grizzle, C. Chevallereau, J. H. Choi, and B. Morris. *Feedback Control of Dynamic Bipedal Robot Locomotion*. CRC Press, Boca Raton, June 2007.