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Gait design for an ice skating humanoid robot

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HIGHLIGHTS

- Unmodified ZMP-based walking gaits are unsuitable for walking on low-friction surfaces.
- A skating-style gait for a humanoid robot using only lateral motions is possible and improves stability.
- Modified ZMP-based walking gaits maintain higher speeds, but are less stable than skating-style gaits.

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ABSTRACT

Basic walking gaits are a common building block for many activities in humanoid robotics, such as robotic soccer. The nature of the walking surface itself also has a strong affect on an appropriate gait. Much work is currently underway in improving humanoid walking gaits by dealing with sloping, debris-filled, or otherwise unstable surfaces. Travel on slippery surfaces such as ice, for example, greatly increases the potential speed of a human, but reduces stability. Humans can compensate for this lack of stability through the adaptation of footwear such as skates, and the development of gaits that allow fast but controlled travel on such footwear.

This paper describes the development of a gait to allow a small humanoid robot to propel itself on ice skates across a smooth surface, and includes work with both ice skates and inline skates. The new gait described in this paper relies entirely on motion in the frontal plane to propel the robot, and allows the robot to traverse indoor and outdoor ice surfaces more stably than a classic inverted pendulum-based walking gait when using the same skates. This work is demonstrated using Jennifer, a modified Robotis DARwIn-OP humanoid robot with 20 degrees of freedom.

1. Introduction

Over the past decade, dynamically stable humanoid walking gaits have been developed to allow robots to traverse flat terrain. Such gaits generally make the assumption that the ground is level (or nearly level), free of debris, and has a surface with sufficient friction to prevent the robot's feet from slipping (e.g. smooth concrete, thin carpet, ceramic tiles). When any one of these assumptions is violated the gait becomes unstable and the robot may fall over.

While such basic gaits remain very common building blocks to current humanoid robot applications (e.g. robotic soccer, or basic locomotion for more advanced FIRA HuroCup challenges such as the obstacle run), such gaits must be greatly improved to make humanoid robots more broadly applicable to the real world. Most of the real world involves uneven terrain—robotic firefighters must be able to traverse a debris field, for example. Even in relatively forgiving environments such as domestic service, humanoid robots must contend with common household obstacles such as carpet edges, stairs, or toys left on the floor.

The ability of a humanoid robot to traverse completely unstructured environments with the ease of humans is a long term goal. Further research in sensors, materials, power, intelligent control, and the interactions between all these, will be necessary to achieve this. In the nearer term, however, there is much we can do to improve walking gaits in order to move towards this goal. Challenges such as those in the FIRA HuroCup [1], which force robots to make broader use of upper body movements and complex motion planning, challenge walking gaits to be more adaptive, for example [2]. Much work is being done on adaptations to various types of uneven or unstable terrain (e.g. [3–5]), including debris and slopes.

In addition to these types of variations, it is equally important to consider variations in the nature of the walking surface and their effects on gait. Humans walk differently on a surface that can be slippery, such as wet linoleum indoors or ice outdoors—or rather, there is a significant danger of falling if a human gait is not adapted for such conditions. The most obvious adaptations are for stability; even children readily see that it is possible to travel much faster on slippery surfaces than normal indoor terrain, provided

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that expectations of the ability to stop or change direction quickly are relaxed. The types of human gaits required to travel on ice or other slippery surfaces quickly are modified further through the addition of specialised footwear such as speed or figure skates, which support greater speed and control.

In this paper, we describe the development of Jennifer, the world's first ice skating humanoid robot. Areas that support skating, such as skating rinks, frozen lakes, and icy concrete have little friction, but are generally assumed to be flat and free of debris. Our goal in this work is to explore gaits that support controlled travel on skates, in order to better support a broader range of walking motions. By designing a stable gait to facilitate movement across ice or other low-friction surfaces, we move closer to designing a robot capable of traversing heterogeneous surfaces, shifting between walking and skating gaits as needs dictate.

Beyond this goal, however, there are also practical reasons for supporting gaits for travel on ice. Navigating over ice patches is a requirement for any humanoid robot that is intended to be useful in outdoor environments in polar or sub-polar regions, or in temperate regions during the winter months. The geography of Canada includes all of these regions. Furthermore, skating is the fastest method of humanoid locomotion without additional mechanical support. Partly because of the speed afforded, travel on skates has historically been an important means of everyday human transportation, such as on frozen canals in the Netherlands in the 16th and 17th centuries [6]. By allowing a humanoid robot to move over slippery environments stably, while taking advantage of these low-friction surfaces with a skating-style gait, we can ultimately make robots able to traverse terrain more quickly than a standard walking gait would allow.

The remainder of this paper is organised as follows. Section 2 relates our work to the state of the art in humanoid robotics. Section 3 relates the differences between travel on slippery vs. non-slippery surfaces, and Section 4 follows this with a description of the robot hardware used in this work, including the design of ice skates and a modification supporting inline skates for use when ice surfaces are unavailable for testing. Section 5 describes a gait that allows a humanoid robot to propel itself on ice skates across a smooth surface, and discusses the evolution of this gait from attempts to modify an existing robot walking gait to the development of a new gait specifically designed for moving on skates. This new gait relies entirely on motion in the frontal plane to propel the robot forwards. Experimental results comparing the speed and stability of the skating gait with a standard walking gait are presented in Section 6.

2. Related work

Humanoid walking gaits for robots have seen significant development over the last decade. Dynamically stable gaits based on the linear inverted pendulum model [7,8] have become the current standard. These gaits model the robot as an inverted pendulum; the robot's support foot contains the fulcrum, the support leg forms the rod, and the upper body forms the mass, as shown in Fig. 1. By varying the length and angle of the rod – flexing or extending the ankle, hip, and knee joints – and by manipulating the location of the zero moment point (ZMP), the robot's centre of mass (CoM) can be controlled, propelling it forward or backward, or keeping it stationary in a stable position.

Gaits based on the inverted pendulum model consist of two distinct phases: the single support phase (SSP) and the double support phase (DSP). During the DSP the robot is statically stable with both feet on the ground with the CoM located above the support polygon formed by the feet. During the SSP the robot is unstable: the front foot is the support leg and the robot pivots about the ZMP, falling forwards. While the robot is falling forward, it swings its non-support leg (the "swing leg") forward as well. The SSP terminates when the swing leg lands, beginning a new DSP. These phases are illustrated in Fig. 2 (taken from Baltes and Lam [9]).

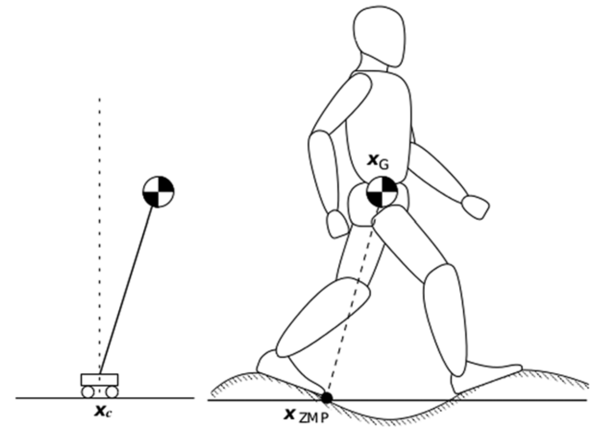

Fig. 1. An inverted pendulum (left) and a humanoid system, showing the fulcrum, rod, and mass of the pendulum (Sugihara et al. [8]).

Because walking gaits such as that described above are cyclical in nature, they rely on an internal timer to control the timing of transitions between SSP and DSP, and vice versa. On level terrain with good traction this does not cause problems. However, when presented with uneven terrain (e.g. inclines, variable-level terrain) the gait can become unstable [5]: when the gait's internal timing no longer corresponds to the robot's physical state the robot can fall over. One strategy for stabilising the gait is the use of gyroscopic sensor data with walking phase modification [10,9,11,3].

If a robot is traversing uneven terrain, it is likely that the transition from SSP to DSP may occur at unexpected times: a slight elevation in the terrain may cause the swing leg to touch the ground early. Likewise, a depression may cause the swing leg to touch the ground too late. In either case, the gait's internal timing no longer corresponds with reality, and the robot can become unstable.

Walking phase modification allows the robot to dynamically control the start and end timing of each phase. By using gyroscopes to measure a robot's angular velocity along the X, Y, and Z axes, it is possible to detect when a robot has transitioned from the SSP to DSP and vice versa. If the sensors detect that the swing leg has touched the ground earlier than anticipated, the remaining time in the SSP can be discarded, and the robot can begin the DSP. Similarly, if the SSP time expires but the sensors indicate that the swing leg has not yet touched the ground, the SSP can be continued. This technique has been shown to stabilise statically stable gaits [11] as well as dynamic gaits [10].

Skating robots are relatively uncommon, though some work has been done on non-humanoid robots equipped with inline skates [12,13]. Statically stable gaits using 4-DOF robots equipped with inline skates have been demonstrated to be able to propel themselves forward and turn in either direction by swinging the skates in cyclical patterns [13]. These robots rely on a central, omnidirectional caster for balance, unlike a humanoid robot which must balance on skates.

3. Mechanical differences between skating and walking

Skating and walking are both forms of bipedal motion, but differ significantly when analysed from a mechanical perspective. The differences lie primarily in how they exploit ground reaction forces: walking uses high-traction surfaces to push the subject