Dynamic Walking of Humanoid Robots: Research Proposal

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1 Introduction

Humanoid robots have remained an open problem for the last few decades. Over the last ten years, we have seen tremendous growth in the field, with the emergence of more and more academic research laboratories generating knowledge and industry spearheading the commercializing of general-purpose legged robots. This rapid progress has been possible due to the advances in both the hardware platforms and the sophisticated control approaches for the loco-manipulation problems in legged robotics. Despite these advances, many challenges and problems remain for these robots to be safe, useful, and reliable in the real world. This is due to the complexity of robot dynamics, the uncertainty of the environment, and the many different modeling, planning, control, and algorithmic choices.

In this work, we focus on the dynamic locomotion problem. There exist different kinds of model-based hierarchical frameworks and approaches that attempt to decompose the problem of generating and executing walking motions into smaller subproblems [1], [2], [3], [4]. We can generally split the problem into low-level control, high-level control, and planning. This terminology may vary from study to study, however, we will define what we mean for each in the context of this one. Low-level control refers to the control of motor current and torque, given some desired position, velocity, or torque command.

High-level control is the approach we use to generate the low-level commands, given some motion plans or trajectories. There is a need for control frameworks and approaches that reconcile multiple motion tasks subject to system dynamics and contacts between the robot and the environment (whole-body control). High-level control can be split into predictive and reactive controllers [1]. Predictive controllers utilize the system model to make sense of the consequences of the actions to predict the future state of the robot and iteratively devise and improve motion plans given the current state. Reactive controllers, on the other hand, are a problem of instantaneous control since they only consider the control action at the current state.

Another major area of research is planning and generating trajectories that are dynamically feasible for different behaviors, including walking. The planning part of the problem depends on the planning space and the horizon (i.e. how far into the future am I planning). The planning module can take care of, for example, devising a long-horizon nominal plan for footstep locations to go from Point A to Point B in a room, or short-horizon planning for COM motion given user-specified parameters, which can also be taken care of in a predictive controller.

2 Research Problem

Planning and control frameworks for dynamic humanoid walking must be efficient and optimal. If the system is not fast enough, it may not be able to respond to environmental disturbances or even system inaccuracies in the real world, and if it is not optimal, the robot may be unstable and fall. A crucial consideration in designing planning and control frameworks for bipedal walking is the choice of dynamic models used in the problem formulation. Ideally, the whole-body (or full-body) dynamics model of the robot would be used in the control framework. However, the dynamics of humanoid robots are high-dimensional and nonlinear, which leads to inefficient and sub-optimal plans and controls, which are not feasible due to real-time requirements. An alternative to the high-dimensional whole-body model is to use simplified or reduced models. Common examples of this include centroidal dynamics, linear inverted pendulum (LIP), spring-loaded inverted pendulum SLIP), and single-rigid-body (SRB) models, all of which have their assumptions, advantages, and disadvantages. In general, however, the models either contain nonlinearities or impose artificial restrictions on possible movements [1]. *What is a model that is descriptive enough for the walking problem under disturbances, but is also tractable for online planning and controls?*

The walking problem is a broad one and can be framed in different ways. One way that has been done is the go-to problem, where the robot goes from one place to another given an environment. Typically, the robot uses a contact planner that plans nominal footsteps, and then a high-level controller generates dynamically feasible motions tasks to follow the footstep plan [4], [3], [2], [5]. Another way is to consider high-level user-specified goal objectives such as step duration, step length, COM height, and pelvis heading [6], or speed and velocity command and gait type [7]. The system then generates motion plans to achieve these high-level goals. In this work, we are interested in the latter way of framing the walking problem. Our proposed study is inspired by the work of the former. In that work, the authors present a model-based locomotion controller based on online short-term planning. They leverage low-dimensional models to allow for online planning using preview optimization. Stance dynamics are modeled with the SLIP model, and projectile motion equations are used for the flight dynamics. Although their results are impressive, there are some limitations to their work. Mainly, their low-dimensional model (SLIP) does not consider angular momentum regulation, since SLIP assumes a point-mass model. This leads to another question: *how would employing a different low-dimensional model that allows for angular momentum regulation improve the performance of walking? Even further, how does angular momentum regulation through a more descriptive model improve walking under external disturbances?*

Another key limitation of the previous work is the allowance of inter-limb collisions. Although this may be enough for the research in animation and computer graphics, to extend this work to the application of real humanoid robots, inter-limb collisions, and general kinematic constraints are crucial for the task of walking. *How can we incorporate these kinematic constraints in a way that still allows for online planning?*

A final question remaining is *how we can test the results of a new preview optimization block by integrating a whole-body controller.*

3 Objectives

- Formulate and implement a momentum-based predictive controller (preview optimization block) that uses a simplified model that accounts for angular momentum.
- Consider inter-limb collision constraints in the approach.
- Compare the performance of the proposed method with the old approach (preview optimization with SLIP).
- (Stretch) Integrate a whole-body controller to test the performance of the new approach in simulation.
- (Stretch) Test the approach on HURON hardware.

4 Literature Review

A lot of work has gone into devising planning and control frameworks for dynamic humanoid walking. A common approach to decompose the problem is to use model-based hierarchical frameworks. The problem can be split into low-level control, high-level control, and planning. If we ignore the motor control problem and assume that the lowest level of the problem is generating joint torques, velocities, or positions, then the problem is mainly decomposed into two main modules, a planning module and a tracking module [8]. The planning module, which is the main focus of this study, is responsible for generating trajectories and motion plans for different behaviors. A planner for a walking behavior, for example, could specify CoM motion, contact locations and forces, and swing leg trajectories. A planner for a back-flip behavior would then generate other kinds of trajectories, including angular momentum and angular excursion trajectories [9].

The planning module could be based on "hand-designed" motions from human studies. In [10] and [11], a quadratic Bézier curve with smoothing techniques is used to generate a CoM trajectory based on a human motion database. Although the approach is very simple, it lacks formal dynamic stability guarantees and does not account for external disturbances. With these kinds of planners based on motion capture and databases, trajectories for every desired situation, as well as the desired type and style of motion would be required, which is intractable.

An alternative, and a more accepted approach in the last few years, is to plan based on models that help us understand the dynamic properties of human motion. The planning module can be based on different dynamic models (full or simplified). As mentioned, full-body body dynamics are high-dimensional and nonlinear, making online planning a hard and possibly intractable problem. Simplified (aka. low-dimensional or reduced) models are then employed. Recent surveys offer a good overview of these models in the context of optimization-based methods [1] [12]. The Linear Inverted Pendulum Model (LIPM), originally proposed as a 2D model in [13], describes the motion of the CoM as a second-order ODE. It has been extended to the 3D case [14]. Several studies have based their work on this simplified model [15], [16], [3]. Its main limitations are that it restricts the CoM height to a constant height and assumes zero angular momentum, which removes orientation dynamics. To enable more versatile motions, the Spring-Loaded Inverted Pendulum (SLIP) model has been proposed [17], which removes the constant height assumption by adding a stiffness-like parameter. Studies have used this model for running motions [18]. While SLIP dynamics are nonlinear, an approximate SLIP model has been derived by decoupling and linearizing the inverted pendulum (IP) model for horizontal motion and adding a spring with constant stiffness in the vertical motion [6]. Our study is closely related to this one. However, the main limitation of the SLIP model is that it assumes a point mass, which ignores angular momentum, limiting the range of possible motions.

A more descriptive simplified model that could be used instead is the centroidal dynamics model [19], [20]. In this model, the whole-body dynamics are exactly projected at the CoM, while relaxing joint-space constraints. Although the model addresses the issue of high dimensionality, it ignores the kinematic and joint actuation constraints. This has motivated planning methods that consider centroidal dynamics with whole-body kinematics [21]. However, their formulation cannot be solved online. More recently, the authors in [22] and [8] attempt to use centroidal dynamics with whole-body kinematics in real-time within a model predictive control scheme. Our work is closely related to these as well. Their work is demonstrated on a quadrupedal robot with a manipulator. We will attempt to demonstrate a similar approach but on a humanoid robot by taking high-level user-specified parameters as inputs, like in [6].

The tracking module is usually based on a version of the original operational-space control formulation [23]. These methods are also known as reactive control [1], whole-body control (WBC) [24], or task-space inverse dynamics [25]. A recent survey provides a good overview of the different WBC approaches [24]. Although not the focus of our proposed study, we briefly mention the different main approaches. WBC techniques can be categorized in two main classes of approaches: closed-form (or null-space control) approaches [15] [26] [27] [28] [29] and optimization-based approaches [30] [31] [32] [25] [33] [34] [35] [36] [16] [3]. The output of our predictive controller, desired walking trajectories, will be executed through an optimization-based prioritized WBC, or hierarchical quadratic program (HQP), as in [34].

5 Proposed Methodology

We propose a dynamic walking framework similar to the one in [6] and [8]. The proposed framework takes user-specified goals as high-level inputs, including step length, step duration, COM height, and pelvis orientation. The framework contains three main blocks 1. Given the user-specified inputs, the planning module generates dynamically feasible trajectories at the highest level using short-horizon model predictive control (MPC). Instead of using the SLIP model as in [6], we follow a similar approach as in [8] and [36], employing the centroidal dynamics model and full kinematics. This middle ground provides the simplicity of the simpler dynamics while considering the expressiveness needed to consider kinematic constraints, like self-collision avoidance constraints. This approach is also an upgrade from SLIP as we can express a wider range of motions, including angular momentum. The tracking module, or whole-body controller, uses the optimal reference trajectories from the planning module to define prioritized tasks to be tracked. The WBC outputs desired joint torques to be sent to the robot. Since we plan to start with simulation, we will assume that we have a state estimator block that provides the current state of the robot, including floating-base and joint positions and velocities.

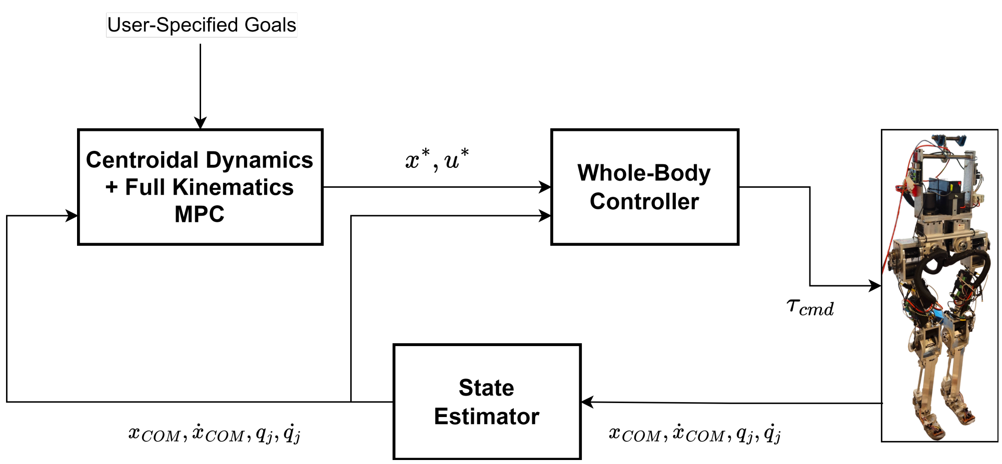

Figure 1: Proposed dynamic walking framework for HURON: User-specified goals (step length, duration, COM height, and pelvis orientation) guide the planning module, utilizing centroidal dynamics and full kinematics MPC to generate feasible trajectories. Optimal trajectories serve as task references for the hierarchical whole-body controller, generating desired joint torques. A state estimator provides feedback for MPC and WBC blocks.

We plan to use the *Pinocchio* library [37] [38] to compute the necessary kinematic transforms, Jacobians, and Centroidal Momentum Matrix (CMM) of the robot. Additionally, we also plan to use the *TSID* library [39], a C++ library for optimization-based inverse-dynamics control based on *Pinocchio* library. *TSID* uses hierarchical quadratic programming (HQP) to implement prioritized whole-body control. This will help us implement the WBC block.

6 Work Plan and Timeline

Our work will be conducted within one semester. The work will be split into two phases: Phase 1 and Phase 2. In Phase 1, we will work on formulating and implementing the planning module (centroidal dynamics and full kinematics MPC), which is the focus of our work. We will also implement the previous work from [6] to compare the performance of the SLIP preview optimization against our centroidal MPC planner. Some metrics to compare will be maximum running frequency, ability to avoid self-collisions, and ability handle model noise and external disturbances. The expected results will be figures and plots comparing performance. This should be completed by *mid-to-end of March*.

In Phase 2, we will implement the whole-body control block using existing the framework and library *TSID* and integrate it into the framework to track the generated trajectories by the planning module. This will allow us to visualize an actual simulation of the robot. We will use Gazebo [40] as our simulator. We will then be able to run another set of experiments for walking, with different user-specified goals and in the presence of external disturbances. This should take us about two to three weeks and be completed by *mid-April*.

A stretch goal of Phase 2 will be to run the proposed framework on the hardware. This will be fully dependent on whether the robot is ready or not. There are many missing components to the completion of HURON hardware, including finalized mechanical fabrication and assembly. Most importantly, the robot hardware is currently missing a reliable state estimation system. On the hardware side, I believe the robot does not have an IMU, which is crucial for floating-base state estimation. Also, system identification and filtering methods will most likely be needed to overcome model mismatches and noise. These challenges are beyond the scope of this thesis but are crucial for experimentation on hardware. Please see [35] for more details. Lastly, we will also need to be able to reliably send torque motor commands to the joint actuators.

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