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A Reactive Online Optimization Based Whole Body Contol for Quadruped Locomotion Over Challenging Terrain\*

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*Abstract*— This electronic document is a “live” template. The various components of your paper [title, text, heads, etc.] are already defined on the style sheet, as illustrated by the portions given in this document.

# INTRODUCTION

In the field of Civil Engineering, robots are being come up with as alternatives in restricted or hazardous environments. Especially in dangerous environments such as disaster relief situation, the need for robots is increasing. UAV, wheeled robots, and legged robots have been proposed to replace the workforce.

In the disaster environment, robots should make lots of interactions with its surroundings like activate valves, pull the lever, and go up and down the uneven platform. Wheeled robots, which have been widely used in the field, have limited performance to uneven terrain, large gaps, and obstacles made of debris, and so on due to their physical configuration. While UAVs can overcome some of these problem, they are easily affected by the climate like heavy fog and windy weather, and their payload capacity and energy autonomy can be limiting. Legged robots are better solution in the challenging environment mentioned above. Furthermore, since they can interact surroundings directly through anthropomorphous manipulators, they have a potential to perform versatile tasks.

Compliance is the essential ability for robot in order to interact safely with complex environments. The robots controlled by a traditional ‘joint position control method’ generally uses a high gain to maintain the endpoint position accuracy, thus their joints has high stiffness. To maintain robot compliance without sacrificing position accuracy, inverse dynamic control method is widely used.

Nowadays, researches have been conducted to control legged robot through inverse dynamics control method. Various studies have extended the ‘operational space control framework’ proposed by Khatib(1987) and applied to floating based system, through Quadratic Programming (QP) method. In other words, using the convex optimization to calculate the reference control that finest follows the desired motion which given in the task space, while satisfying various constraints. Hutter et al. (2014) and Hearzog et al (2014), using hierarchical method, projected secondary tasks to null space of the high-priority tasks, thus implemented secondary tasks without interfering with the high-priority desired motions. However, there were disadvantages in that it is hard to implement desired motions with same priority, and in specific situation, there is no feasible solution. In contrast to the hierarchical method that formulates the cost functions as hard constraints, Feng et al (2015) used soft constraints by adding corresponding terms with weight in the cost function.

Unlike the fixed base system, a contact force term exists in the equation of motion of the float base system, thus its sensing is needed. However, due to the characteristics of the force/torque sensor, the sensor noise is severe, if the low pass filter is used, the overall control bandwidth is decreased because of the phase delay. To compromised this issue, Sentis (2007), Aghili (2005) and Mistry et al. (2010) solved the QP problem using optimization states consisting of joint accelerations and joint torque except contact force by mapping the equation of motion to a support-consistent manifold. However, using the reduced optimization states has an issue that it is hard to handle the contact force constraint explicitly. Therefore, De Lasa et al. (2010), Bouyarmane et al. (2012) and Feng et al. (2015) considered to use full optimization states, which consisting of joint acceleration, joint torque and contact force. Although using the full optimization states can affect the computation time due to high dimensionality of QP, according to Feng (2015), it is still solvable in real time (3ms).

A method for generating a desired motion of a floating base system has also been intently studied. Zero Moment Point (ZMP) (Vukobratović et al., 2004; Kajita et al., 2003) based method generates reference CoM trajectory of robot through reference foot positions. However, ZMP based method generates the CoM trajectory from the predetermined foot positions, thus that the robot movement is highly restricted and its robustness against unexpected disturbance is degraded.

The method based on Capture Point (CP) (Pratt et al., 2006; Rebula et al., 2007) is to calculate the approximation of foot positions that can eventually stop the robot. It requires only the information about the CoM position and velocity of the robot. Moving speed of the robot could be adjusted by stepping CP with an offset. In contrast to the ZMP method, this method generates the reference foot positions that can maintain the stability by using feedback of the current CoM information. Thus, it is robust to external disturbance.

In this study, we propose a control framework, which has the following characteristics: highly compliant (safe interaction with environment), reactive to disturbance, and energy efficient. The framework integrates the work of previous researches in the humanoid field that gives the floating base legged robot abilities to work in a challenging environment. High-level controller performs optimization that formulates desired motion and reference foot positions for each control time step based on CP approach. In the low-level controller, we formulate the floating base inverse dynamics as a QP problem, and we directly optimize a quadratic cost in terms of optimization states consists of joint accelerations, joint torques, and contact forces.

The expected contribution of this study will be as follows:

The two-level optimization based control framework considers the reactive balance recovery strategy and full body inverse dynamics control problem separately, and it has potential to enable fast, dynamic, versatile interactions safely and robustly.

High-level controller: Contrary to general CP approach that only outputs a step location to maintain the stability of the robot, we use an optimization based CP approach with a simplified model that can handle physical constraints and solve for optimal controls that best track the CP.

Low-level controller: In contrast to the hierarchical method that formulates the cost functions as hard constraints, we use soft constraints by adding corresponding terms with weight in the cost function to handle the unfeasible solution and equal-priority motion problem. Furthermore, we use full optimization states (joint acceleration, joint torque, contact force) to formulate the convex optimization problem, since this choice of states is able to handle state dependent constraints such as non-slip friction constraints, joint torque limit, etc. Although the low-level controller is similar in spirit to Feng (2015)’s work, but the objective cost functions according to behavior motion are focused on quadrupedal robot rather than bipedal robot.

We will verify and show that the proposed optimization control framework can robustly stabilize the quadruped robot under large external disturbances.

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