[[1]](#footnote-1)

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

First A. Author, Second B. Author, Jr., and Third C. Author, Member, IEEE

*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, their priority 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(past), have limited approach to uneven terrain, large gaps, and obstacles made of debris due to their physical limitation. Although, UAVs have been adduced to solve these complication described above. However, they are easily affected by the climate like heavy fog and windy weather, and there are issues such as payload, and energy consumption. Legged robots are better fitted for the challenging terrains mentioned above. Furthermore, since they can interact surroundings directly through anthropomorphous manipulators, they have a potential to perform versatile tasks.

Compliance is the basic 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 with hierarchical method with high constraints feature, Feng et al (2015) used soft constraints method that put weight at objective 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 variables 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 variables 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 variables, which consisting of joint acceleration, joint torque and contact force. Although using the full optimization variables can affect the computation time due to high dimensions 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.

Aghili F (2005) A unified approach for inverse and direct dynamics of constrained multibody systems based on linear projection operator: Applications to control and simulation. IEEE Transactions on Robotics 21(5): 834–849.

Bouyarmane, K., Vaillant, J., Keith, F., & Kheddar, A. (2012). Exploring humanoid robots locomotion capabilities in virtual disaster response scenarios. In 12th IEEE-RAS International Conference on Humanoid Robots (Humanoids) (pp. 337–342), Osaka, Japan.

De Lasa, M., Mordatch, I., & Hertzmann, A. (2010). Featurebased locomotion controllers. ACM Transactions on Graphics, 29(4), 131:1–131:10.

Khatib O (1987) A unified approach for motion and force control of robot manipulators: The operational space formulation. *IEEE Journal of Robotics and Automation* 3(1): 43–53.

Herzog, A., Righetti, L., Grimminger, F., Pastor, P., & Schaal, S. (2014). Balancing experiments on a torque-controlled humanoid with hierarchical inverse dynamics. In IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), Chicago.

Hutter, M., Sommer, H., Gehring, C., Hoepflinger, M., Bloesch, M., & Siegwart, R. (2014). Quadrupedal locomotion using hierarchical operational space control. The International Journal of Robotics Research, 33(8), 1047–1062.

Feng, S., Whitman, E., Xinjilefu, X., & Atkeson, C. G. (2015). Optimization‐based full body control for the DARPA Robotics Challenge. Journal of Field Robotics, 32(2), 293-312.

Mistry M, Buchli J and Schaal S (2010) Inverse dynamics control of floating base systems using orthogonal decomposition. In: Proceedings of International conference on robotics and automation (ICRA), Anchorage, AK, 3–8 May 2010, pp. 3406–3412.

Sentis L (2007) Synthesis and control of whole-body behaviors in humanoid systems. PhD Thesis, Stanford University.

Raibert, M. H. (1986). Legged robots that balance. MIT press.

Vukobratović, M., & Borovac, B. (2004). Zero-moment point—thirty five years of its life. International journal of humanoid robotics, 1(01), 157-173.

Pratt, J., Carff, J., Drakunov, S., & Goswami, A. (2006, December). Capture point: A step toward humanoid push recovery. In Humanoid Robots, 2006 6th IEEE-RAS International Conference on (pp. 200-207). IEEE.

Rebula, J., Canas, F., Pratt, J., & Goswami, A. (2007, November). Learning capture points for humanoid push recovery. In Humanoid Robots, 2007 7th IEEE-RAS International Conference on (pp. 65-72). IEEE.

1. \*Resrach supported by ABC Foundation.

   F. A. Author is with the National Institute of Standards and Technology, Boulder, CO 80305 USA (corresponding author to provide phone: 303-555-5555; fax: 303-555-5555; e-mail: author@ boulder.nist.gov).

   S. B. Author, Jr., was with Rice University, Houston, TX 77005 USA. He is now with the Department of Physics, Colorado State University, Fort Collins, CO 80523 USA (e-mail: author@lamar. colostate.edu).

   T. C. Author is with the Electrical Engineering Department, University of Colorado, Boulder, CO 80309 USA, on leave from the National Research Institute for Metals, Tsukuba, Japan (e-mail: author@nrim.go.jp). [↑](#footnote-ref-1)