Introduction: Motion Planning, Optimization and Biped Gait Generation

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Humanoid robots have been experiencing remarkable progress especially in their hardware and software in last two decades. They are now expected to be utilized in various applications, including disaster response [3], manufacturing in large-scale assembly [1], entertainments [7] and evaluation of devices instead of human subjects [14].

Humanoid robots can be characterized by two main features with respect to conventional manipulators with fixed base or wheeled mobile robots: high redundancy with much larger degrees of freedom (DOFs), typically more than 30, and their base is not fixed but "floating," and cannot be directly controlled but through contacts with environments usually with feet for walking gaits. This floating base (FB) introduces an additional equation that relates external forces to its behavior [18].

When we, humans, move our body, we usually have some objective to achieve, for example, walking to a place, taking an object, or executing a particular task. Before moving, we think about how to move based on the objective itself, the environment and the current state of our body. Although humanoid robots nowadays still have difficulty in moving like humans in every situation, the same principle is used to make them move: first sensing the environment, then planning the motion, and finally executing it, possibly adapting the motion to the environmental changes. This Part "Humanoid Motion Planning, Optimization and Gait Generation (HMP)" focuses on the second step, where a "path" from one configuration to another is planned. The most relevant robotics research field is motion planning whose theoretical basis can be learned with textbooks that are available [10, 12, 2].

Motion Planning usually refers to geometric and kinematic planning of a path to be followed by a robot and has made progress especially on fixed manipulators and

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wheeled mobile robots. However, due to the aforementioned two features, namely the redundancy and the FB, HMP requires a special care when applying the basic motion planning theory. The field of HMP emerged in early 2000's [9] and has experienced a significant growth, and it is still accelerating its progress, even after publication of a book with a good coverage of cutting-edge HMP research in 2010 [4]. This Part is organized to cover the well-established research on HMP from the viewpoint of dealing with the two features of humanoid robots in a comprehensive way.

Concerning the redundancy, motion planning technique has experienced rapid and significant growth with close relationship with sampling-based method [8, 5, 13] and hierarchical redundancy resolution with prioritized tasks [17, 15], which are different methodologies of dealing with a redundant system with many DOFs. In this Part, the chapter titled "Whole-body Motion Planning (Yoshida, Kanehiro, and Laumond)" discusses the recent evolution of a general framework of integrating those two redundancy resolution techniques for several whole-body tasks of humanoid robots. This Part also presents recent advances in redundancy resolution for humanoid robots from various complementary perspectives. The chapter titled "Obeying Constraints During Motion Planning (Berenson)" focuses on algorithmic basis of dealing with constraints using Task Space Regions for HMP. More detailed discussions with respect to manipulation task execution are provided in the chapter titled "Manipulation and Task Execution by Humanoids (Harada and Roa)" with respect to different level of motions: grasp and manipulation planning as well as whole-body motion planning. Since humanoid robots have similar morphology to humans, motion generation of redundant anthropomorphic systems by learning from human motions has been studied also since early 2000's [16]. the chapter titled "Human Motion Imitation (Kulic)" summarizes this from different approaches: direct reproduction, motion primitives, and control policy.

Regarding the feature of FB, the long history of research on bipedal walking gait generation [6] plays an indispensable role in the progress of HMP. Although the floating base was not recognized in the context of planning, bipedal walking theory offers a way to convert the desired path of FB into bipedal locomotion. As a fundamental research on generation of FB paths, the chapter titled "Principles Underlying Locomotor Trajectory Formation (Sreenivasa, Laumond, Mombaur and Berthoz)" illustrates an original analysis on humanoid locomotor path planning inspired from both non-holonomic motion planning [11] and human locomotion principle based on the idea of inverse optimal control. Once high-level locomotor path is planned, it should be transformed into biped or non-gaited motion by a humanoid. the chapter titled "Biped Footstep Planning (Perrin)" offers an in-depth survey of formal description and solution for bipedal footstep planning mainly in 2D. From the planned footsteps to reach the goal, the trajectory of Zero Moment Point (ZMP) can be derived to generate dynamic bipedal walking pattern based on model predictive control (MPC) [6]. Extended studies on locomotion planning on rough terrains are presented in the chapter titled "Adaptive Locomotion on Uneven Terrains (Hauser)" in terms of software architecture, mathematical modeling approaches, and implementation of the major components of terrain-adaptive systems. the chapter titled "SLAM and

Vision-based Humanoid Navigation (Stasse)" concentrates on the usage of sensing information into the locomotion planning methods mentioned above, especially based on Simultaneous Localization and Mapping (SLAM).

In recent research in humanoid motion planning, the dynamics of humanoid robots including FB has been studied intensively, to build motion planner of humanoid dynamic motions by taking into account the whole-body stability with contacts and mechanical constraints. Model-based optimal controller has also been investigated to achieve the planned motions under the dynamics and constraints including the FB. the chapter titled "Multi-contact Motion Planning and Control (Bouyarmane, Caron, Escande, Kheddar)" addresses an optimization-based framework to plan and control the humanoid motions including multiple contacts with the environments or other objects. Several approaches on model-based dynamic optimization for humanoid whole-body motions are introduced in the chapter titled "Humanoid Motion Optimization (Mombaur)."

As described above, this Part overall forms a combined survey on planning, optimization and control of humanoid robot motions, with a wide spectrum of motions including locomotion, manipulation and multi-contact tasks. The Chapters present not only well-established techniques for HMP but also advanced topics that are currently being investigated. From those chapters, the readers may notice that HMP is an active research area that is evolving and that motion planning and control for humanoid robots is now being merged: the loop of sensing and planning is becoming shorter for reactive planning, and planners is integrating optimal controller in such a way that the output of the planner can be executed with smaller errors. The Editors hope the Part provides the readers with an opportunity to familiarize and to participate in the exciting field of Humanoid Motion Planning.

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