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Recent Research on Humanoid Robots at Sapienza University of Rome

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***Abstract*— We review some recent research on humanoid robots carried out at the DIAG Robotics Lab of Sapienza University of Rome. In particular, we discuss (1) a general framework for intrinsically stable gait generation based on MPC, complete with stability and feasibility analysis, and (2) a unified approach for whole-body motion planning in loco-manipulation tasks.**

I. RESEARCH ON HUMANOIDS: OPEN PROBLEMS

While humanoid robots are the subject of increasing attention and start to make their way outside laboratories, a number of open research problems remain that must be addressed in order to push this technology to a readiness level compatible with their actual use in real-life applications. Among these, there are still some fundamental issues such as stable gait generation and whole-body motion planning, on which our research group has been working in the last few years in the context of the H2020 project COMANOID [1]. The accompanying video shows a compilation of results.

II. STABLE GAIT GENERATION

Balance of a walking humanoid can be guaranteed by enforcing the condition that the Zero Moment Point (ZMP, the point where the horizontal component of the moment of the ground reaction forces becomes zero) remains at all times within the support polygon of the robot. Therefore, in many gait generation methods the ZMP is driven along a trajectory consistent with the desired footstep sequence. Due to the complexity of the full humanoid dynamics, simplified models are generally used in this phase; among these, the Linear Inverted Pendulum (LIP) is a popular choice for computing an evolution of the Center of Mass (CoM) resulting in the chosen ZMP trajectory.

However, there is a potential instability issue at the heart of the problem. Due to the nature of the CoM/ZMP dynamics, the trajectory of the CoM will in general be *divergent* with respect to that of the ZMP, resulting in a gait which is in theory balanced but in practice unrealizable for the humanoid. In the literature, this issue has often been dealt with rather heuristically, e.g., by adopting a Model Predictive Control (MPC) approach and enforcing a terminal constraint (such as the *capturability* constraint), which is generally considered to be beneficial for stability in MPC contexts.

In [2], we have introduced a novel MPC approach for gait generation (called Intrinsically Stable MPC, or IS-MPC) which relies on the inclusion of an explicit stability constraint in the formulation of the problem. In particular, the idea was to enforce a condition on the future ZMP velocities (representing the control inputs) so as to guarantee that the generated CoM trajectory remains bounded with respect to the ZMP trajectory. Since the control horizon of the MPC algorithm is finite, only part of the future ZMP velocities are decision variables and can therefore be subject to a constraint; the remaining part, called tail, must be conjectured.

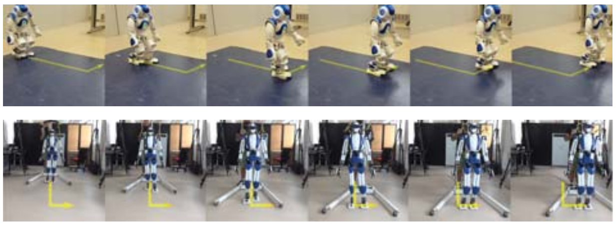

Fig. 1. NAO and HRP-4 successfully walking along an L-shaped path under the action of IS-MPC. Use of an anticipative tail is required along this kind of path, resulting in a terminal constraint that is different from the standard capturability constraint.

This approach was fully developed into a complete framework in [3], where different tail conjectures are proposed depending on the available preview information on the reference motion. Each of these conjectures corresponds to a specific version of the stability constraint, which in turn is shown to be equivalent to a different terminal constraint. Most importantly, a rigorous study was performed to identify conditions under which recursive feasibility of the MPC is guaranteed, and it was proven that recursive feasibility of IS-MPC implies internal stability of the CoM/ZMP dynamics.

A gait generation method with an explicit proof of internal stability is a clear advancement of the state of the art. In fact, our results show that, contrarily to what is often claimed in the literature, simply adding a capturability constraint does not guarantee stability per se, since the appropriate tail to be used in the stability constraint (equivalently, the appropriate terminal constraint) depends upon the future characteristics of the commanded motion. Indeed, to guarantee recursive feasibility one should always choose the *anticipative* tail, which makes the most use of the available preview information. Another advantage of IS-MPC is that it is general enough to be applicable to different humanoids without significant adaptation. For example, experimental results proved that the proposed method performs successfully on two very dissimilar humanoid platforms like NAO and HRP-4 (see Fig. 1).

Another benefit of the recursive feasibility analysis is paving the road for the design of robust versions of IS-

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MPC. A first step in this direction is [4], where IS-MPC was adapted to allow gait generation in the presence of persistent disturbances. To this end, the basic scheme is extended by incorporating a disturbance observer, whose output is used to correct appropriately the stability constraints. The resulting observer-based IS-MPC scheme is validated on a NAO humanoid, showing successful gait generation for a wide range of applied disturbances, including unmodeled dynamics.

Other extensions of IS-MPC that we have proposed include [5], where a more sophisticated multi-mass model is considered in place of the LIP to account for the contribution of the swinging leg motion to the total ZMP, and [6], where the constant CoM height hypothesis associated to the LIP is removed to design a full 3D version of IS-MPC. In [7], the 3D controller is combined with a footstep planner to obtain an integrated method for planning and executing humanoid motions on uneven ground.

Finally, IS-MPC has been used in [8] to realize evasive maneuvers for avoiding malicious pursuers (humans or other humanoids), also in the presence of obstacles (see Fig. 2).

III. WHOLE-BODY MOTION PLANNING

In addition to achieving stable locomotion, researchers are interested in using it as a building block to generate complex whole-body motions for executing actual tasks in interaction with the world (e.g., reach a certain location and pick up an object). These motions should be feasible, i.e., comply with the various kinematic and dynamic constraints of the specific robot; at the same time, collisions should be avoided with the obstacles that are invariably present in the robot workspace. Due to the complexity of the humanoid dynamics, and in particular in view of their intrinsic nature of underactuated systems, most approaches available in the literature rely on a separation between locomotion and manipulation, thus failing to exploit the rich motion capabilities of these mechanisms.

In [9] we have proposed an innovative approach that does not separate locomotion from manipulation. This is realized by a randomized planner that builds a solution by concatenating whole-body motions. Each whole-body motion realizes a CoM movement selected from a set of primitives and simultaneously accomplishes a portion of the task. The CoM primitives, which can be generated using IS-MPC, are representative of typical humanoid actions such as walking gaits (static and dynamic), and can in principle include more sophisticated movements (e.g., jumping, crouching, etc). The proposed method can provide sensible plans for a variety of composite tasks requiring a combination of navigation and manipulation.

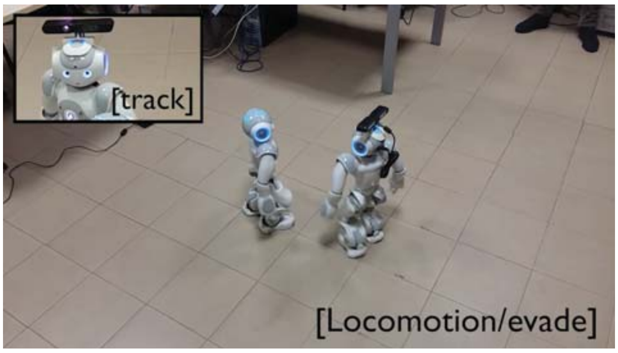

Fig. 2. The NAO on the right is performing an evasion maneuver under the action of IS-MPC. The NAO on the left is acting as a malicious pursuer.

The planning approach based on CoM primitives was extended in [10] to the case where the assigned task is deformable, introducing a mechanism that allows to exploit this feature to increase the possibility of finding a solution, and specialized in [11] for loco-manipulation tasks, to achieve a more graceful execution of this kind of operation.

While the works mentioned so far only deal with the off-line planning case, in which the robot has complete knowledge of the environment geometry in advance, an online version of the whole-body planner is developed in [12], [13], obtaining a method that can be used without a priori information.

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