Multi-contact Locomotion of Legged Robots in Complex Environments – The Loco3D project

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***Abstract*—Planning, adapting and executing multi-contact locomotion movements on legged robots in complex environments remains an open problem. In this proposal, we introduce a complete pipeline to address this issue in the context of humanoid robots inside industrial environments. This pipeline relies on a multi-stage approach in order to simplify the process flow and to exploit at best state-of-the-art techniques both in terms of contact planning, whole-body control and perception. The main challenges lie in the choice of the different modules composing this pipeline as well as their mutual interactions: e.g. at which frequency rates each module has to work in order to allow safe and robust locomotion? or which information must transit between the modules? We named this project Loco3D standing for Locomotion in 3D, in contrast to the classic locomotion on quasi-flat terrains, where the motion of the center of mass of the robot is mostly limited to a 2D plane.**

I. Motivation

As mentioned by Chris Atkeson et al. in [1], *"Except for egress, no robots in the DRC Finals used the stair railings or any form of bracing"* and they also add that *"In programming robots we avoid contacts and the resultant structural changes in our models and in reality."*. Then, multi-contact locomotion of legged robots in complex environments remains a challenge for the whole robotics community. Such task involves numerous expertises:

- in **perception** for physical localization and stabilization of the robot but also for building a semantic map of the environment;
- in **planning** to determine reachable contact areas and to compute a rough path avoiding collisions with the environment;
- in **control** to follow this rough path while authorizing dynamic movements that respect robot hardware constraints, provide robustness with respect to uncertainties and unexpected interactions;
- in **robotic hardware and architecture** to build or exploit a suitable and effective platform to achieve complex motions.

To solve the multi-contact locomotion problem, we propose a multi-stage approach that decouples the global but hard problem into various subproblems of smaller dimensions, simpler to solve.We aim to apply this pipeline on our two humanoid robots, namely HRP-2 and TALOS, the new humanoid platform from PAL robotics [12].

II. Pipeline description

This pipeline is composed of five main modules that are summarized below. We refer to their reference papers for further details.

1) Contact sequence planner: the first stage consists in an interactive acyclic contact planner [14] able to compute a sequence of contacts for various scenarios, from a matter of few hundreds of milliseconds up to few seconds depending on the complexity of the environment. This planner reduces the complexity of the problem by considering only the root of the robot together with the reachability sets of the end-effectors. More precisely, it verifies that the root configuration of a robot is close, but not too close from obstacles: close to allow contact creation, not too close to avoid collision. With this approximation of the space of admissible root configurations we decompose the hard contact planning problem into simpler sub-problems: first, to plan a guide path for the root without considering the whole-body configuration; then, to generate a discrete sequence of whole-body configurations in static equilibrium along this path. The complete workflow is depicted in Fig. 1. We recently extended this framework to also take into account dynamic transition [9].

2) Centroidal pattern generator: we introduced in [4] an optimal control formulation based on the centroidal dynamics and using contact forces as control inputs. This formulation takes as input the contact sequence (generated by stage 1) and the initial state of the robot and tries to minimize a tailored cost function to obtain a smooth control while satisfying the friction cone constraints. In addition to that, the formulation seeks a final state that is viable [15]. To be effective, we proposed to translate this optimal control problem into a multiple-shooting formulation. This approach is fast enough to be implemented in a receding horizon way.

We recently improved our formulation to directly take into account the constraints [5, 3] due to the whole-body when relying on reduced models. It allows for example to directly

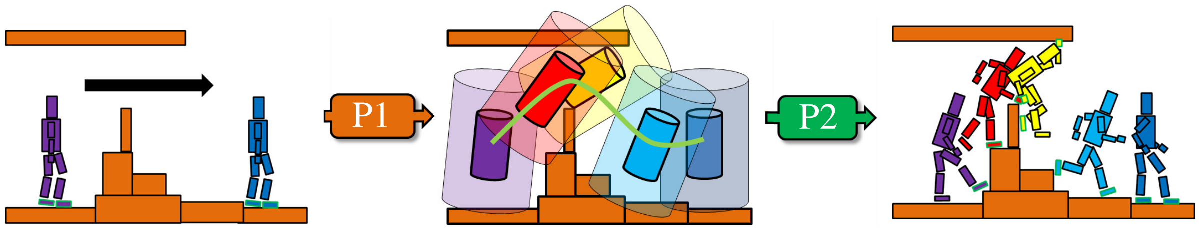

Fig. 1: Overview of our two-stage framework. Given a path request between start and goal positions (left image), P1 is the problem of computing a guide path in the space of equilibrium feasible root configurations. We achieve this by defining a geometric condition, the reachability condition (abstracted with the transparent cylinders on the middle image). P2 is then the problem of extending the path into a discrete sequence of contact configurations.

transcript the center of mass reachability region inside the reduced optimal control formulation. Fig. 2 illustrates climbing motions using the stair railing applied to two humanoid robots, namely HRP-2 and the new TALOS platform.

3) Whole-body motion generator: the next question concerns the whole-body motion aspects. More precisely, how to plan the trajectories of swing end-effectors? A *Differential Dynamic Programming* approach as proposed in [13] should work, but may become inefficient in case of cluttered environments. We propose an RRT-based approach called *limb-RRT* [4]. This approach computes a whole-body motion resulting in smooth trajectories for each end-effector while following the center of mass trajectory computed by the centroidal pattern generator.

Then, we feed the centroidal trajectory, the contact forces, and with the end-effector trajectories to an inverse-dynamics controller, which can also account for certain model uncertainties [6].

4) Low level torque control: The robot interaction with its environment requires the control of the contact forces. We made the choice to rely on a joint-torque control strategy. We identified the motor parameters together with the friction induced by the use of harmonic-drives on both HRP-2 and TALOS, then we deploy a control strategy similar to the one presented in [7]. The reference of joint torques are provided by the whole-body motion generator module.

In addition to that, HRP-2 has some flexible parts in its feet which allow to absorb impacts. These flexibilities are not directly controlled and measured, inducing some uncertainties in the robot placement. Hence, we developed an extended kalman filter to fusion the measurements of the force sensors located in the ankles and the IMU located in the chest of the robot [2, 11]. This estimator is fundamental to track the center of mass trajectory provided by the centroidal motion generator.

5) Exteroception: finally, the last module is devoted to the localization of the robot inside its environment. We made the choice to only rely on vision and inertial measurements. The fusion of these two measurements is performed with an optimal estimator approach which enables us to accurately predict the motion of landmarks inside classic SLAM approaches [10]. Such approach seems to be sufficient and cheaper than using the standard LIDAR sensors as suggested by Fallon et al. [8].

In addition to that, the exteroception can fusion some information provided by the proprioception in order to build a global and robust estimator of the robot state.

6) Hardware: currently, all our efforts are targeted on two humanoid robots, namely HRP-2 and TALOS. Therefore, we make all our software developments independent from the hardware in order to be compatible with these two robots and with most existing humanoid robots or even with quadrupedal robots.

III. Conclusion

In this proposal, we have introduced a complete pipeline to address the multi-contact locomotion problem of legged robots inside complex environments. This pipeline relies on a multi-stage strategy enabling us to exploit state-of-the-art solutions: interactive computation of contact placements that ensure collision avoidance, real-time computations of the CoM trajectory followed by a robust inverse-dynamics controller together with a fast torque controller and an optimal estimator to track and precisely localize the robot inside its environment.

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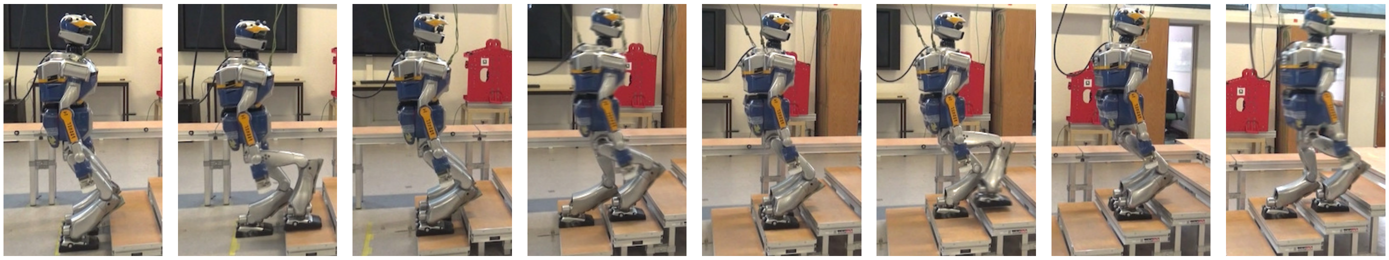
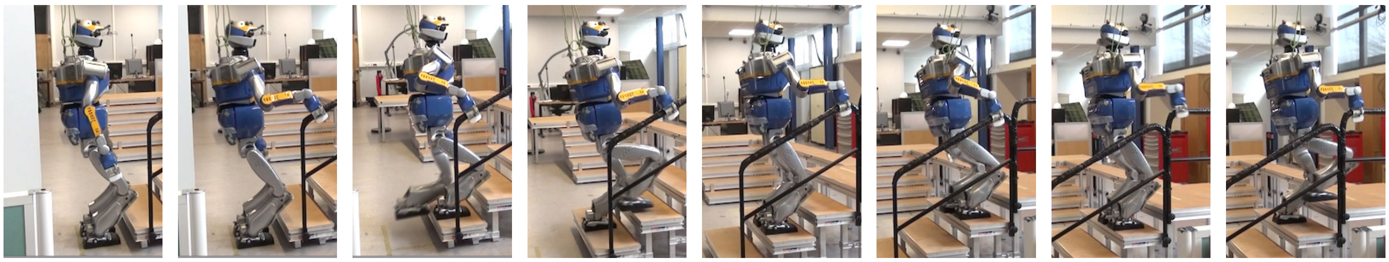


(a) Snapshots of the climbing up 10-cm high steps motion with the HRP-2 robot.



(b) Snapshots of the climbing up 15-cm high steps motion with the HRP-2 using the stair railing.

(c) Snapshots of the climbing 15-cm high steps motion with stair railing by the TALOS robot in simulation.

Fig. 2: Illustration of the centroidal pattern generator applied on various contextes and robots.

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