Combining Active Compliance with Force-Feedback for on-the-fly Motion Replanning

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I. Introduction

The ability to move from one place to another is one of the most basic and important skills for autonomous robots. Although wheels offer great efficiency on flat terrain, they are often unsuitable for crossing highly unstructured and challenging terrain. Nature shows that typically legged locomotion has far more potential in these areas in terms of agility and performance.

Hydraulic actuation was shown to be efficient in the context of legged locomotion. It is robust, can withstand impacts, can be torque controlled and allows for high bandwidth control. In addition, torque sensors enable haptic sensing through estimation of the force at the end-effectors.

In this abstract we show how to combine active compliance with a force-based update of the environment. We exploit the active compliance of our system to smoothly interact with the environment for small perception and execution inaccuracies, e.g.<2 cm. For larger discrepancies, detected by the force-feedback, we replan the motion according to this new information. This combination increases the robustness of the locomotion framework against perception and execution inaccuracies.

II. Related Work

Earlier work in quadrupedal locomotion produced successful control strategies ([1], [2]), although they were still somewhat stiff in their execution. Systems with these control strategies can be improved by use of compliant elements within the structure or the actuation system, e.g. *BigDog* [3] and *StarlETH* [4]. A step towards compliance without the use of passively compliant elements was taken by [5], where the inverse dynamics approach in [6] was used in tandem with a low-gain joint PD controller. This approach uses active compliance to compensate for discrepancies between the real world and the robot's internal representation of it. Although the robot will not stiffly execute a commanded motion, the robot still believes that its foot is at the originally desired position. The body pose and swing-leg trajectory is not changed with respect to this different foothold, which can cause subsequent execution to fail due to stability or kinematic joint limitations.

III. Developed Framework

In order to make our framework (Fig. 1) robust against inaccuracies of up to 15 cm, two different components are

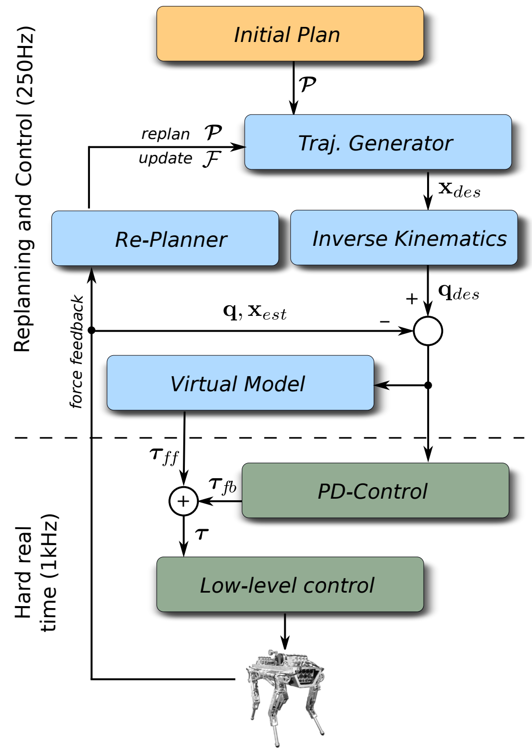

Fig. 1. Control loop to robustly execute a motion plan P. The desired states are mapped to joint angles using inverse kinematics. From these desired joint states feed-back and feed- forward torques are calculated to create the compliant behaviour. In a feedback-loop the joint torques are used to estimate the contact forces at the feet and update motion-plans accordingly.

necessary: The first is *active compliance*, created by a low-gain joint-level PD controller combined with a virtual model controller [7]. This component deals with minor inaccuracies in perception, execution and state estimation in a fast and computationally inexpensive way. If the discrepancies between the previous planned state and the actual state become too large, the motion must be deliberately *replanned* to ensure successful execution. The following paragraphs describe these two components of our locomotion framework. A detailed explanation can be found in [8].

A. PD and Virtual Model Controller

As seen in Fig. 1 the torque for each joint is produced by a low gain PD controller summed with the feed-forward torque of the virtual model controller. These low PD gains

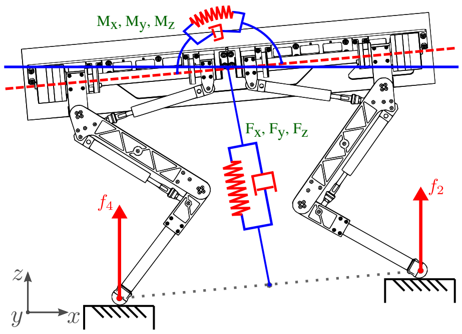

Fig. 2. The virtual elements used to calculate forces and moments around the trunk of the robot. The virtual forces and moments are transformed to forces at the feet and subsequently to feedforward torques for the legs that are in stance [7].

make the system highly compliant, but also require a feed-forward torque for accurate tracking of desired motions.

We follow a virtual model control approach similar to [9] as seen in Fig. 2. We want to impose virtual forces (F_x, F_y, F_z) and moments (M_x, M_y, M_z) onto the robot's body according to a desired state and the current state of the system. Since these cannot be applied directly, they are transformed to forces that the feet in contact need to apply. The contact forces are then mapped to feed-forward torques for the joints of the legs that are in stance, using the Jacobian of the system's current state.

This component creates the active compliance and copes with *minor* inaccuracies in perception, execution and state estimation.

B. *Re-Planner*

Especially in the real world, inaccuracies in perception, execution or state-estimation can become quite large. For instance, the robot may make contact with the environment at a significantly different time as specified in the motion plan due to an unperceived obstacle. Although the active compliance limits the effect of such unexpected contacts and ensures a smooth interaction with the environment, the robot's body pose and swing-leg trajectory is not adapted to this new foothold. This is likely to cause the robot to fail to execute its desired motion in future steps due to stability or kinematic joint limitations.

To avoid such difficulties, online force-feedback detects the contact condition of the swing-leg. This is done by mapping the measured joint torques to the foot using the leg Jacobian of the current state. If this force is greater than a threshold, e.g. 30 N, contact of the foot with the environment is assumed. In the opposite case, if no forces are sensed even after the planned swing has been completed, the foot is slowly moved vertically down until a contact is detected. At contact, the motion is stopped and the current foot position is used to update the initial plan. This allows to replan optimal body poses and swing-leg trajectories with respect to this changed foothold on-the-fly. For example, the robot might choose to increase its pitch angle to cope with a higher-than-expected contact of a front leg.

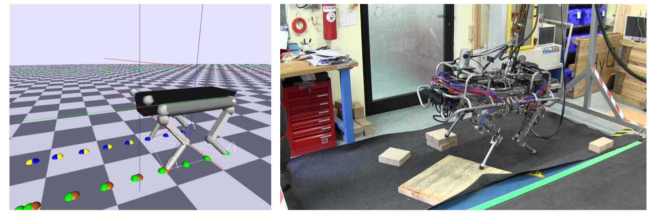

Fig. 3. *Left*: The internal map and motion plan of the robot. The task is straight walking on obstacle free terrain. *Right*: The robot successfully executing the planned motion despite unseen, randomly placed obstacles of up to 15cm height (20% of the leg length). The robot uses active compliance combined with force-based motion replanning.

This component allows the robot to compensate for *major* inaccuracies of up to 15 cm by actively replanning its body pose and swing-leg trajectories with respect to this haptically sensed foothold.

IV. Conclusion and Future Work

The performance of our framework is validated by the experiment described in Fig. 3. The use of active compliance for small inaccuracies and force-based replanning for larger deviations from expected contacts makes the approach very robust to perception inaccuracies and contributes greatly to the overall stability of the locomotion behaviour.

In the future we aim to apply our framework to dynamic motions such as jumping and rearing. In addition we wish to extend the force-feedback capabilities to detect foot-slippage and movable obstacles.

Acknowledgements

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References

[1] J. Z. Kolter, M. P. Rodgers, and A. Y. Ng, "A control architecture for quadruped locomotion over rough terrain," in *ICRA'08*, 2008, pp. 811–818.

[2] P. Vernaza, M. Likhachev, S. Bhattacharya, A. Kushleyev, and D. D. Lee, "Search-based planning for a legged robot over rough terrain," in *IEEE International Conference on Robotics and Automation*, 2009. [Online]. Available: http://www.cs.cmu.edu/~pvernaza/papers/pennLittledog.pdf

[3] D. V. Lee and A. A. Biewener, "BigDog-inspired studies in the locomotion of goats and dogs," *Integrative and Comparative Biology*, vol. 51, no. 1, pp. 190–202, 2011.

[4] M. Hutter, M. Hoepflinger, C. Gehring, M. Bloesch, C. D. Remy, and R. Siegwart, "Hybrid operational space control for compliant legged systems." in *Robotics: Science and Systems*, 2012.

[5] M. Kalakrishnan, J. Buchli, P. Pastor, M. Mistry, and S. Schaal, "fast, robust quadruped locomotion over challenging terrain," in *robotics and automation (icra), 2010 ieee international conference on*, 2010, pp. 2665–2670. [Online]. Available: http://www-clmc.usc.edu/publications/K/kalakrishnan-ICRA2010.pdf

[6] M. Mistry, J. Buchli, and S. Schaal, "Inverse dynamics control of floating base systems using orthogonal decomposition," in *Robotics and Automation (ICRA)*. IEEE, 2010, pp. 3406–3412.

[7] I. Havoutis, C. Semini, and D. G. Caldwell, "Virtual model control for quadrupedal trunk stabilization," in *Dynamic Walking*, 2013.

[8] A. Winkler, I. Havoutis, S. Bazeille, J. Ortiz, M. Focchi, R. Dillmann, D. Caldwell, and C. Semini, "Path planning with force-based foothold adaptation and virtual model control for torque controlled quadruped robots," in *IEEE international conference on Robotics and Automation (ICRA)*, 2014.

[9] J. Pratt, C.-M. Chew, A. Torres, P. Dilworth, and G. Pratt, "Virtual model control: An intuitive approach for bipedal locomotion," *The International Journal of Robotics Research*, 2001.