Hybrid Operational Space Control for Compliant Quadruped Robots

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Abstract - **This work introduces the concept of *hybrid operational space control*, a method that unifies kinematic tracking of individual joints of a robot with an inverse dynamics task space controller for its remainder. The proposed control strategy allows for a hierarchical task decomposition while simultaneously regulating the inner forces between the contact points. At the same time it improves fast tracking for compliant systems by means of appropriate low level position controllers. Introducing StarlETH, a compliant quadrupedal robot, the applicability of the controller and the hardware is demonstrated in realtime simulations and hardware experiments. We perform static walking in challenging terrain and show how the controller can combine precise and fast position control with robust and compliant interaction with the environment.**

1 Introduction

The dynamic walking community seeks for hardware devices that are *compliant* and *torque controllable.* The first requirement is motivated by safety and efficiency considerations: Legged systems should interact softly with their environment to ensure robustness against disturbances such as terrain irregularities or slippage, to protect their hardware from damage through unexpected collisions, and to safely work hand-in-hand with human collaborators. At the same time - and this is similar to muscles and tendons found in nature -, they should be able to use their passive system compliance to locomote *fast* and *efficiently* through periodically storing and releasing energy. The second requirement, full torque controllability, is needed to make the system highly *versatile.* Different control concepts (e.g. [6],[2], [3],...) based on inverse dynamics methods have shown impressive performance in terms of executing highly complex maneuvers or compliantly interacting with the environment while simultaneously optimizing the contact force distribution [5]. At the same time - and again similar to nature -, torque control enables the natural dynamics of pendulum motion.

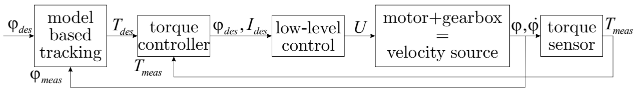

Figure 1: Position control of compliant joints (SEA) that are considered as "torque controllable" significantly limits the performance due to the cascaded structure.

Unifying the requirements of compliance and torque controllability in one single legged device, we developed the quadruped robot Starl*ETH* that was presented to the community at DW2011. Using high compliant series elastic actuators, this system is perfectly suited for dynamic maneuvers. The springs protect the motor and gearbox, allow for energy storage during stance phase, and provide means for precise torque control. As a substantial drawback, the integration of compliance in the system is accompanied by a loss of torque control bandwidth. While this is not an issue for compliant interaction with the environment, it greatly limits the performance in terms of fast and accurate position tracking control - skills that are indispensable for foot or hand positioning while walking or manipulating. The problematic is obvious: Control approaches that consider the actuator as torque sources translate position tracking tasks into desired joint torques. This results in a cascaded structure that lowers the bandwidth in every loop.

We are approaching this problem by considering the motor as a velocity source. A position controller is implemented on joint level as an LQG control structure that includes the series-elasticity model. This setup performs significantly better in fast and precise tracking tasks [1] than a cascaded structure as depicted in Fig. 1. Using a combination of low level position and torque controllers, we present the method of hybrid operational space control: In this framework, all dynamic tasks are brought into a prioritized task space control structure (similar to [7]) while certain joints are position controlled based on traditional inverse kinematics control methods. This framework measures and estimates the influence of the position controlled joints onto the torque controlled parts such that we can compensate for these effects and achieve exactly the same task space behavior as with a purely torque controlled system, while at the same time tracking performance of the kinematically controlled segments can be improved. Several cases such as legged locomotion or robot-human interaction fit perfectly into this scenario. In this work we focus only on quadrupedal walking using Starl*ETH* in simulations and for experimental validation. The focus thereby is put on locomotion in very rough terrain that requires precise foot tracking, compliant Center of Gravity (CoG) control, and contact force regulation with respect to changing surface normals to avoid slippage.

2 Inverse Dynamics with Position Control and Internal Forces

The equations of motion for a floating base system are

$$\mathbf{M}\ddot{\mathbf{q}} + \mathbf{b} + \mathbf{g} + \mathbf{J}_s^T\mathbf{F}_s = \mathbf{S}^T\boldsymbol{\tau}. \tag{1}$$

Since the contact constraints $\ddot{\mathbf{r}}_s = \mathbf{J}_s\ddot{\mathbf{q}} + \dot{\mathbf{J}}_s\dot{\mathbf{q}} = \mathbf{0}$ needs to be fulfilled, a support null-space projection allows to get rid of the contact force [4]:

$$\begin{aligned} \mathbf{P}\left(\mathbf{M}\ddot{\mathbf{q}} + \mathbf{b} + \mathbf{g}\right) &= \mathbf{P}\mathbf{S}^T\boldsymbol{\tau} && (2) \\ \mathbf{P}\mathbf{J}_s^T &= \mathbf{0} \qquad \forall \mathbf{q} && (3) \end{aligned}$$

Using the description (2), inverse dynamics can be used to solve for the actuator torque $\boldsymbol{\tau}_m$ required to generate a certain motion

$$\boldsymbol{\tau}_m = \left(\mathbf{P}\mathbf{S}^T\right)^+ \mathbf{P}\left(\mathbf{M}\ddot{\mathbf{q}} + \mathbf{b} + \mathbf{g}\right). \tag{4}$$

2.1 Hierarchical Task Decomposition

In our framework, the desired joint space acceleration $\ddot{\mathbf{q}}$ is obtained by a hierarchical task decomposition, whereby each individual task is described as

$$\ddot{\mathbf{r}}_i = \mathbf{J}_i\ddot{\mathbf{q}} + \dot{\mathbf{J}}_i\dot{\mathbf{q}}. \tag{5}$$

Tasks with lower priority are projected into the null space $\mathbf{N} = \mathcal{N}\left(\mathbf{J}\right)$ of higher prioritized tasks:

$$\ddot{\mathbf{q}} = \sum_{j=1}^{n} \mathbf{N}_{j-1}\ddot{\mathbf{q}}_j \tag{6}$$

Using (5) and (6) allows calculating the joint acceleration $\ddot{\mathbf{q}}_i$ for the i^{th} task by

$$\ddot{\mathbf{q}}_i = \left(\mathbf{J}_i\mathbf{N}_{i-1}\right)^+ \left(\ddot{\mathbf{r}}_i - \dot{\mathbf{J}}_i\dot{\mathbf{q}} - \mathbf{J}_i\sum_{j=1}^{i-1}\mathbf{N}_{j-1}\ddot{\mathbf{q}}_j\right). \tag{7}$$

2.2 Hybrid OSC

To step from a purely torque controlled system to a combination of low level position and torque controllers, we separate the dynamics using the selection matrices $\mathbf{S}_p$ and $\mathbf{S}_t$:

$$\ddot{\mathbf{q}} = \mathbf{S}_p^T\ddot{\mathbf{q}}_p + \mathbf{S}_t^T\ddot{\mathbf{q}}_t \tag{8}$$

Instead of demand torque signals, the kinematically controlled joints $\mathbf{q}_p$ take position and velocity commands as low level control input. To compensate for their influence on the rest of the system, we need to estimate the joint acceleration $\ddot{\mathbf{q}}_p = \hat{\ddot{\mathbf{q}}}_p$. Since this is hardly measurable (sensor noise when joint encoder values are double differentiated), we rely on measured torques $\hat{\boldsymbol{\tau}}_p$ in the corresponding joints. After some matrix algebra, the accelerations of the position controlled joints can be estimated as

$$\hat{\ddot{\mathbf{q}}}_p = \left(\mathbf{S}_p\mathbf{M}\mathbf{S}_p^T\right)^{-1}\left(\hat{\boldsymbol{\tau}}_p - \mathbf{S}_p\mathbf{M}\mathbf{S}_t^T\ddot{\mathbf{q}}_t - \mathbf{S}_p\left(\mathbf{b} + \mathbf{g}\right)\right). \tag{9}$$

2.3 Contact Force Optimization

In addition to generating a desired motion, this framework allows also to modulate the contact force of this multi-contact system without influencing $\ddot{\mathbf{q}}$ through the null-space of $\mathbf{P}\mathbf{S}^T$ (4):

$$\boldsymbol{\tau} = \boldsymbol{\tau}_m + \mathcal{N}\left(\mathbf{P}\mathbf{S}^T\right)\boldsymbol{\tau}_0 = \boldsymbol{\tau}_m + \mathbf{N}_P\boldsymbol{\tau}_0 \tag{10}$$

$\boldsymbol{\tau}_0$ allows to change the total contact force about

$$\mathbf{F}_{s0} = \left(\mathbf{J}_s^T\right)^+ \mathbf{S}^T\mathbf{N}_P\boldsymbol{\tau}_0 = \mathbf{A}\boldsymbol{\tau}_0. \tag{11}$$

In most cases, this additional contact force is required to minimize a certain cost function that can be stated in the form

$$\underset{\boldsymbol{\tau}_0}{\text{minimize}} \quad \left\|\mathbf{F}_{des} - \mathbf{D}\left(\mathbf{F}_{sm} + \mathbf{A}\boldsymbol{\tau}_0\right)\right\|_2. \tag{12}$$

In this formulation, $\mathbf{D}$ can be used as a selection matrix to load or unload specific legs before/after lift-off such that $\mathbf{F}_{des} = \mathbf{D}\mathbf{F}_s$ can be freely chosen. Hence, at the same time while shifting the CoG the leg that just made contact can be continuously loaded and the successive swing leg can be unloaded. This ensures a very smooth transition between different support states while walking.

Similar to that, using $\mathbf{D}$ as a projection matrix also allows to increase walking robustness through aligning the contact forces with the corresponding surface normal direction, respectively to minimize the contact forces projected into the tangential contact plane. In both cases, the analytical optimal solution can be found using a pseudo-inverse

$$\boldsymbol{\tau}_0 = \left(\mathbf{D}\mathbf{A}\right)^+\left(\mathbf{F}_{des} - \mathbf{D}\mathbf{F}_{sm}\right). \tag{13}$$

As long as $\mathbf{D}\mathbf{A}$ has full rank, the desired force is achievable, otherwise this returns the least-square optimal value. To minimize slippage, $\mathbf{D}$ is set to select the tangential contact directions with the corresponding desired force $\mathbf{F}_{des}$ equal to zero.

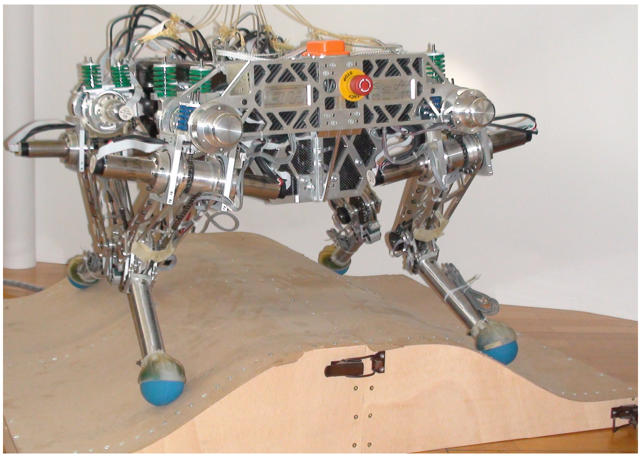

Figure 2: Experiments with Starl*ETH* on a tree stem.

3 Simulation and Experimental Results

The presented structure was tested in walking simulations and experiments with the quadrupedal robot Starl*ETH*. As a first outcome, we could show that the hybrid OSC framework allows position control in the swing leg joints and simultaneous torque control in the support leg joints. It combines advantages of both strategies and is a solution to the bandwidth problem of SEAs. In simulations we were able to approve that hybrid OSC is exactly equal to standard inverse dynamics in case of perfect joint torque sensing. Since legged systems usually have a very lightweight leg structure (end-effector), the controller is robust even in case of large torque measurement errors of $\hat{\boldsymbol{\tau}}_p$ in the range of 100%. In addition to the simulation results, we also demonstrated the applicably in actual experiments.

As a second contribution, both aspects like smooth contact force distribution as well as tangential force minimization were tested based on the least-square optimal solution (13) as well as through constraint friction minimization that is implemented using an SQP solver. It turns out that the least square optimization performs nearly as good as the complex optimization in terms of robustness against slipping but requires much less computational power.

We are currently extending these principles to more challenging terrains. Inspired by the Japanese TV show Takeshi's Castle, we perform tests such as walking on a tree stem (Fig. 2) that require *(i)* compliant CoG control, *(ii)* precise and fast foot point tracking, and *(iii)* modulation of the internal forces.

4 Conclusion & Open questions

This work presents two important aspects of inverse dynamics control with compliant walking machines. Firstly, a hybrid operational space control implementation with low level position control at the swing leg and torque control at the stance leg joints solves the bandwidth problematic of series elastic systems. Second, the contact force optimization of specific directions highly improved system robustness against slippage and at the same time allowed a smooth contact force distribution among the support legs.

We would like to discuss our results in detail with people that were working with similar control frameworks (whole body control, inverse dynamics, etc.). Since most researcher in this field are more focused on high-level control using existing hardware platforms, it would be great to share their experience and problems. Is a hybrid task decomposition necessary? What are our/their performance limitations? How are other people dealing with passive system compliance? Is compliance really the right way to go or do we have to build stiff systems and control them soft to get rid of the bandwidth problematic? What are the requirements of the community for novel types of actuators?

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