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AUTONOMOUS SYSTEMS LAB

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Hybrid Operational Space Control for Compliant Quadrupeds

For more details on this topic, please consult: M. Hutter et. al., "Hybrid Operational Space Control for Compliant Legged Systems," *RSS*, 2012

Motivation

Hierarchical, task-space inverse dynamics controllers are a promising approach to control very complex (floating base) systems in an intuitive and highly sophisticated way. Tasks like foot placement, keeping balance, or modulating contact forces can be handled at once with different priorities.

We present **hybrid OSC**, a method that **unifies kinematic tracking** of individual joints of a robot with an **inverse dynamics task-space** controller. The proposed control strategy allows for a hierarchical task decomposition while simultaneously **optimizing the contact forces**. At the same time it improves fast tracking for compliant systems by means of appropriate low level position controllers.

Bandwidth Limitations in Compliant Systems

Compliant, torque controllable systems are mainly motivated by safety (soft contact interaction, motor protection) and efficiency (energy storage in passive compliance) considerations [1].

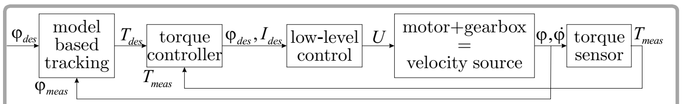


Fig. 1: Position control of compliant joints (SEA) that are considered as "torque actuators" significantly limits the performance due to the cascaded structure.

The integration of compliance is accompanied by a loss of torque control bandwidth. While this is not an issue for **compliant** interaction with the environment, it drastically **lowers the position control performance** when working with standard OSC (Fig.1).

We tackle this problem by considering the motor as a velocity source with a low level LQG position controller that includes the SEA model [2]. This setup performs significantly better in joint position control tasks than the standard cascaded structure (Fig.1).

[1] M. Hutter, et. al., "ScarlETH: Design and Control of a Planar Running Robot," *IROS*, 2011
[2] M. Hutter, et. al., "High Compliant Series Elastic Actuation for the Robotic Leg ScarlETH," *CLAWAR*, 2011

Simulation Results

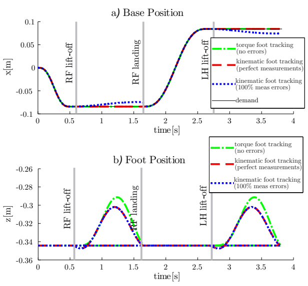
Hybrid OSC validation

A first set of experiments was conducted in simulation demonstrating that in the ideal case the proposed method is exactly equal to control techniques that rely on full torque controlled systems [3].

Walking on a Tree Stem

In a second experiment, StarlETH was walking on a tree stem using a crawl gait. The contact forces were optimized for 2 objectives:

- Smooth loading/unloading of the legs before/after contact change
- Adaptation to surface normal directions to reduce slippage



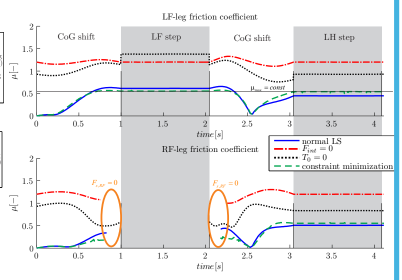


Fig. 2: (left) CoG (a) and foot position (b) tracking in a walking experiment with perfect torque actuation (green dash-dotted) and with position controlled swing leg tracking with perfect joint torque measurements (red dashed), respectively 100% wrong measurements (blue dotted).

Fig. 3: (right) Required friction coefficient of different force distribution methods in the tree-stem experiment: the best results were achieved with the normal least-square solution (blue-solid) and a constraint minimization problem (green dashed). Both the non-smooth solution with zero null-space torque (black-dotted) and the solution with no internal forces show unsatisfying results.

[3] L. Sentis et. al., "Synthesis and Control of Whole-Body Behaviors in Humanoid Systems," *PhD Thesis*, 2007

Hierarchical Task-Space Control

Similar to the prioritization presented in [4], we use a formulation that handles multiple tasks with different priorities at once. To this end, we write the desired joint acceleration as a sum pre-multiplied with the null-space of higher priority tasks:

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

Every task is described using the corresponding Jacobians:

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

This can be solved for the acceleration of the i[th] task:

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

[4] L. Sentis et. al., "Control of Free-Floating Humanoid Robots Through Task Prioritization," *ICRA*, 2005

Floating Base Inverse Dynamics

The equations of motion for a floating base system are

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

Due to the contact constraint $\ddot{\mathbf{r}}_s = \mathbf{J}_s\ddot{\mathbf{q}} + \dot{\mathbf{J}}_s\dot{\mathbf{q}} = \mathbf{0}$, a support null space projection [5] allows to get rid of the contact force

$$\mathbf{P}(\mathbf{M}\ddot{\mathbf{q}} + \mathbf{b} + \mathbf{g}) = \mathbf{P}\mathbf{S}^T\boldsymbol{\tau}$$
$$\mathbf{P}\mathbf{J}_s^T\mathbf{F}_s = \mathbf{0} \quad \forall\mathbf{q}$$

This can finally be solved for the desired joint torque

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

with the corresponding contact force amounting to

$$\mathbf{F}_{sm} = (\mathbf{J}_s^T)^{+}\left(\mathbf{S}^T\boldsymbol{\tau}_m - (\mathbf{M}\ddot{\mathbf{q}} + \mathbf{b} + \mathbf{g})\right)$$

[5] L. Righetti et. al., "Inverse Dynamics Control of Floating-Base Robots with external Constraints: a Unified View," *ICRA*, 2011

Separation of Position and Torque Controlled Joints

In the present work, we separate **position** from **torque** controlled joints using the selection matrices $\mathbf{S}_p$ and $\mathbf{S}_t$:

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

For all relevant cases that require fast end-effector position tracking, it holds that the support kinematics is independent of the position controlled joints

$$\mathbf{S}_t\mathbf{J}_s^T = \mathbf{0}$$

Since joint acceleration is not directly measurable (noise!), we predict the acceleration of the position controlled joints based on accurate torque measurements $\tilde{\boldsymbol{\tau}}_p$:

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

Contact Force Optimization

In a multi-contact problem, the inversion of $\mathbf{P}\mathbf{S}^T$ has a corresponding null-space that allows modulating the contact force without changing the motion:

$$\boldsymbol{\tau} = (\mathbf{P}\mathbf{S}^T)^{+}\mathbf{P}(\mathbf{M}\ddot{\mathbf{q}} + \mathbf{b} + \mathbf{g}) + \mathbf{N}_\mathbf{P}\boldsymbol{\tau}_0 = \boldsymbol{\tau}_m + \mathbf{N}_\mathbf{P}\boldsymbol{\tau}_0$$

This allows to shape the total contact force to

$$\mathbf{F}_s = \mathbf{F}_{sm} + (\mathbf{J}_s^T)^{+}\mathbf{S}^T\mathbf{N}_\mathbf{P}\boldsymbol{\tau}_0 = \mathbf{F}_{sm} + \mathbf{A}\boldsymbol{\tau}_0$$

Similar to [6], we optimize the contact force for a least square objective:

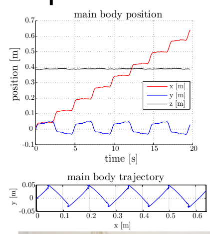
$$\min_{\boldsymbol{\tau}_0}\left\|\mathbf{F}_{des} - \mathbf{D}(\mathbf{F}_{sm} + \mathbf{A}\boldsymbol{\tau}_0)\right\|_2 \Rightarrow \boldsymbol{\tau}_0 = (\mathbf{D}\mathbf{A})^{+}(\mathbf{F}_{des} - \mathbf{D}\mathbf{F}_{sm})$$

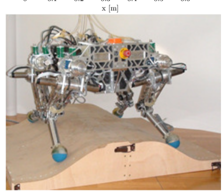
With $\mathbf{D}$ being a selection matrix and $\mathbf{F}_s$ the desired force in these directions. This is used for 2 purposes:

1. Un-/Loading legs after/before lift-off with $\mathbf{D} = [\mathbf{0} \quad \mathbf{I}_3 \quad \mathbf{0}]$
2. Tangential contact force minimization as a function of the local normal respectively the corresponding tangential directions $\mathbf{D} = \left[\alpha_1\mathbf{t}_1^T \quad \dots \quad \alpha_n\mathbf{t}_n^T\right]^T$

[6] L. Righetti et. al., "Control of legged robots with optimal distribution of contact forces," *Humanoids*, 2011

Experiments with StarlETH





Exp. 1, static walk:
The presented control framework was successfully tested in static walking experiments on flat ground. While robustly and fast walking, the system reacts compliantly against disturbances acting on the body or on the feet. Using a low-level joint position controller thereby ensures accurate and fast position control of the swing legs.

Exp. 2, internal force regulation:
Inspired by Takeshi's Castle, we performed experiments with StarlETH standing on a concave surface. Thereby, keeping stability is only possible through the application of internal contact forces as a function of the surface normal directions.

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