Whole-Body Control of Series-Parallel Hybrid Robots

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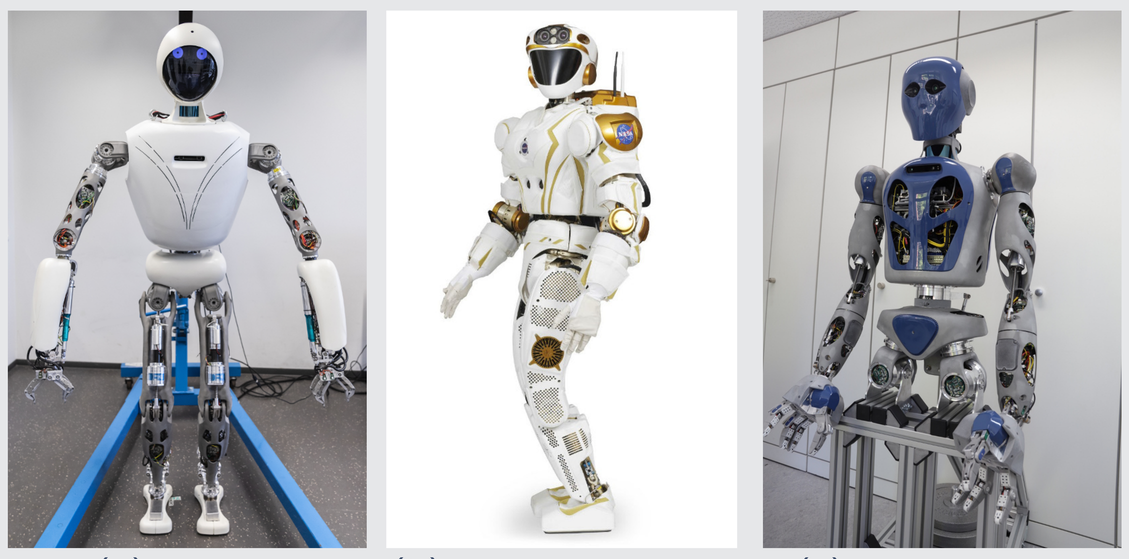
Introduction

Series-parallel hybrid robots are a combination of serial and parallel mechanisms. They offer higher stiffness, accuracy and payload-to-weight ratio than serial robots, with the downside of a higher complexity in modeling and control.



(a) RH5 [1] (b) NASA Valkyrie [2] (c) RH5 Manus [3]

Figure: Humanoids with series-parallel hybrid architecture

SoTA Whole-Body Control (WBC) frameworks

- can only deal with serial or tree-type robots
- abstract parallel submechanisms as serial chains
- resolve kinematics & dynamics of the parallel submechanisms in a separate function

Disadvantages

1. Physical limitations of the actuators within parallel submechanisms cannot be considered
2. Singularities of parallel submechanisms cannot be dealt with
3. The solution does not capture the correct dynamics of the parallel submechanisms
4. Custom and complicated control software stacks

Contribution We develop a WBC framework for series-parallel hybrid robots to overcome the limitations of SoTA WBC approaches. The framework allows to exploit the entire robot workspace on position- and velocity-level when integrating box constraints for parallel subsystems.

Constrained Kinematics and Dynamics

Robots with closed loops can be described by spanning tree joints $\mathbf{q} \in \mathbb{R}^n$, actuated joints $\mathbf{u} \in \mathbb{R}^p$ or independent joints $\mathbf{y} \in \mathbb{R}^m$. These systems are subject to loop constraints[1]:

Type	position	velocity	acceleration
implicit:	$\phi(\mathbf{q}) = \mathbf{0}$	$\mathbf{K}\dot{\mathbf{q}} = \mathbf{0}$	$\mathbf{K}\ddot{\mathbf{q}} = \mathbf{k}$
explicit:	$\mathbf{q} = \gamma(\mathbf{y})$	$\dot{\mathbf{q}} = \mathbf{G}\dot{\mathbf{y}}$	$\ddot{\mathbf{q}} = \mathbf{G}\ddot{\mathbf{y}} + \mathbf{g}$

Table: Loop constraints of a multi-body system [4]

where $\mathbf{K} = \frac{\partial \phi}{\partial \mathbf{q}}$, $\mathbf{k} = -\dot{\mathbf{K}}\dot{\mathbf{q}}$, $\mathbf{G} = \frac{\partial \gamma}{\partial \mathbf{y}}$, $\mathbf{g} = \dot{\mathbf{G}}\dot{\mathbf{y}}$.

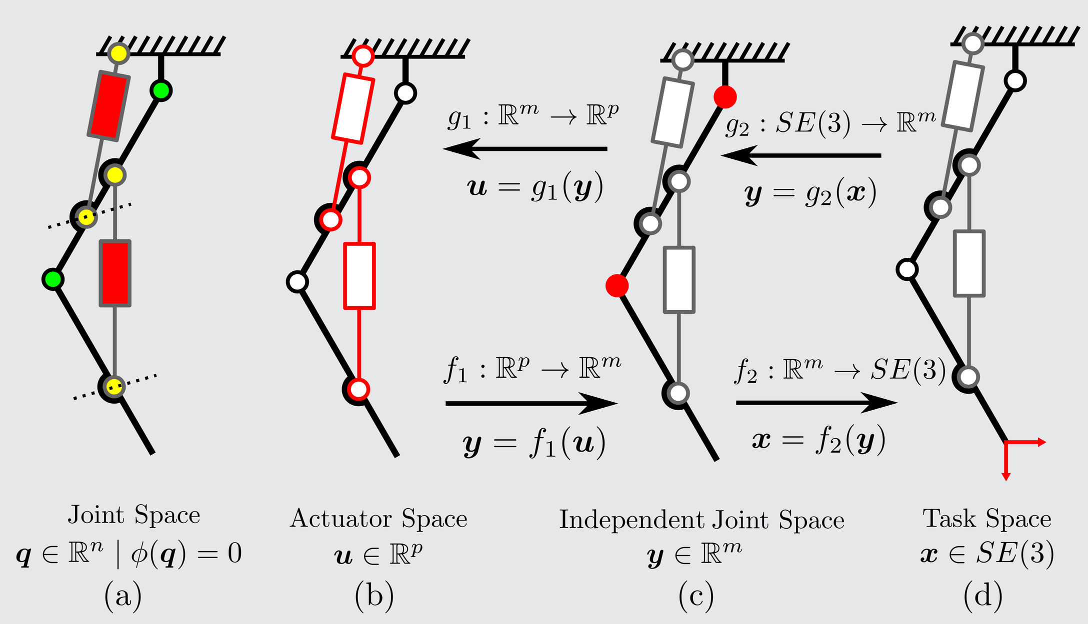


Figure: Abstraction in series-parallel hybrid robots [5]

Equations of motion

Equations of motion (EOM) for systems with closed loops:

$$\boldsymbol{\tau} + \boldsymbol{\tau}_c = \mathbf{H}\ddot{\mathbf{q}} + \mathbf{C}$$

where $\mathbf{H} \in \mathbb{R}^{n\times n}$ - mass-inertia matrix, $\mathbf{C} \in \mathbb{R}^n$ - bias forces, $\boldsymbol{\tau} \in \mathbb{R}^n$ joint forces/torques, $\boldsymbol{\tau}_c \in \mathbb{R}^n$ - loop constraint forces.

Using the loop closure Jacobian $\mathbf{G} \in \mathbb{R}^{n\times m}$ with $\boldsymbol{\tau}_y = \mathbf{G}^T\boldsymbol{\tau}_q$ and $\mathbf{G}^T\boldsymbol{\tau}_c = \mathbf{0}$, and the actuator Jacobian $\mathbf{G}_u \in \mathbb{R}^{p\times m}$ with $\dot{\mathbf{u}} = \mathbf{G}_u\dot{\mathbf{y}}$ we arrive at EOM in actuator coordinates:

$$\mathbf{H}_u\ddot{\mathbf{u}} + \mathbf{C}_u = \boldsymbol{\tau}_u$$

with the mass-inertia matrix:

$$\mathbf{H}_u = \mathbf{G}_u^{-T}\mathbf{G}^T\mathbf{H}\mathbf{G}\mathbf{G}_u^{-1}$$

the bias (Coriolis-Centrifugal + Gravity) forces:

$$\mathbf{C}_u = \mathbf{G}_u^{-T}\mathbf{G}^T(\mathbf{C} + \mathbf{H}\mathbf{g} - \mathbf{H}\mathbf{G}\mathbf{G}_u^{-1}\mathbf{g}_u)$$

and the net actuator forces $\boldsymbol{\tau}_u = \mathbf{G}_u^{-T}\boldsymbol{\tau}_y$.

[1] Assuming fully actuated robots for the sake of simplicity

Whole-Body Control Architecture

Tree-type WBC approaches underestimate the robot workspace as they model actuator limits as box constraints in independent coordinates.

Solution: Define WBC problem in actuator space.

On velocity level:

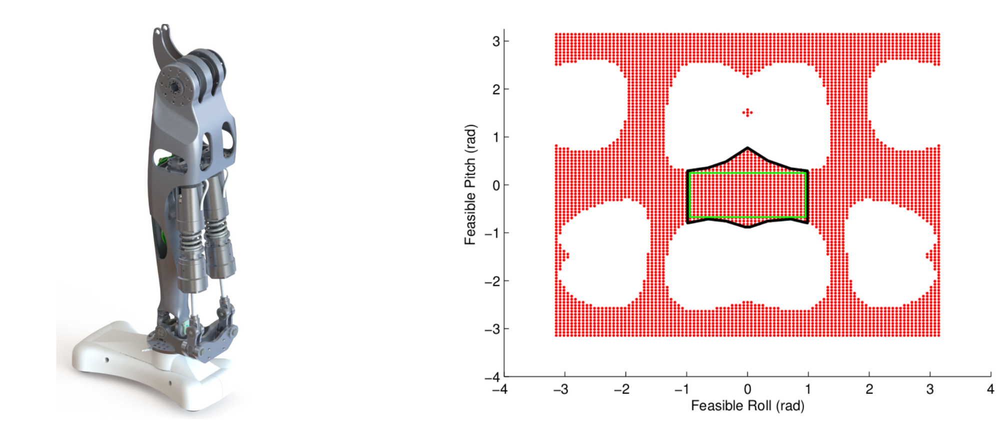
$$\begin{aligned} \min_{\dot{\mathbf{u}}} \quad & \|\mathbf{J}_u\dot{\mathbf{u}} - \mathbf{v}_d\|_2 \\ \text{s.t.} \quad & \mathbf{J}^j_{cu}\dot{\mathbf{u}} = 0, \quad \forall j \\ & \dot{\mathbf{u}}_m \leq \dot{\mathbf{u}} \leq \dot{\mathbf{u}}_M \end{aligned}$$

with $\mathbf{J}_u = \mathbf{J}\mathbf{G}\mathbf{G}_u^{-1}$ - Jacobian in actuator space, $\mathbf{J}_c$ - contact Jacobian, $\mathbf{v}_d \in \mathbb{R}^6$ - desired spatial velocity and $\{\dot{\mathbf{u}}_m, \dot{\mathbf{u}}_M\} \in \mathbb{R}^p$ - actuator velocity limits.

On acceleration level:

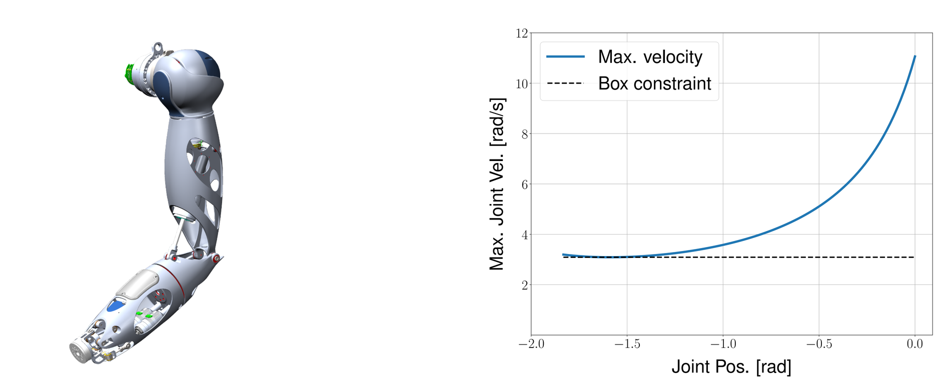
$$\begin{aligned} \min_{\ddot{\mathbf{u}},\boldsymbol{\tau}_u,\mathbf{f}} \quad & \|\mathbf{J}_u\ddot{\mathbf{u}} + \dot{\mathbf{J}}_u\dot{\mathbf{u}} - \dot{\mathbf{v}}_d\|_2 \\ \text{s.t.} \quad & \mathbf{H}_u\ddot{\mathbf{u}} + \mathbf{C}_u = \boldsymbol{\tau}_u + \textstyle\sum_j \mathbf{J}^j_{cu}\mathbf{f}_j \\ & \mathbf{J}^j_{cu}\ddot{\mathbf{u}} = -\dot{\mathbf{J}}^j_{cu}\dot{\mathbf{u}}, \quad \forall j \\ & \boldsymbol{\tau}_{um} \leq \boldsymbol{\tau} \leq \boldsymbol{\tau}_{uM} \end{aligned}$$

where $\mathbf{f}_j \in \mathbb{R}^6$ - contact wrenches, $\dot{\mathbf{v}}_d \in \mathbb{R}^6$ - desired spatial accelerations, $\{\boldsymbol{\tau}_{um}, \boldsymbol{\tau}_{uM}\} \in \mathbb{R}^p$ - force/torque limits.



(a) RH5 ankle mechanism (b) Admissible independent joint space (black) and box constraints (green)

Figure: Example: Box constraints for actuator positions

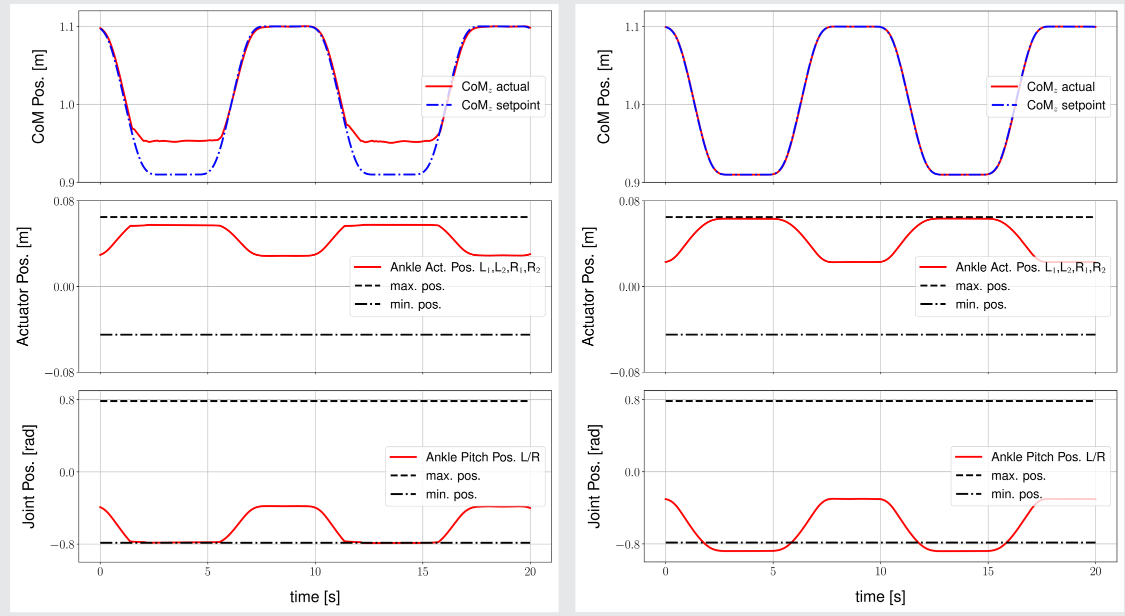


(a) RH5 Manus elbow mechanism (b) Admissible independent joint space (black) and box constraints (green)

Figure: Example: Box constraints for actuator velocities

Experiments

Squatting movements on RH5 humanoid:



(a) Tree-type WBC approach (b) Hybrid WBC approach

Figure: Exploitation of admissible position workspace

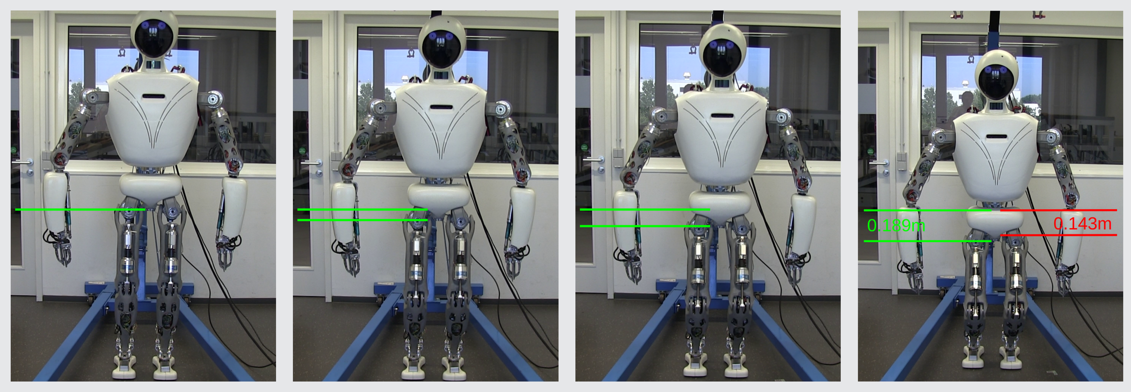
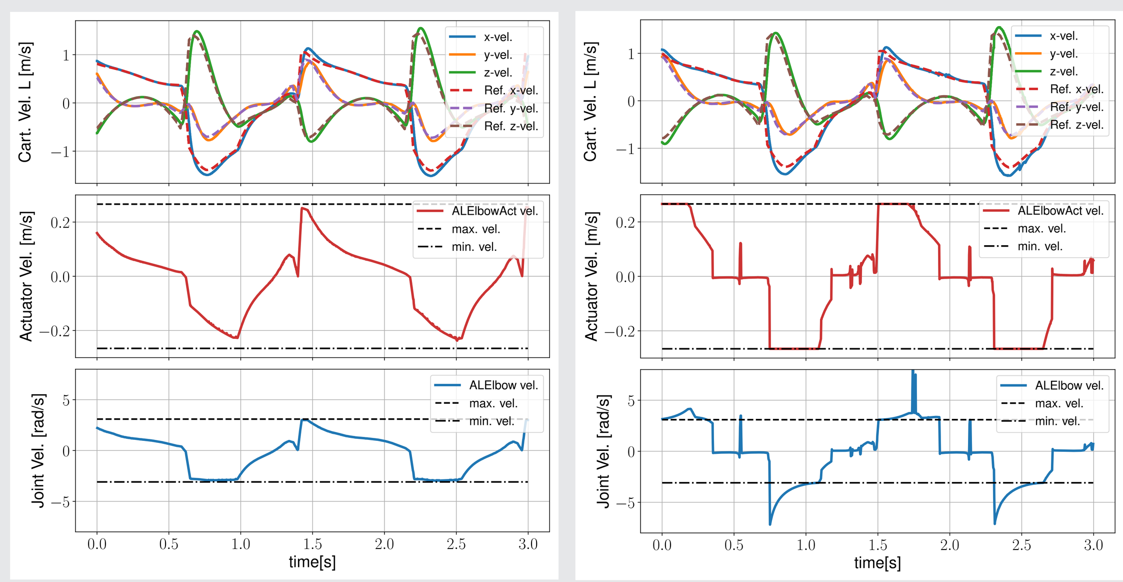


Figure: Squats on RH5 [6], red: Serial, green: Hybrid

Boxing movements on RH5 Manus Humanoid:



(a) Tree-type WBC approach (b) Hybrid WBC approach

Figure: Exploitation of admissible velocity workspace

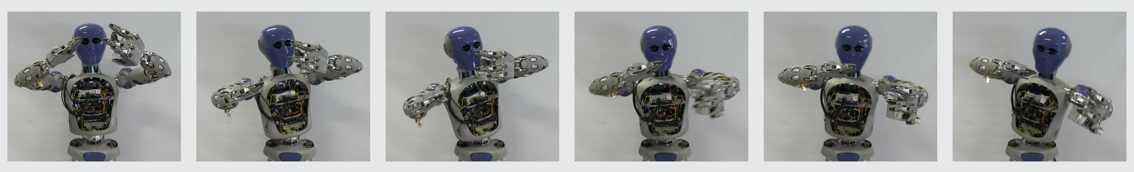


Figure: Boxing movements on RH5 Manus [6]

Conclusion

- Overcome limitations of SoTA WBC approaches
- Achieve a larger admissible workspace
- Require a slightly larger computational effort

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