Dynamic Walking Over Rough Terrains by Nonlinear Predictive Control of the Floating-Base Inverted Pendulum

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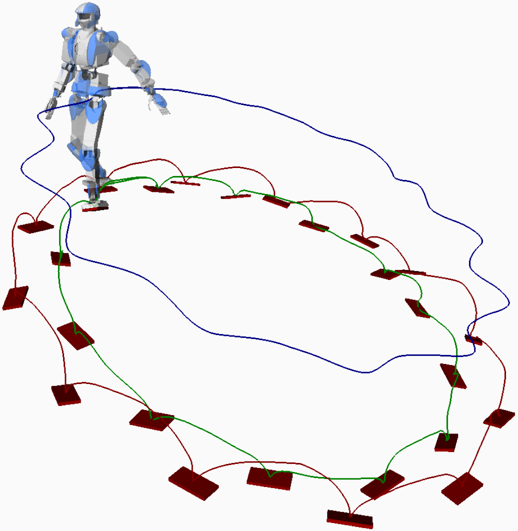
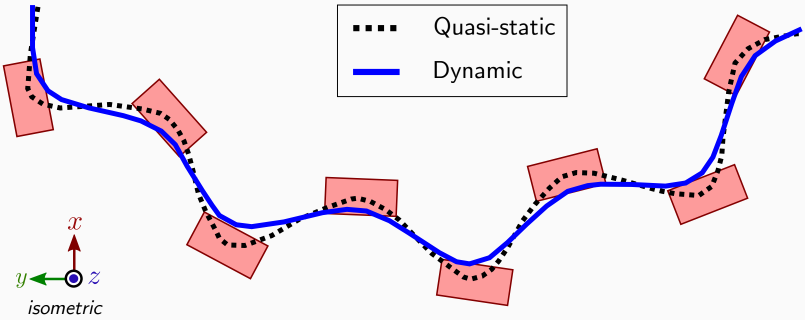
GOAL



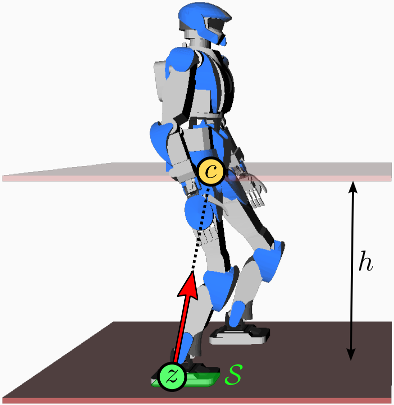

Quasi-static
Dynamic
x
y
z
isometric

Equation of motion

$$\ddot{c} = \omega^2 (c - z) + \vec{g}$$

Feasibility conditions

- Constant: $\omega = \sqrt{g/h}$
- ZMP support area: $z \in \mathcal{S}$
- Friction?



Linear Inverted Pendulum

$$\ddot{c} = \omega^2(c - z) + \vec{g}$$

Feasibility conditions

- Constant: $\omega = \sqrt{g/h}$
- ZMP support area: $z \in \mathcal{S}$
- Friction?

Inverted Pendulum

$$\ddot{c} = \lambda(c - z) + \vec{g}$$

Feasibility conditions

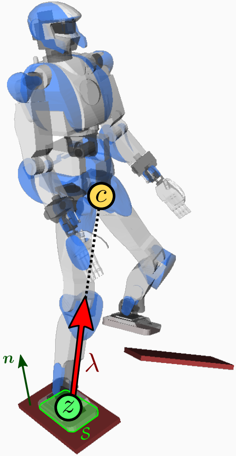
- Unilaterality: $\lambda \geq 0$
- ZMP support area: $z \in \mathcal{S}$
- Friction?

Equation of motion

$$\ddot{c} = \lambda(c - z) + \vec{g}$$

Feasibility conditions

- Unilaterality: $\lambda \geq 0$
- ZMP support area: $z \in \mathcal{S}$
- Friction?

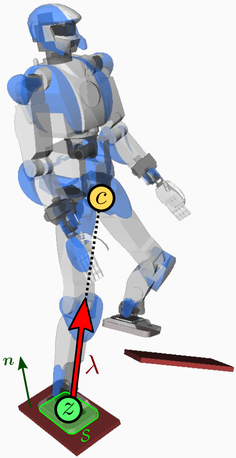


Equation of motion

$$\ddot{c} = \lambda(c - z) + \vec{g}$$

Feasibility conditions

- Unilaterality: $\lambda \geq 0$
- ZMP support area: $z \in \mathcal{S}$
- Friction?

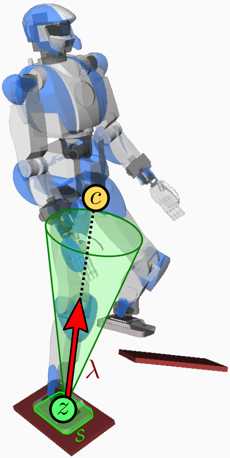


Equation of motion

$$\ddot{c} = \lambda(c - z) + \vec{g}$$

Feasibility conditions

- Unilaterality: $\lambda \geq 0$
- ZMP support area: $z \in \mathcal{S}$
- Friction: $c - z \in \mathcal{C}$

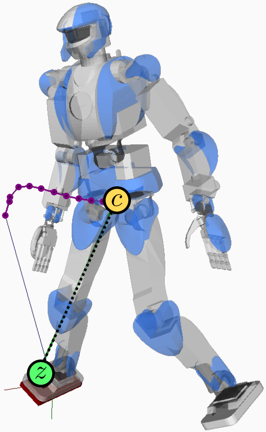


Equation of motion

$$\ddot{c} = \lambda(c - z) + \vec{g}$$

Forward integration[1]

- Direct multiple shooting[2]
- Discretization: # of sample points, integration step
- Resolution of integrator?



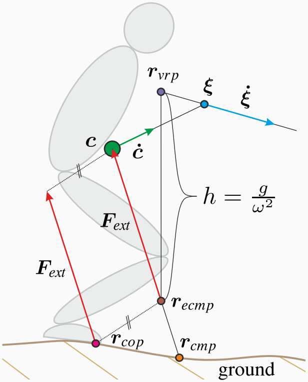
[1] See also Takasugi *et al.* (this session): "3D Walking and Skating..."
[2] Carpentier, Tonneau, Naveau, Stasse, and Mansard 2016.

Equation of motion

$$\ddot{c} = \omega^2(c - z) + \vec{g}$$

Virtual Repellent Points

- The ZMP/eCMP/VRP[2] can leave the contact area
- Fwd integration is exact: $c(t) = \alpha e^{\omega t} + \beta e^{-\omega_t} + \gamma$
- Feasibility conditions?



(Figure adapted from [2])

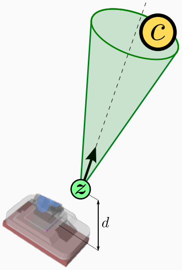
[3] Englsberger, Ott, and Albu-Schaffer 2015.

Equation of motion

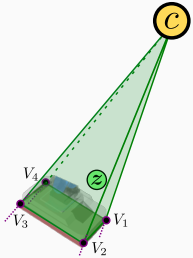
$$\ddot{c} = \omega^2 (c - z) + \vec{g}$$

Floating-base pendulum

- Floating ZMP (eCMP)
- Exact forward integration
- **New** feasibility condition



Friction cone



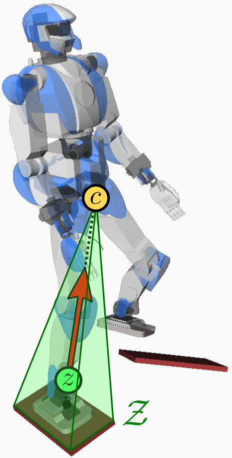
ZMP support cone

Equation of motion

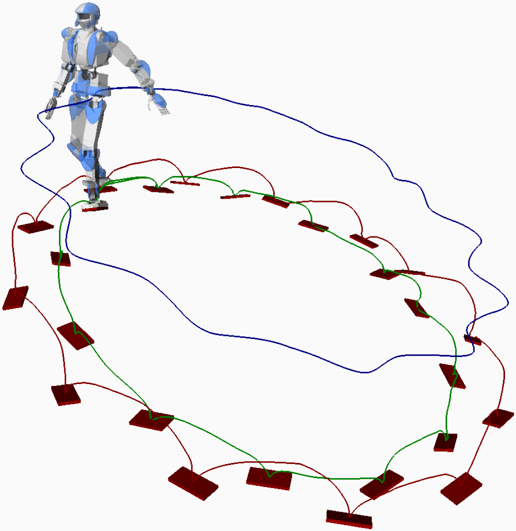
$$\ddot{c} = \omega^2(c - z) + \vec{g}$$

Feasibility conditions

- Constant: $\omega > 0$
- ZMP support cone: $z \in \mathcal{Z}$



GOAL

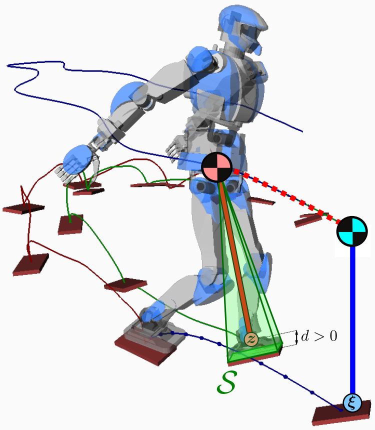


Nonlinear optimization...

- DMS over FIP model
- Adaptive step timings
- Runs at 30 Hz

... but significant failures

- Model is **nonconvex**
- Noise and delays in ZMP control / COM estimation $\Rightarrow$ jumps in PO map



This communication:

Constrained LQ regulator

- Linear EoM + linearized ZMP cones = Quadratic Program
- Runs at 300 Hz, recovers locally from failures

[4] Caron and Mallein 2017.

This communication:

Constrained LQ regulator

- Linear EoM + linearized ZMP cones = Quadratic Program
- Runs at 300 Hz, recovers locally from failures

Next communication:[3]

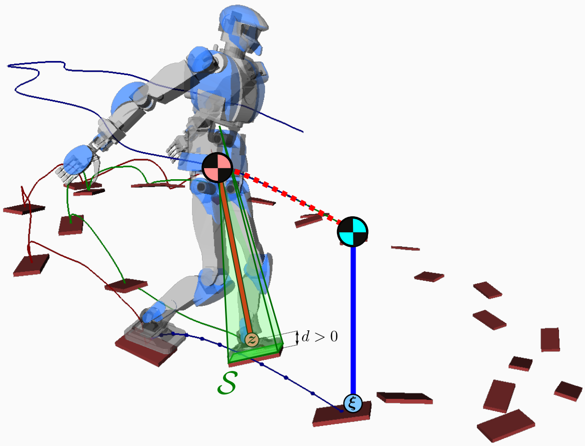
Spoiler!

A *convexly-constrained* model: one global optimum, 1000 Hz

`https://scaron.info/research/3d-balance.html`

[4]Caron and Mallein 2017.

CHECK IT OUT!



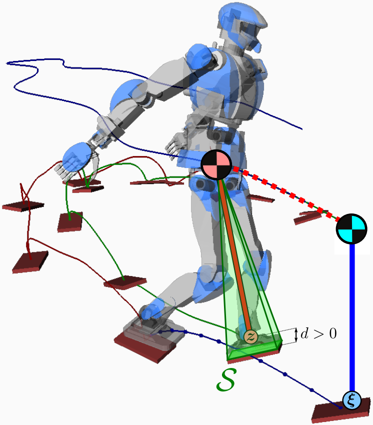
https://github.com/stephane-caron/dynamic-walking

Floating-base Pendulum

- LTI model for 3D walking
- ZMP support area ⇒ cone

Nonlinear Predictive Control

- Can solve full problem
- Failures (nonconvexity)
- Recovery: constrained LQR



THANK YOU FOR YOUR ATTENTION!

Caron, Stéphane and Bastien Mallein (2017). ``Balance control using both ZMP and COM height variations: A convex boundedness approach''. working paper or preprint. URL: https://scaron.info/research/3d-balance.html.

Carpentier, J., S. Tonneau, M. Naveau, O. Stasse, and N. Mansard (2016). ``A versatile and efficient pattern generator for generalized legged locomotion''. In: *2016 IEEE International Conference on Robotics and Automation (ICRA)*, pp. 3555–3561.

Englsberger, Johannes, Christian Ott, and Alin Albu-Schaffer (2015). ``Three-dimensional bipedal walking control based on divergent component of motion''. In: *IEEE Transactions on Robotics* 31.2, pp. 355–368.