

# STAIR CLIMBING STABILIZATION OF THE HRP-4 HUMANOID ROBOT

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December 11 and 14, 2018

JRL Seminar, CNRS-AIST Joint Robotics Laboratory, Tsukuba (December 11)

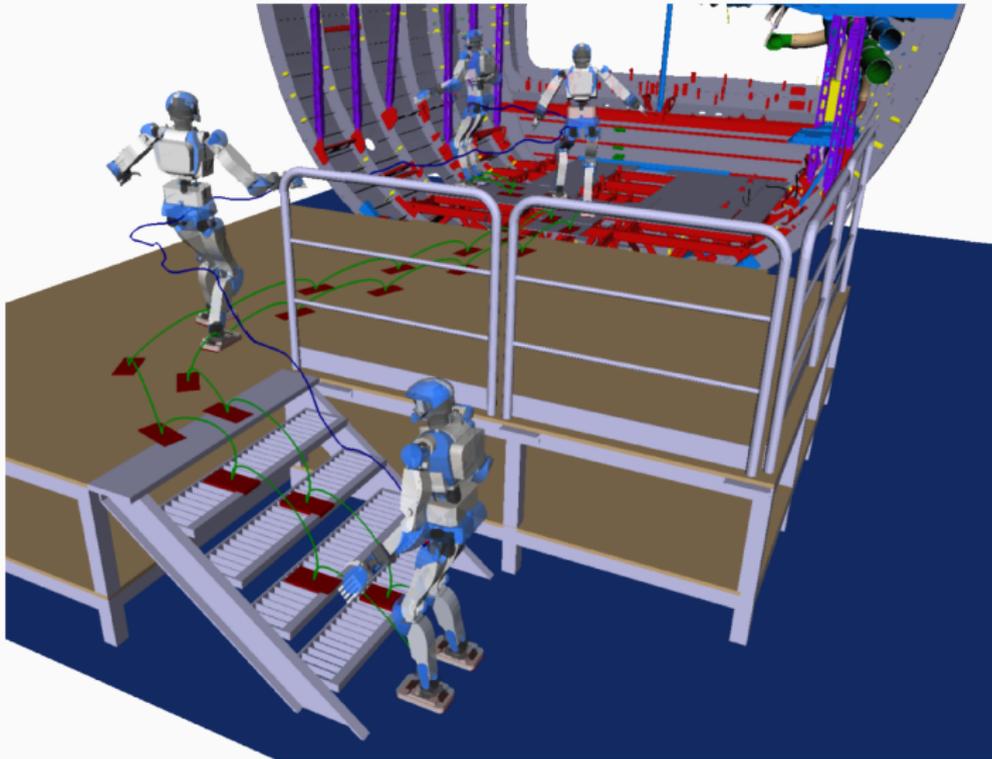
Seminar at the Department of Mechano-Informatics, the University of Tokyo (December 14)





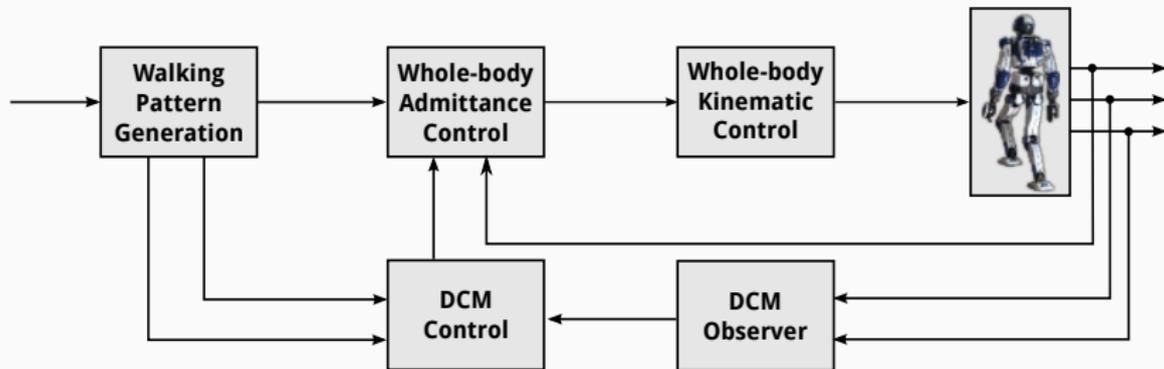
COMANOID project - <https://comanoid.cnrs.fr>

## DEMONSTRATOR SCENARIO

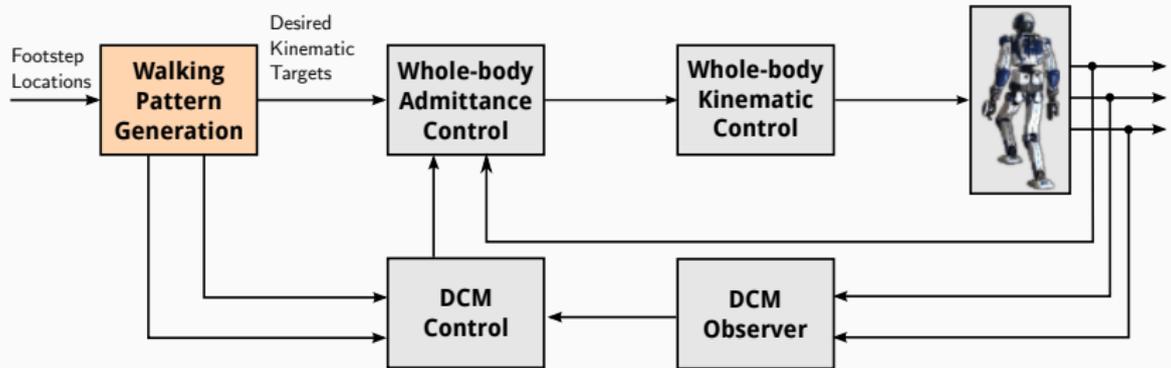




<https://www.youtube.com/watch?v=vFCFKAunsYM>



# WALKING PATTERN GENERATION



- Equation of motion :

$$M\ddot{q} + N = S^T\tau + J^Tf$$

- Floating base dynamics :

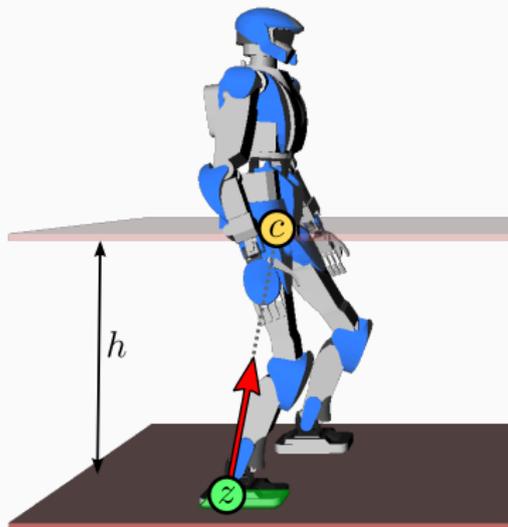
$$\ddot{c} = \frac{1}{m} \sum_i f_i$$

$$\dot{L}_c = \sum_i (p_i - c) \times f_i$$

- Angular momentum  $\dot{L}_c = 0$  :

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

with  $\omega^2 = g/h$  and  $z$  the ZMP



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1. Shuuji KAJITA, Fumio KANEHIRO, Kenji KANEKO, Kazuhito YOKOI et Hirohisa HIRUKAWA. « The 3D Linear Inverted Pendulum Mode : A simple modeling for a biped walking pattern generation ». In : *IEEE/RSJ International Conference on Intelligent Robots and Systems*. 2001.

- LIPM equation of motion :

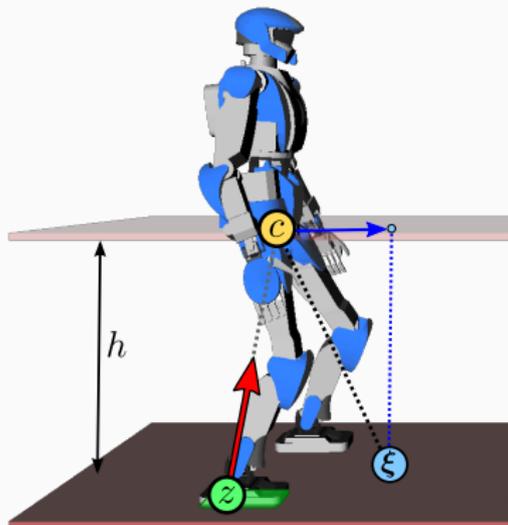
$$\ddot{c} = \omega^2(c - z)$$

- Divergent Component of Motion :

$$\xi = c + \frac{\dot{c}}{\omega}$$

- Unstable dynamics :

$$\dot{\xi} = \omega(\xi - z)$$



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2. Johannes ENLSBERGER, Christian OTT, Maximo ROA, Alin ALBU-SCHÄFFER, Gerhard HIRZINGER et al. « Bipedal walking control based on capture point dynamics ». In : *IEEE/RSJ International Conference on Intelligent Robots and Systems*. 2011.

Generate a CoM-ZMP trajectory that is :

## Consistent

$$\forall t > 0, \ddot{c}(t) = \omega^2(c(t) - z(t))$$

## Feasible

- ZMP belongs to support area
- Contact force within friction cone

## Viable

Not falling. For this system, same as bounded :  $\exists M > 0, \forall t > 0, \|c(t)\| \leq M$

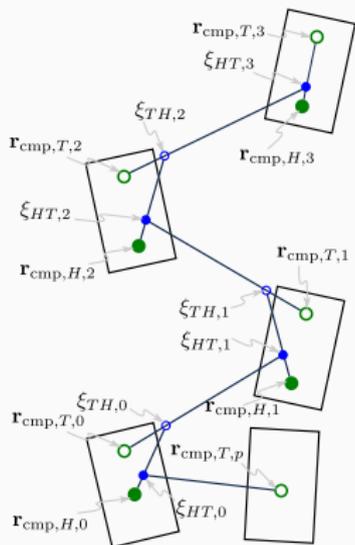


Figure adapted from [Gri+17].

So far we have tested three methods :

- Linear Model Predictive Control [Wie06]
- Foot-guided Agile Control through ZMP Manipulation [SY17]
- Capturability of Variable-Height Inverted Pendulum [Car+18]

Formulate preview control [Kaj+03] as a Quadratic Program (QP) :

## Cost function

- Track desired ZMP reference
- Track desired CoM velocity
- Minimize CoM jerk

## Constraints

- Consistency : state equation
- Feasibility : ZMP in support area
- Viability : terminal DCM

Allows a number of extensions :

- Variable CoM height : [Bra+15]
- Variable step timings : [BW17]
- Guarantee of recursive feasibility : [CWF17]

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3. Pierre-Brice WIEBER. « Trajectory free linear model predictive control for stable walking in the presence of strong perturbations ». In : *IEEE-RAS International Conference on Humanoid Robots*. 2006.

## Predictive control with ZMP as input

$$\begin{array}{ll}
 \text{minimize}_{z(t)} & \int_0^T (z(t) - z^d)^2 dt \quad \Rightarrow \text{Feasibility (best effort)} \\
 \text{subject to} & \ddot{c} = \omega^2(c - z) \quad \Rightarrow \text{Consistency} \\
 & c(T) + \frac{\dot{c}(T)}{\omega} = \xi^d \quad \Rightarrow \text{Viability}
 \end{array}$$

- Finite horizon, continuous time dynamics
- **Analytical solution :**

$$z^*(0) = z^d + 2 \frac{(\xi(0) - z^d) - (\xi^d - z^d)e^{-\omega T}}{1 - e^{-2\omega T}}$$

- Call many times to adapt step timings

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4. Tomomichi SUGIHARA et Takanobu YAMAMOTO. « Foot-guided Agile Control of a Biped Robot through ZMP Manipulation ». In : *IEEE/RSJ International Conference on Intelligent Robots and Systems*. 2017.

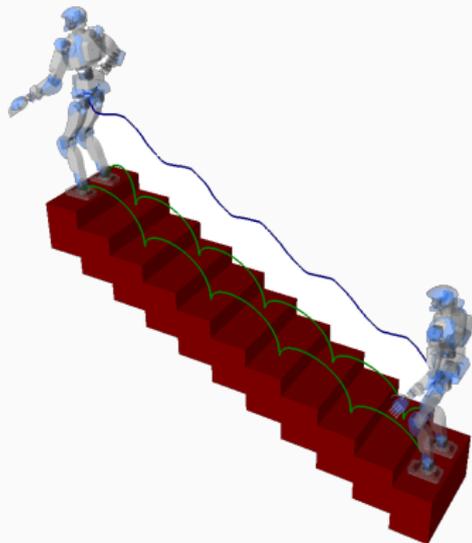
- New input  $\lambda > 0$  for height variations :

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

- Viability  $\Rightarrow$  boundedness condition :

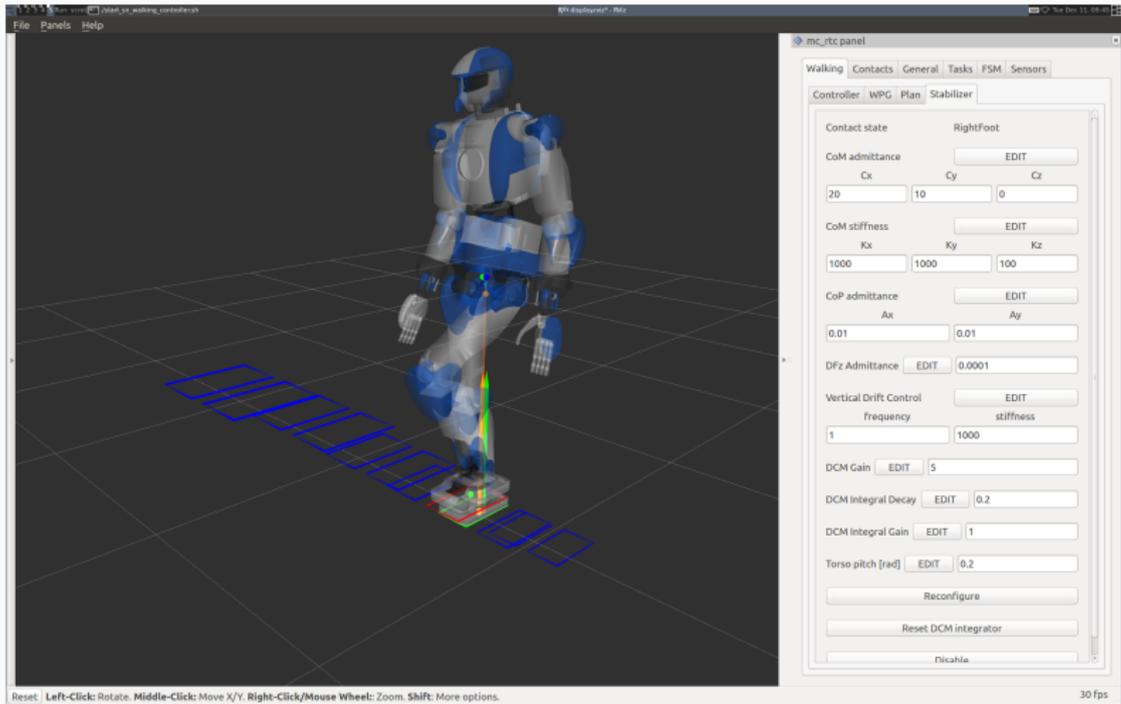
$$\xi(0) = \int_0^{\infty} (\lambda(t)r(t) - g)e^{-\Omega(t)} dt$$

- Solve : tailored optimization (30-50  $\mu$ s)
- Call many times to adapt step timings



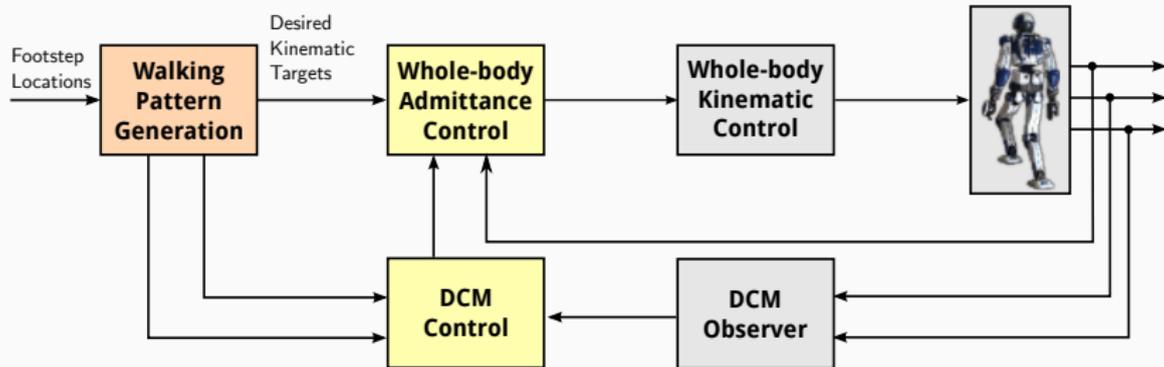
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5. Stéphane CARON, Adrien ESCANDE, Leonardo LANARI et Bastien MALLEIN. « Capturability-based Analysis, Optimization and Control of 3D Bipedal Walking ». 2018. URL : <https://hal.archives-ouvertes.fr/hal-01689331/document>.

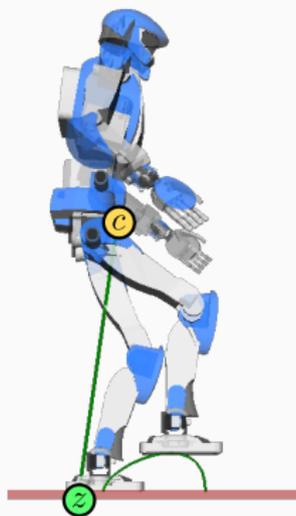


Visualization of stair climbing pattern in mc\_rtc

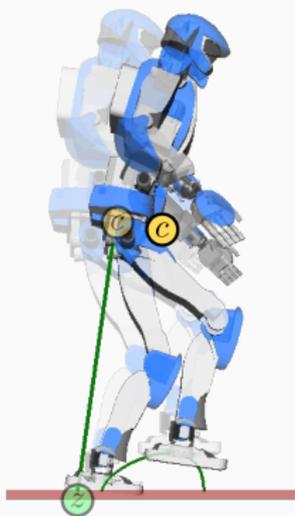
# WALKING STABILIZATION



Actuated joints converge but unactuated floating base *diverges* :



In walking pattern



By robot without stabilization

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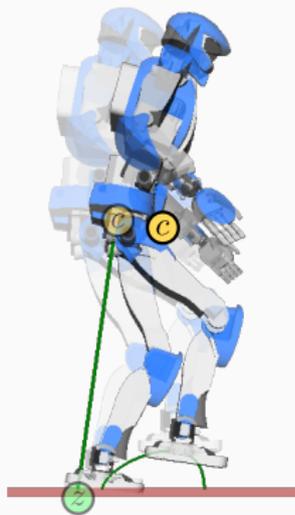
Figure adapted from [Tak+09].

Let's review the facts :

- Floating base translation is unactuated
- Its dynamics are reduced to :

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

- Only way to control it is via **indirect force control** of the ZMP  $z$



... but our robot is **position-controlled**?

Split control into two components :

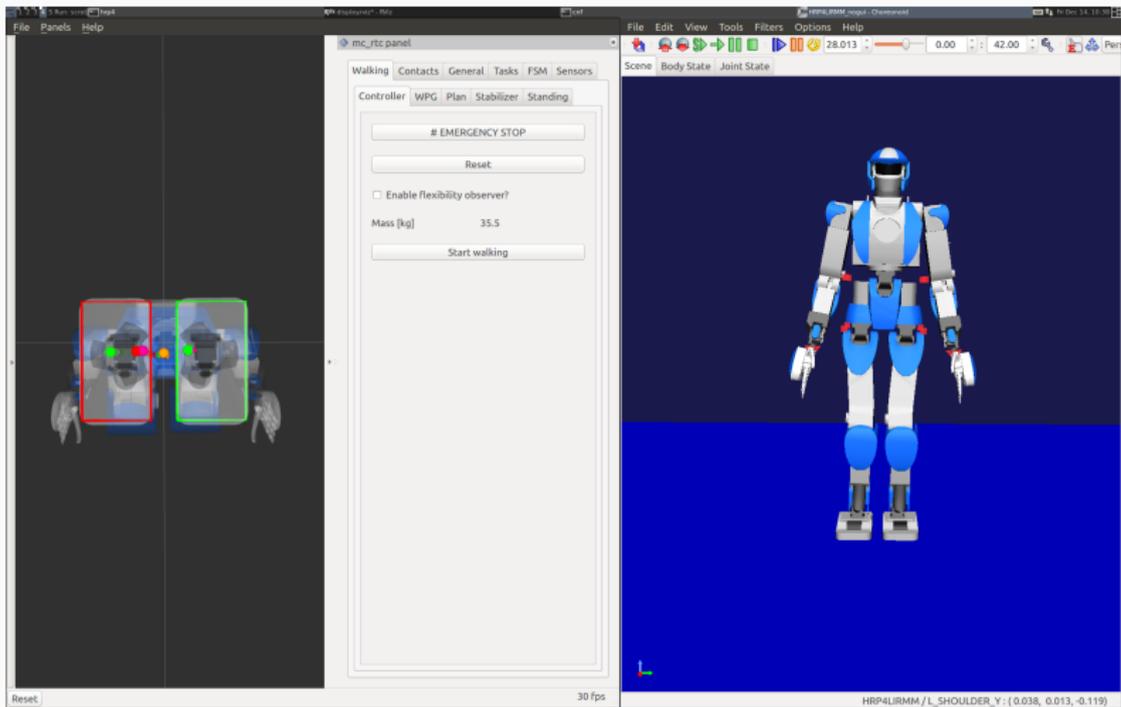
### Admittance control

Allow position changes to improve force tracking

### Floating-base control

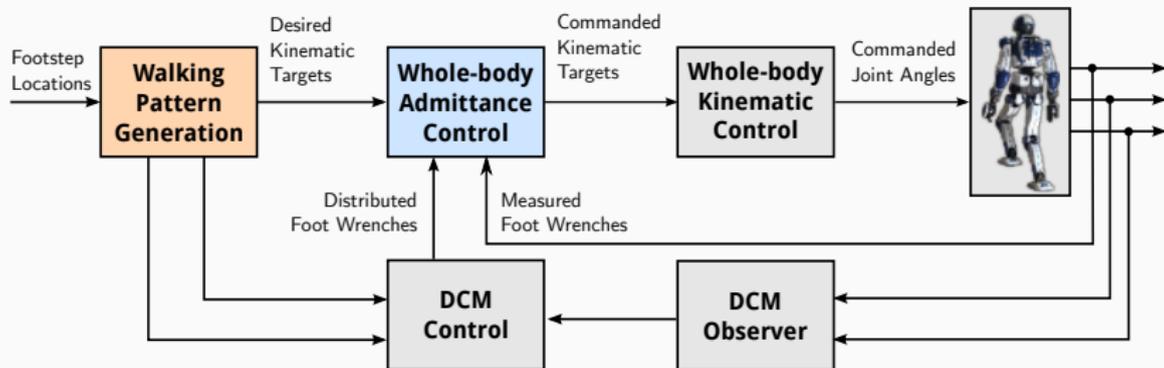
Assuming force control, select reaction force to control the floating base





Standing stabilization under external forces

# ADMITTANCE CONTROL



Different strategies for different components of the net contact wrench :

- CoP at each contact [Kaj+01b]
- Pressure distribution [Kaj+10]
- CoM admittance control [Nag99]



- Rotate end-effector to move its CoP
- Assumes compliance at contact :

$$\tau = K_e(\theta - \theta_e)$$

- Apply damping control :

$$\dot{\theta} = A_{cop}(\tau_d - \tau)$$

- Closed-loop behavior has  $\tau \rightarrow \tau_d$

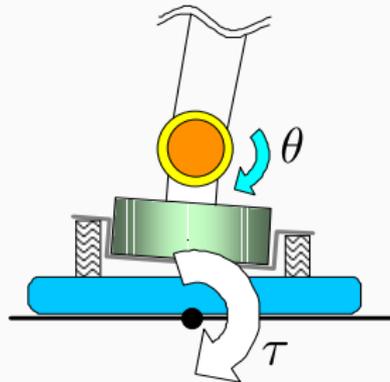


Figure adapted from [Kaj+01b]

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6. Shuuji KAJITA, Kazuhito YOKOI, Muneharu SAIGO et Kazuo TANIE. « Balancing a Humanoid Robot Using Backdrive Concerned Torque Control and Direct Angular Momentum Feedback ». In : *IEEE International Conference on Robotics and Automation*. 2001.

- Net vertical force compensates gravity  $\Rightarrow$  only need to control :

$$\Delta f_z = f_{Rz} - f_{Lz}$$

- Push down with foot that needs more pressure, lift the other one
- Apply damping control :

$$\dot{z}_{ctrl} = A_z(\Delta f_{zd} - \Delta f_z)$$

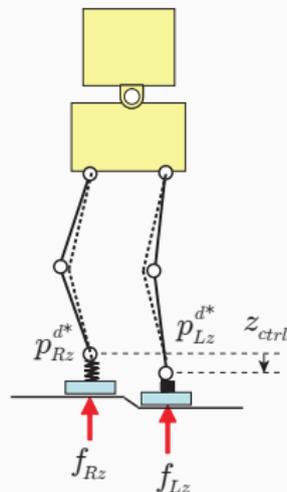


Figure adapted from [Kaj+10]

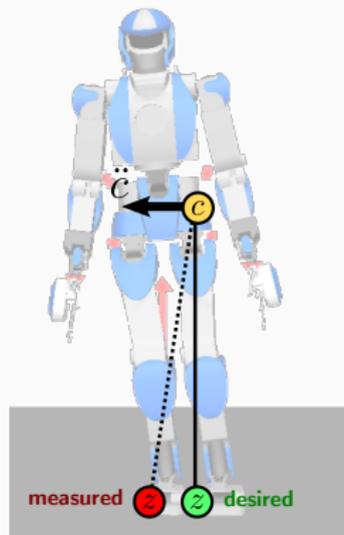
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7. Shuuji KAJITA, Mitsuharu MORISAWA, Kanako MIURA, Shin'ichiro NAKAOKA, Kensuke HARADA, Kenji KANEKO, Fumio KANEHIRO et Kazuhito YOKOI. « Biped walking stabilization based on linear inverted pendulum tracking ». In : *IEEE/RSJ International Conference on Intelligent Robots and Systems*. 2010.

- Recall that  $\ddot{c} = \omega^2(c - z)$
- Accelerate CoM against ZMP error :

$$\ddot{c} = A_c(z - z_d)$$

- Closed-loop behavior : analysis is only possible with delay or disturbance observer<sup>8</sup>



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8. Discussions with Pr T. SUGIHARA.

9. Ken'ichiro NAGASAKA. « Whole-body Motion Generation for a Humanoid Robot by Dynamics Filters ». In : *PhD thesis* (1999). The University of Tokyo, in Japanese.

Which ones to choose ?

### End-effector strategies

- CoP at each contact [Kaj+01b]
- Pressure distribution [Kaj+10]

... are sufficient to control the net wrench,  
yet :

### CoM admittance control [Nag99]

- uses other joints, e.g. hips
- helps recover from ZMP saturation<sup>10</sup>



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10. The effect is similar to *Model ZMP Control* [Tak+09].

# COM ADMITTANCE IN STAIR CLIMBING

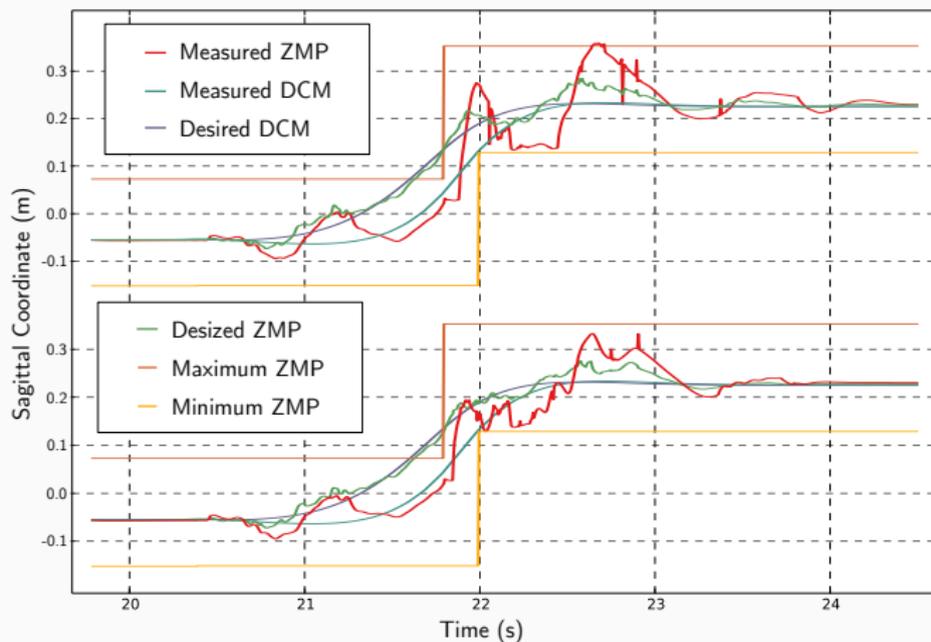
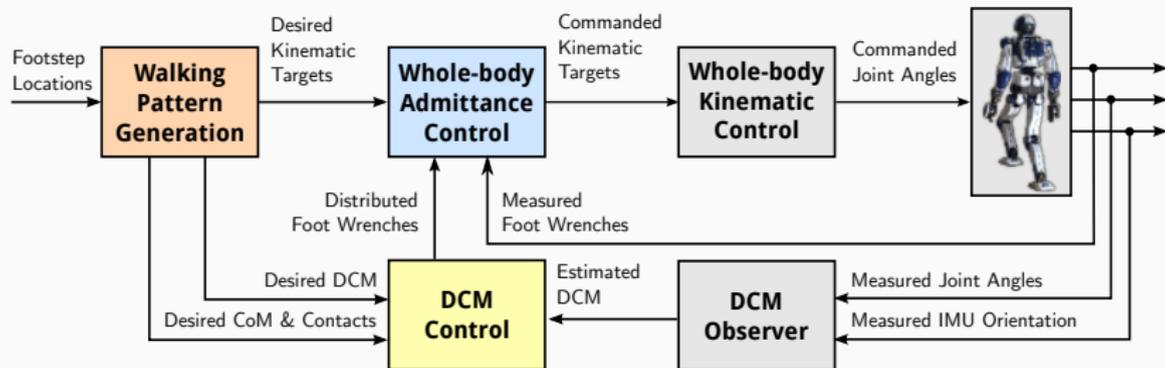


FIGURE 1: Top : no CoM admittance control. Bottom : with  $A_c = 20$  [Hz<sup>2</sup>].

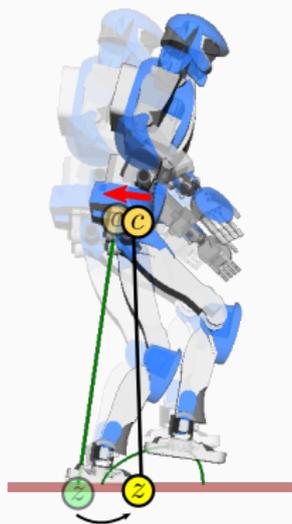


- Assume control of  $z$  in  $\ddot{c} = \omega^2(c - z)$
- Control only the DCM  $\dot{\xi} = \omega(\xi - z)$  :
  - requires less control input [Tak+09]
  - yields best CoM-ZMP regulator [Sug09]
- Apply proportional feedback to it :

$$\dot{\xi} = \dot{\xi}_d + k_p(\xi_d - \xi)$$

$$z = z_d - \left[ 1 + \frac{k_p}{\omega} \right] (\xi_d - \xi)$$

- Equivalent to Inverted Pendulum Compensation [Nag99]




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11. Tomomichi SUGIHARA. « Standing stabilizability and stepping maneuver in planar bipedalism based on the best COM-ZMP regulator ». In : *IEEE International Conference on Robotics and Automation*. 2009.

- Add integral term to eliminate steady-state error :

$$\dot{\xi} = \dot{\xi}_d + k_p(\xi_d - \xi) + k_i \int (\xi_d - \xi)$$

$$z = z_d - \left(1 + \frac{k_p}{\omega}\right)(\xi_d - \xi) - \frac{k_i}{\omega} \int (\xi_d - \xi)$$

- Select gains  $k_p$  and  $k_i$  by *pole placement*
- Link with admittance control gains ?

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12. Mitsuharu MORISAWA, Shuuji KAJITA, Fumio KANEHIRO, Kenji KANEKO, Kanako MIURA et Kazuhiro YOKOI. « Balance control based on capture point error compensation for biped walking on uneven terrain ». In : *IEEE-RAS International Conference on Humanoid Robots*. 2012.

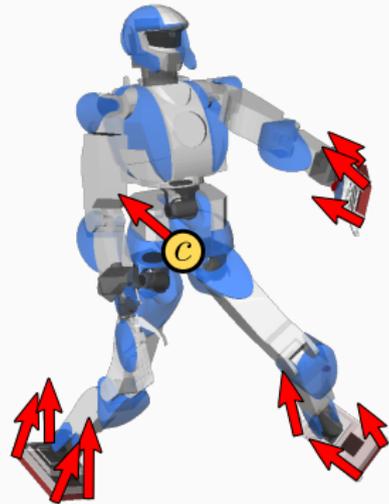
Wrench distribution by QP :

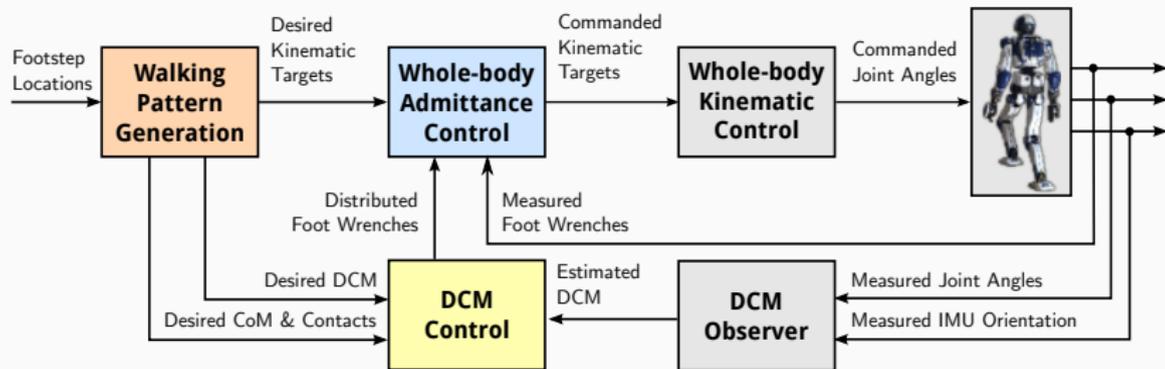
## Cost function

- Realize net wrench
- Minimize ankle torques
- Desired pressure distribution

## Constraints

- Frictional wrench cones
- Minimum pressure on each contact



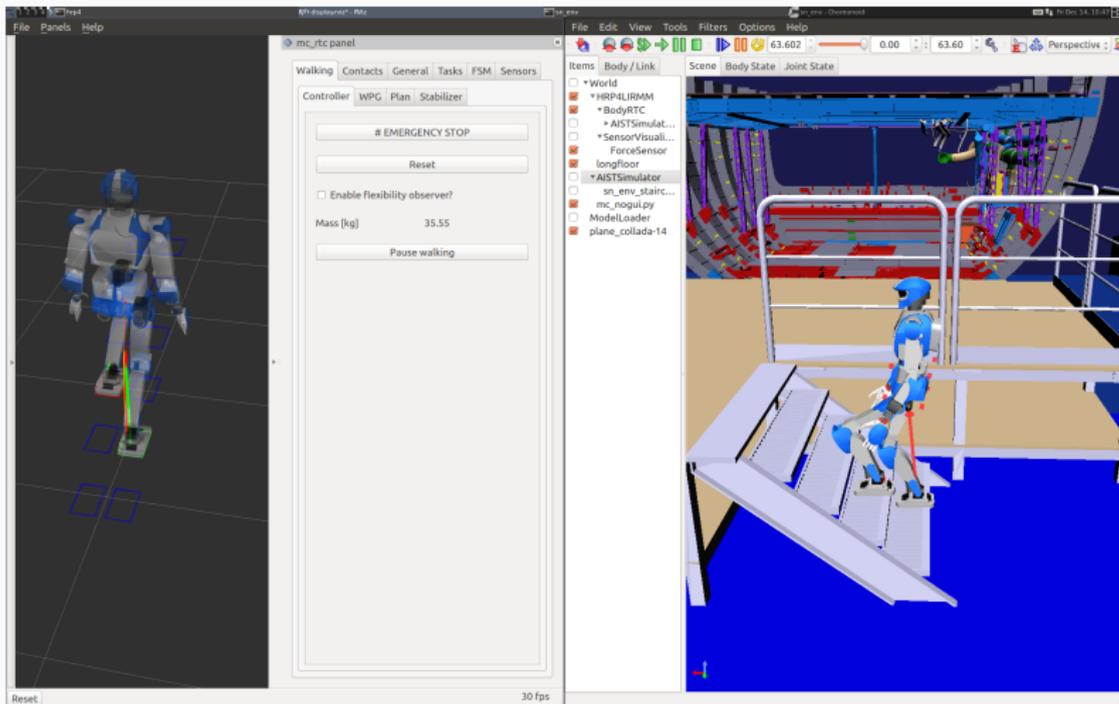




<https://www.youtube.com/watch?v=vFCFKAunsYM>

## CODA : AN ODE TO TWO TOOLS

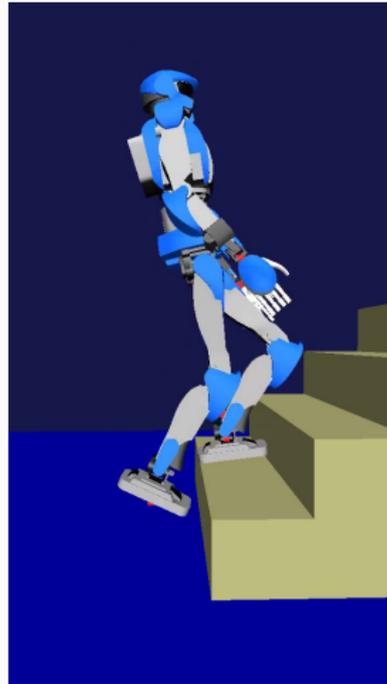
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Controller with mc\_rtc GUI alongside a Choreonoid dynamic simulation



Failure case on real robot



Reproduction in Choreonoid

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<http://choreonoid.org/en/>

Thank you for your attention!



- [Bra+15] Camille BRASSEUR, Alexander SHERIKOV, Cyrille COLLETTE, Dimitar DIMITROV et Pierre-Brice WIEBER. « A robust linear MPC approach to online generation of 3D biped walking motion ». In : *IEEE-RAS International Conference on Humanoid Robots*. 2015.
- [BW17] Nestor BOHORQUEZ et Pierre-Brice WIEBER. « Adaptive step duration in biped walking : a robust approach to nonlinear constraints ». In : *IEEE-RAS International Conference on Humanoid Robots*. 2017.
- [Car+18] Stéphane CARON, Adrien ESCANDE, Leonardo LANARI et Bastien MALLEIN. « Capturability-based Analysis, Optimization and Control of 3D Bipedal Walking ». 2018. URL : <https://hal.archives-ouvertes.fr/hal-01689331/document>.
- [CWF17] Matteo CIOCCA, Pierre-Brice WIEBER et Thierry FRAICHARD. « Strong Recursive Feasibility in Model Predictive Control of Biped Walking ». In : *IEEE-RAS International Conference on Humanoid Robots*. 2017.
- [Eng+11] Johannes ENGLSBERGER, Christian OTT, Maximo ROA, Alin ALBU-SCHÄFFER, Gerhard HIRZINGER et al. « Bipedal walking control based on capture point dynamics ». In : *IEEE/RSJ International Conference on Intelligent Robots and Systems*. 2011.

- [Gri+17] Robert J GRIFFIN, Georg WIEDEBACH, Sylvain BERTRAND, Alexander LEONESSA et Jerry PRATT. « Walking Stabilization Using Step Timing and Location Adjustment on the Humanoid Robot, Atlas ». In : *IEEE/RSJ International Conference on Intelligent Robots and Systems*. 2017.
- [Kaj+01a] Shuuji KAJITA, Fumio KANEHIRO, Kenji KANEKO, Kazuhito YOKOI et Hirohisa HIRUKAWA. « The 3D Linear Inverted Pendulum Mode : A simple modeling for a biped walking pattern generation ». In : *IEEE/RSJ International Conference on Intelligent Robots and Systems*. 2001.
- [Kaj+01b] Shuuji KAJITA, Kazuhito YOKOI, Muneharu SAIGO et Kazuo TANIE. « Balancing a Humanoid Robot Using Backdrive Concerned Torque Control and Direct Angular Momentum Feedback ». In : *IEEE International Conference on Robotics and Automation*. 2001.
- [Kaj+03] Shuuji KAJITA, Fumio KANEHIRO, Kenji KANEKO, Kiyoshi FUJIWARA, Kensuke HARADA, Kazuhito YOKOI et Hirohisa HIRUKAWA. « Biped walking pattern generation by using preview control of zero-moment point ». In : *IEEE International Conference on Robotics and Automation*. 2003.
- [Kaj+10] Shuuji KAJITA, Mitsuharu MORISAWA, Kanako MIURA, Shin'ichiro NAKAOKA, Kensuke HARADA, Kenji KANEKO, Fumio KANEHIRO et Kazuhito YOKOI. « Biped walking stabilization based on linear inverted pendulum tracking ». In : *IEEE/RSJ International Conference on Intelligent Robots and Systems*. 2010.

- [Mor+12] Mitsuharu MORISAWA, Shuuji KAJITA, Fumio KANEHIRO, Kenji KANEKO, Kanako MIURA et Kazuhiro YOKOI. « Balance control based on capture point error compensation for biped walking on uneven terrain ». In : *IEEE-RAS International Conference on Humanoid Robots*. 2012.
- [Nag99] Ken'ichiro NAGASAKA. « Whole-body Motion Generation for a Humanoid Robot by Dynamics Filters ». In : *PhD thesis* (1999). The University of Tokyo, in Japanese.
- [Sug09] Tomomichi SUGIHARA. « Standing stabilizability and stepping maneuver in planar bipedalism based on the best COM-ZMP regulator ». In : *IEEE International Conference on Robotics and Automation*. 2009.
- [SY17] Tomomichi SUGIHARA et Takanobu YAMAMOTO. « Foot-guided Agile Control of a Biped Robot through ZMP Manipulation ». In : *IEEE/RSJ International Conference on Intelligent Robots and Systems*. 2017.
- [Tak+09] Toru TAKENAKA, Takashi MATSUMOTO, Takahide YOSHIIKE, Tadaaki HASEGAWA, Shinya SHIROKURA, Hiroyuki KANEKO et Atsuo ORITA. « Real time motion generation and control for biped robot-4th report : Integrated balance control ». In : *IEEE/RSJ International Conference on Intelligent Robots and Systems*. 2009.
- [Wie06] Pierre-Brice WIEBER. « Trajectory free linear model predictive control for stable walking in the presence of strong perturbations ». In : *IEEE-RAS International Conference on Humanoid Robots*. 2006.