Walking and stair climbing stabilization for position-controlled biped robots

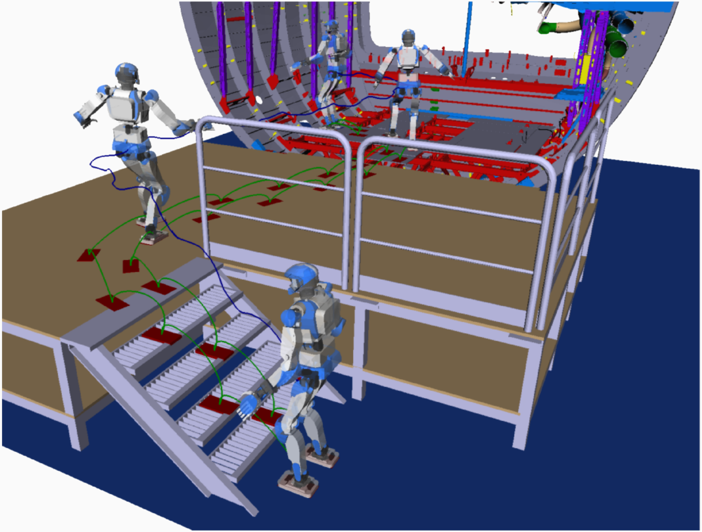
Stéphane Caron

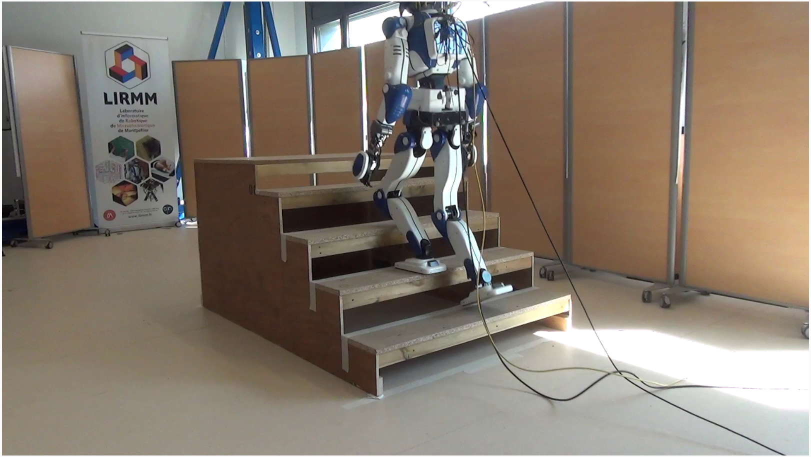
March 19, 2019

Presentation given at Wandercraft, Paris

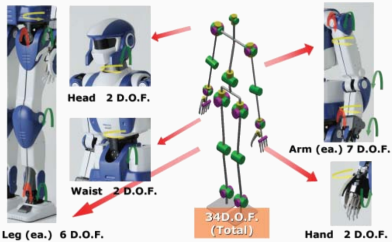
COMANOID project - `https://comanoid.cnrs.fr`

FINAL DEMONSTRATOR





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



Stiff position control on all joints

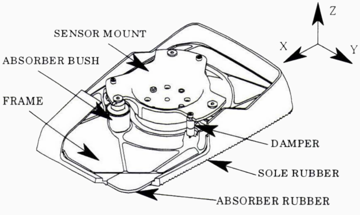
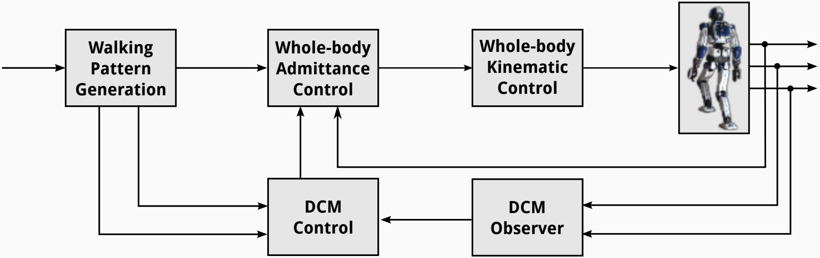
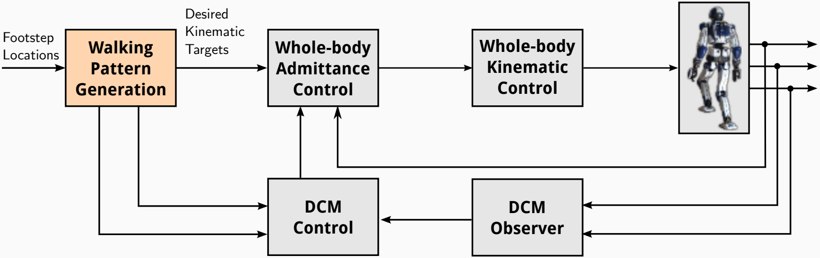


Fig. 18 Spring-damper mechanism of HRP-2 foot

Mechanical flexibility at the ankles

1. Kenji KANEKO, Fumio KANEHIRO, Mitsuharu MORISAWA, Kazuhiko AKACHI, Gou MIYAMORI, Atsushi HAYASHI et Noriyuki KANEHIRA. « Humanoid robot HRP-4 - Humanoid Robotics Platform with Lightweight and Slim Body ». In : *IEEE/RSJ International Conf. on Intelligent Robots and Systems*. 2011.


Walking Pattern Generation
Whole-body Admittance Control
Whole-body Kinematic Control
DCM Control
DCM Observer


Footstep
Locations
Walking
Pattern
Generation
Desired
Kinematic
Targets
Whole-body
Admittance
Control
Whole-body
Kinematic
Control
DCM
Control
DCM
Observer

- Equation of motion :

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

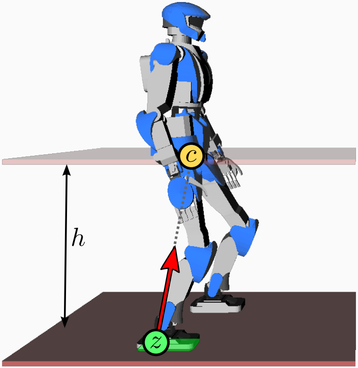
- Floating base dynamics :

$$\ddot{c} = \frac{1}{m} \sum_i f_i$$
$$\dot{L}_c = \sum_i (p_i - c) \times f_i$$

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

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

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



2. 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 :

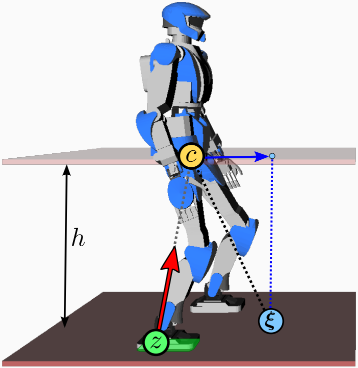
$$\ddot{c} = \omega^2 (c - z)$$

- Divergent Component of Motion :

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

- Unstable dynamics :

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



3. 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.

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 : $\exists M > 0, \forall t > 0, \|c(t)\| \leq M$

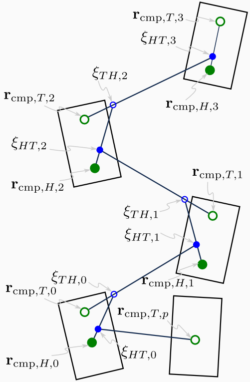


Figure adapted from [Gri+17].

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, including :

- Variable CoM height : [Bra+15]
- Variable step timings : [BW17]

4. 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

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

- 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

5. 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.

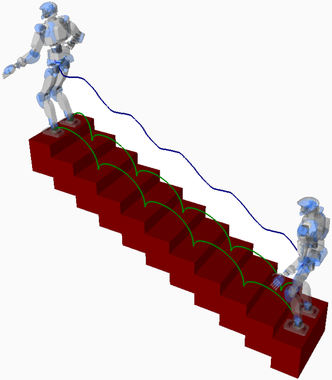
- **New input** $\lambda > 0$ for height variations :

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

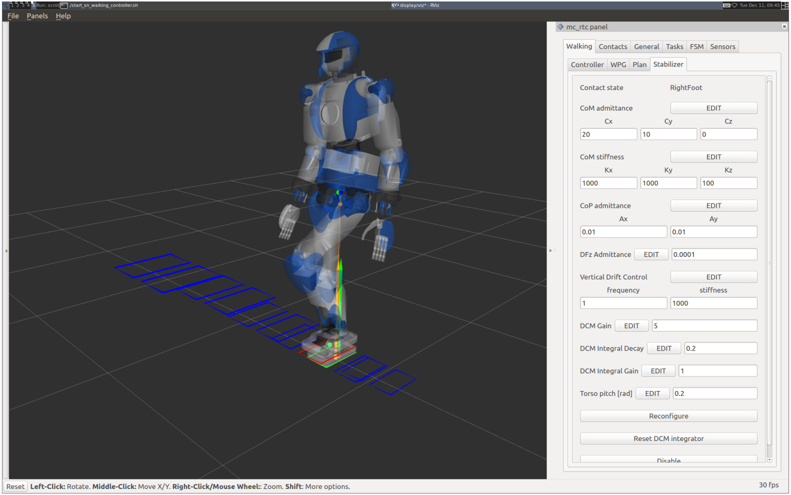
- Viability $\Rightarrow$ boundedness condition :

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

- Solve : tailored optimization (30-50 μs)
- Call many times to adapt step timings

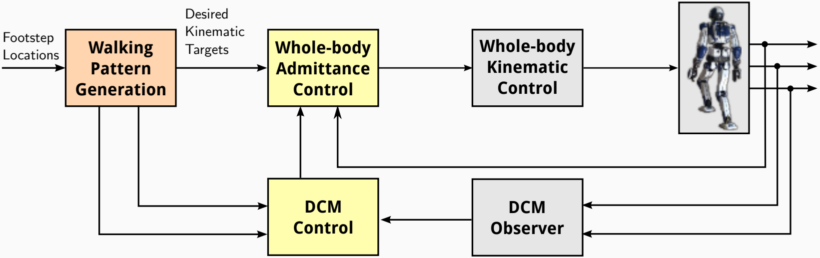


6. Stéphane CARON, Adrien ESCANDE, Leonardo LANARI et Bastien MALLEIN. « Capturability-based Analysis, Optimization and Control of 3D Bipedal Walking ». 2018. URL : `https://hal.archives-ouvertes.fr/hal-01689331/document`.



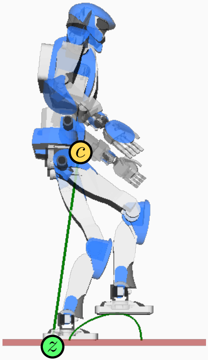
Visualization of stair climbing pattern in mc_rtc

WALKING STABILIZATION

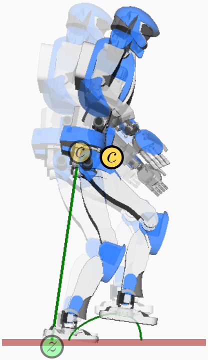


ROLE OF STABILIZATION

Actuated joints converge but unactuated floating base *diverges* :



In walking pattern



By robot without stabilization

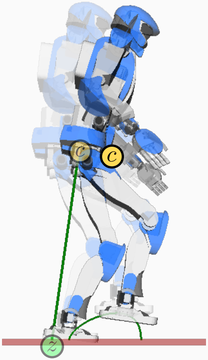
Figure adapted from [Tak+09].

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** ?

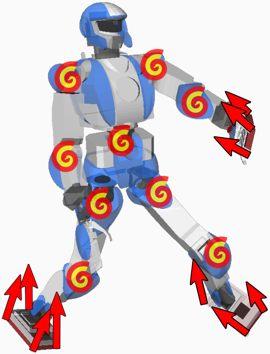
Split control into two components :

Admittance control

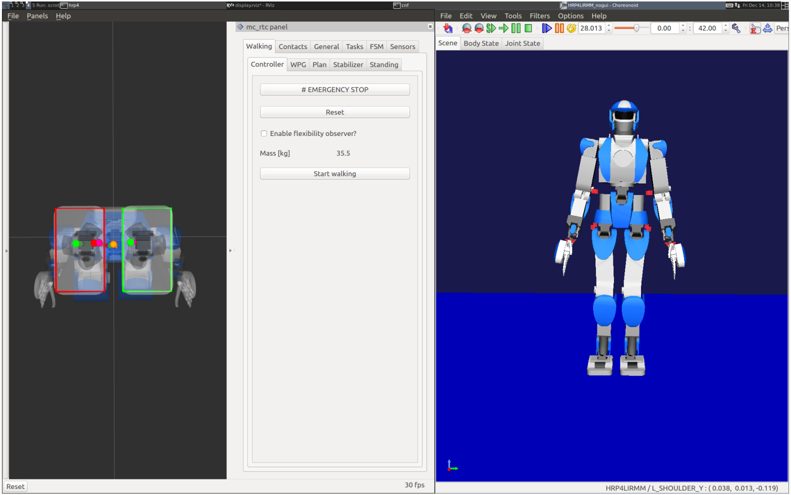
Allow position changes to improve force tracking

Floating-base control

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

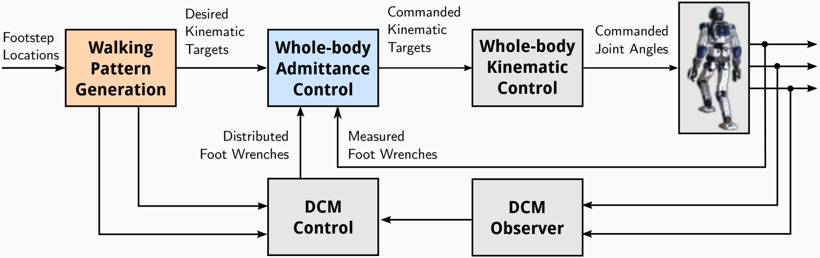


VISUALIZATION



Standing stabilization under external forces

ADMITTANCE CONTROL

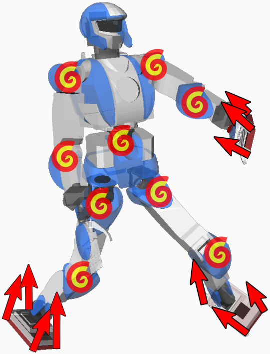


Different strategies for different components of the net contact wrench :

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

This stabilizer implements :

- Ankle strategy : yes
- Hip strategy : translation, no rotation
- Stepping strategy : no



- 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 $\tau \to \tau_d$

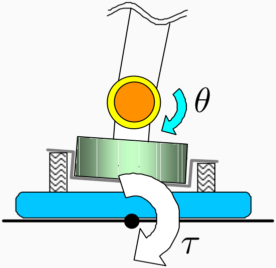


Figure adapted from [Kaj+01b]

7. 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 ⇒ 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 :

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

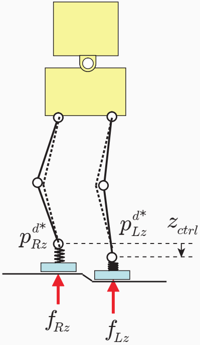


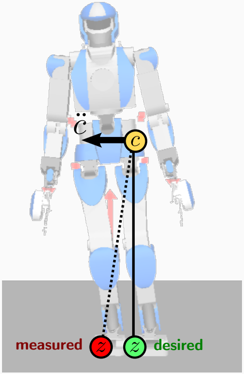
Figure adapted from [Kaj+10]

8. 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 [9]



9. Discussions with Pr T. Sugihara.
10. 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 ?

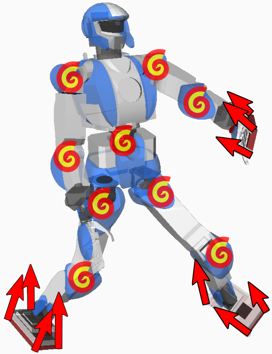
End-effector strategies

- 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 [11]



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

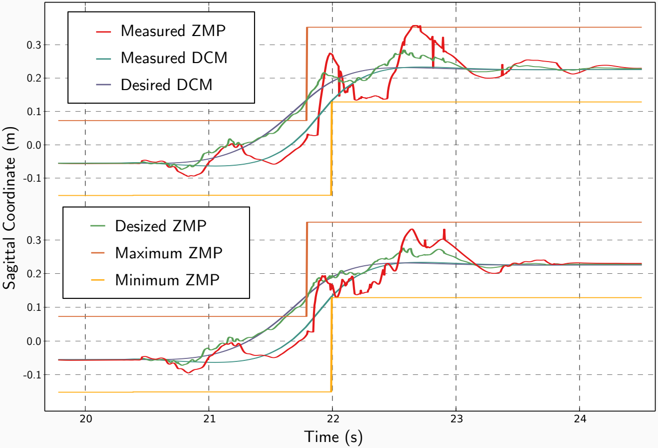
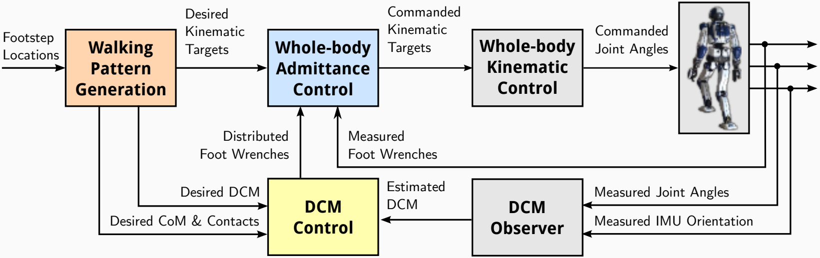


FIGURE 1 : Top : no CoM admittance control. **Bottom :** with $A_c = 20$ [Hz^2].

DCM CONTROL

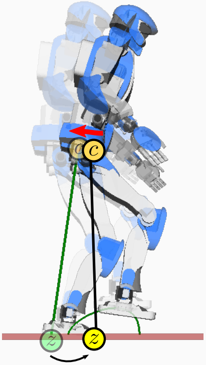


Footstep Locations
Walking Pattern Generation
Desired Kinematic Targets
Whole-body Admittance Control
Commanded Kinematic Targets
Whole-body Kinematic Control
Commanded Joint Angles
Distributed Foot Wrenches
Measured Foot Wrenches
Desired DCM
Desired CoM & Contacts
DCM Control
Estimated DCM
DCM Observer
Measured Joint Angles
Measured IMU Orientation

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

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

This gives us the *net wrench*.



12. 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 damping term, add integral term to eliminate steady-state error :

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

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

- Select gains k_p, k_i, k_z (1) by hand or (2) by *pole placement*
- In practice : how to manage the link with admittance control gains ?

13. 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.

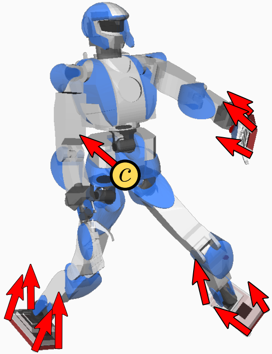
Wrench distribution by QP :

Cost function

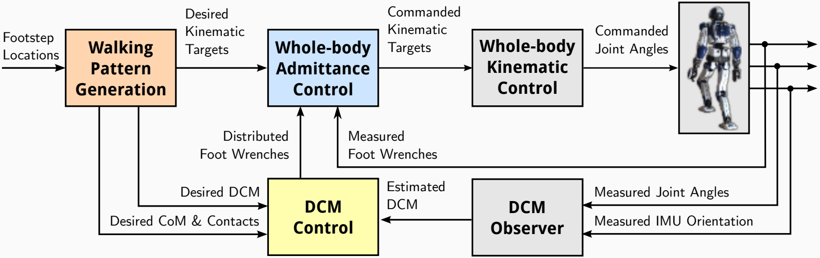
- Realize net wrench
- Minimize ankle torques
- Desired pressure distribution

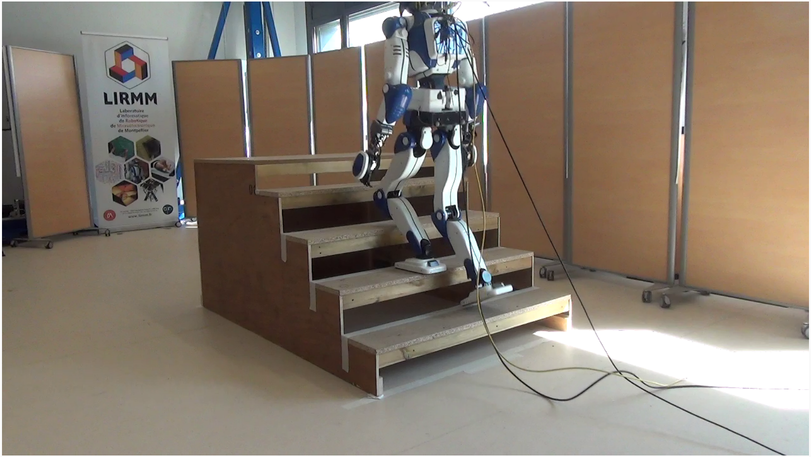
Constraints

- Frictional wrench cones
- Minimum pressure on each contact



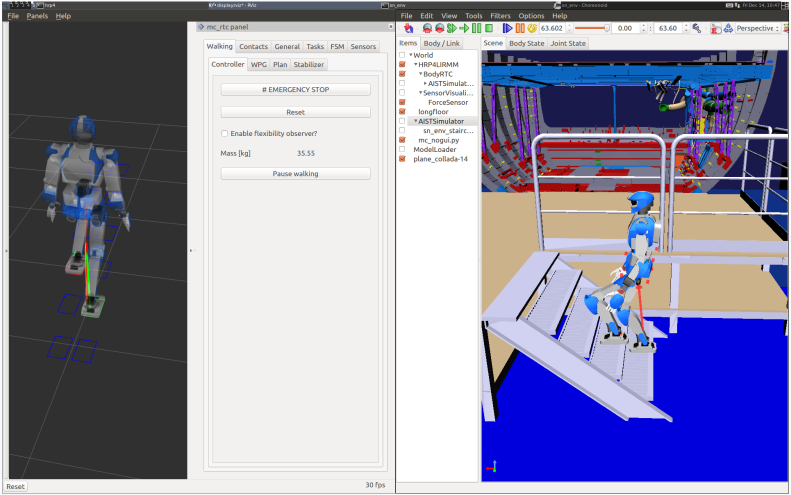
COMPLETE SYSTEM





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

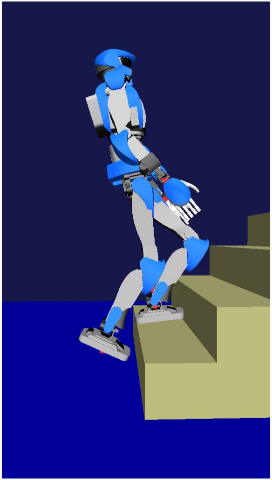
CODA : AN ODE TO TWO TOOLS



Controller with mc_rtc GUI alongside a Choreonoid dynamic simulation

CHOREONOID SIMULATOR BY S. NAKAOKA

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.

[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.

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[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.

[Kan+11] Kenji Kaneko, Fumio Kanehiro, Mitsuharu Morisawa, Kazuhiko Akachi, Gou Miyamori, Atsushi Hayashi et Noriyuki Kanehira. « Humanoid robot HRP-4 - Humanoid Robotics Platform with Lightweight and Slim Body ». In : *IEEE/RSJ International Conf. on Intelligent Robots and Systems*. 2011.

[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.