Université franco-allemande Deutsch-Französische Hochschule

Next generation of high quality and robust humanoid robot

German-French Winter School on Humanoid and Legged Robots

Dec. 5th-7th 2016, LAAS, Toulouse

O. Stasse, M. Naveau, J. Carpentier, N. Mansard

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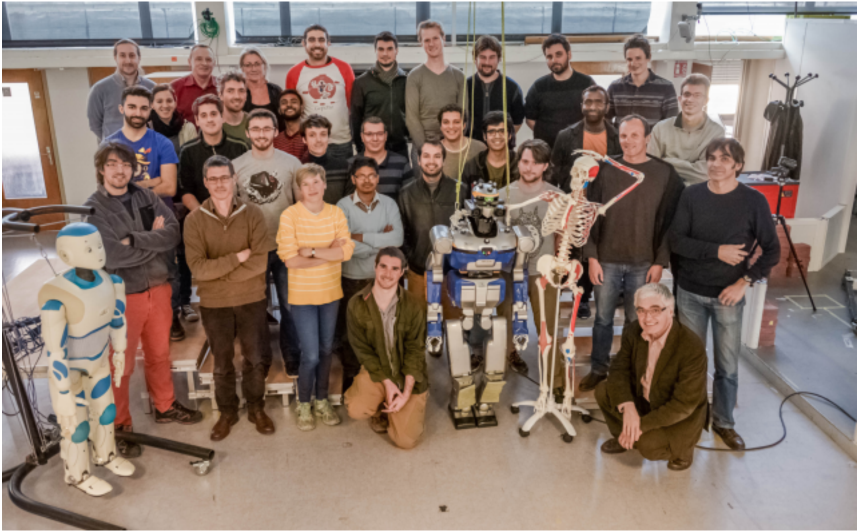
Acknowledgements



Humanoid Robotics: Where are we ?

Boston Dynamics: Everything is solved ?

Not really

What lesson can we learn ?

Feedback from DRC experience

- Robots need to be more autonomous:

    for safety

    for efficiency

- Humanoid robots will fall $\rightarrow$

    works need to be done on mechanical conception and control.

- Excellence in mechatronics integration:

    control, perception, mechanics and software.

- New robots are more powerful and less anthropomorph.
- Repeatability.
- Cobotic:

    tactile perception, skin

    torque control

Feedback from DRC experience

- Robots need to be more autonomous: Motion generation

  for safety

  for efficiency

- Humanoid robots will fall $\rightarrow$ Stiff robot requires a high budget

  works need ~~to be done on mechanical conception~~ and control.

- Excellence in mechatronics integration:

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  Yes but closer to the human functionnal performances

- Repeatability.

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Feedback from DRC experience

- Robots need to be more autonomous: Motion generation

  for safety

  for efficiency

- Humanoid robots will fall → Compliant robot requires an advanced control

  works need to be done on mechanical conception and control.

- Excellence in mechatronics integration:

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  Yes but closer to the human functionnal performances

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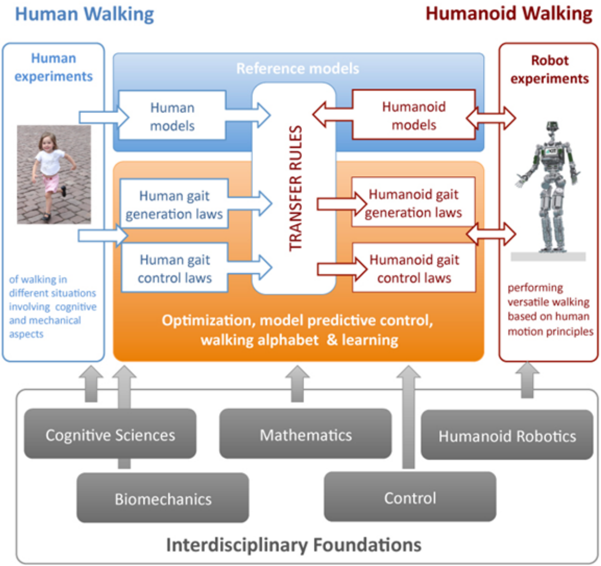
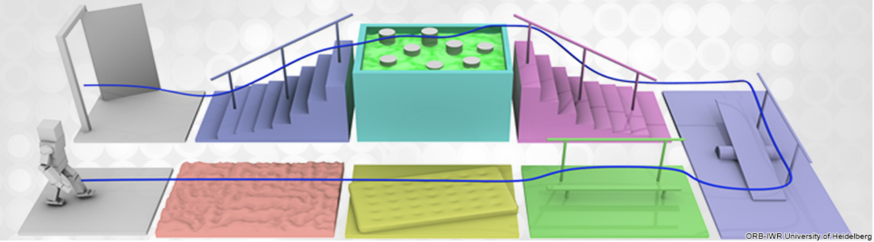
The Koroibot Project



Consortium

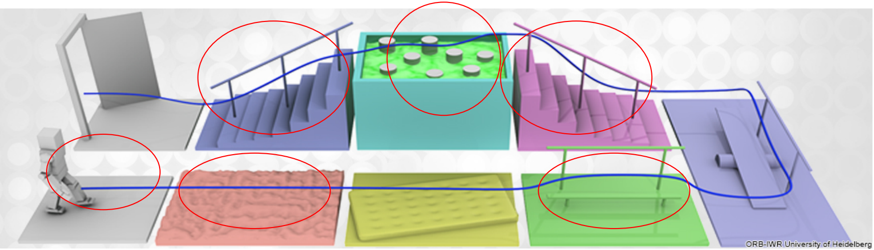
- Partners
    - Univ. Heidelberg (GE),
    - CNRS (FR),
    - KIT (GE),
    - IIT (IT),
    - TUDelft (NE),
    - Weizmann Institute (IS),
    - Univ. Tubingen (GE)
- Improving the humanoid technologies on each platform

The Koroibot Challenge



- Each team build its own setup
- Performance indicator measurements (PIM) at the beginning of the project
- Implementation and improvment of the walking strategies
- PIM at the end of the project

Koroibot Challenge - LAAS version



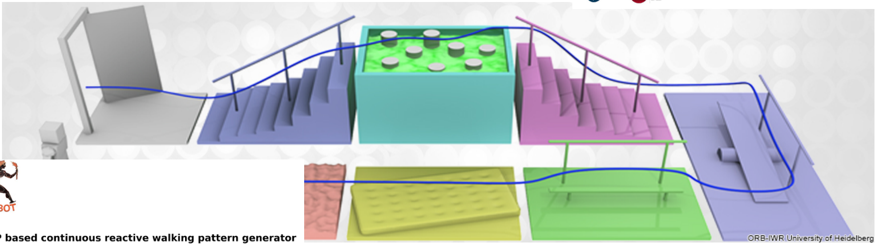
- The Koroibot challenge
  - Flat floor
  - Uneven ground
  - Going up and down stairs
  - Stepping stones
  - Beam

Koroibot Challenge - LAAS version

SQP based continuous reactive walking pattern generator

M. Naveau, M. Kudruss, O. Stasse, C. Kirches, K. Mombaur, P. Soueres

Gepetto TEAM, LAAS-CNRS, Toulouse, France
Interdisciplinary Center for Scientific Computing, Heidelberg University, Heidelberg, Germany



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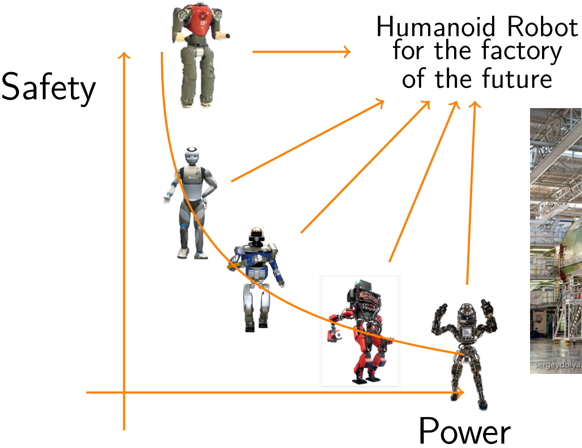
Feedback from Koroibot Challenge

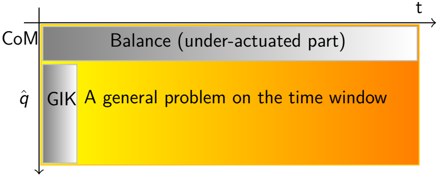
- Kinematics constraints with stairs
  - Complex interaction between the CoM trajectory
  - Average stair case height: 22cm
  - Need for longer legs
- Powerful actuators
  - High torque, high velocity
  - Reactive motion
  - Manipulating high load
- Battery
- Repeatability
- High computational power

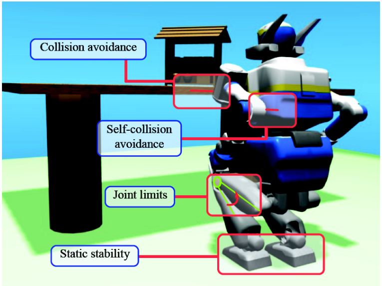
High performance humanoid robot



Motion generation

$$
\begin{cases}
\min f(\mathbf{u}(t), \mathbf{v}(t)) \\
\mathbf{g}(\mathbf{u}(t), \mathbf{v}(t)) < 0 \\
\mathbf{h}(\mathbf{u}(t), \mathbf{v}(t)) = 0
\end{cases}
$$





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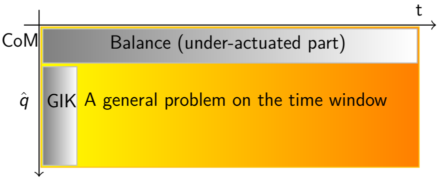
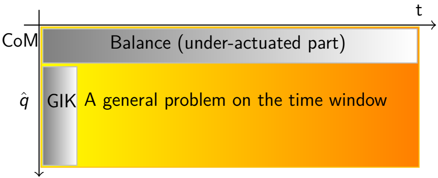


- Planning and control solve the same problem
  - Planning is looking for a global feasible solution
  - Control is looking for on online sensor grounded local solution
- Planning is too long when simulating the control
- Control can fails
  - Local minima leading to an incomplete behavior
  - Mismatch between the control and the hardware
- Accessibility set [Majumdar, ICRA Best Paper Award 2013]

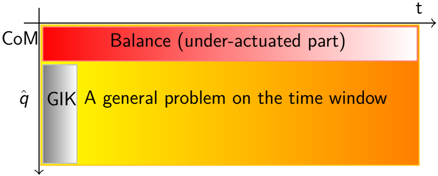
Motion generation

$$\begin{cases} \min f(\mathbf{u}(t), \mathbf{v}(t)) \\ \mathbf{g}(\mathbf{u}(t), \mathbf{v}(t)) < 0 \\ \mathbf{h}(\mathbf{u}(t), \mathbf{v}(t)) = 0 \end{cases}$$



$$\begin{cases} \mathbf{M}_1(q)\ddot{q} + \mathbf{N}_1(q,\dot{q})\dot{q} + \mathbf{G}_1(q) = \mathbf{T}_1(\mathbf{q})\mathbf{u} + \mathbf{C}_1^\top(q)\lambda & \text{Actuated dynamics of the robot} \\ \mathbf{M}_2(q)\ddot{q} + \mathbf{N}_2(q,\dot{q})\dot{q} + \mathbf{G}_2(q) = \mathbf{C}_2^\top(q)\lambda & \text{Underactuated dynamics of the robot} \\ f(\lambda) \in \mathcal{F} & \text{General balance criteria} \\ \mathbf{u}_{min} < \mathbf{u} < \mathbf{u}_{max} & \text{Torques limits} \\ \hat{q}_{min} < \hat{q} < \hat{q}_{max} & \text{Joints limits} \\ d(\mathcal{B}_i(\mathbf{q}), \mathcal{B}_j(\mathbf{q})) > \epsilon, \forall p(i,j) \in \mathcal{P} & \text{(self-)collisions} \\ \ddot{\mathbf{e}}_i = \dot{\mathbf{J}}_i(q)\dot{q} + \mathbf{J}_i(q)\ddot{q} & \text{Tasks} \end{cases}$$

Motion generation



Pattern generator

- Focus on the underactuated part
- Model predictive control

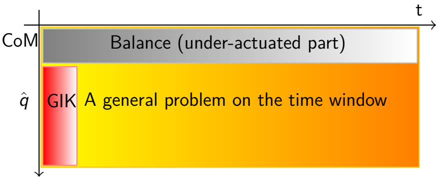
Simplifying the walking problem to control only the CoM reference

$$\begin{cases} \mathbf{M}_1(q)\ddot{q} + \mathbf{N}_1(q,\dot{q})\dot{q} + \mathbf{G}_1(q) = \mathbf{T}_1(\mathbf{q})\mathbf{u} + \mathbf{C}_1^\top(q)\lambda & \text{Actuated dynamics of the robot} \\ \mathbf{M}_2(q)\ddot{q} + \mathbf{N}_2(q,\dot{q})\dot{q} + \mathbf{G}_2(q) = \mathbf{C}_2^\top(q)\lambda & \text{Underactuated dynamics of the robot} \\ f(\lambda) \in \mathcal{F} & \text{General balance criteria} \\ \mathbf{u}_{min} < \mathbf{u} < \mathbf{u}_{max} & \text{Torques limits} \\ \hat{q}_{min} < \hat{q} < \hat{q}_{max} & \text{Joints limits} \\ d(\mathcal{B}_i(\mathbf{q}), \mathcal{B}_j(\mathbf{q})) > \epsilon, \forall p(i,j) \in \mathcal{P} & \text{(self-)collisions} \\ \ddot{\mathbf{e}}_i = \dot{\mathbf{J}}_i(q)\dot{q} + \mathbf{J}_i(q)\ddot{q} & \text{Tasks} \end{cases}$$

Motion generation

Inverse dynamics

- Focus on the inertia matrix
- Forces
- Complete constraints



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\begin{cases}
\mathbf{M}_1(q)\ddot{q} + \mathbf{N}_1(q,\dot{q})\dot{q} + \mathbf{G}_1(q) = \mathbf{T}_1(\mathbf{q})\mathbf{u} + \mathbf{C}_1^\top(q)\lambda & \text{Actuated dynamics of the robot} \\
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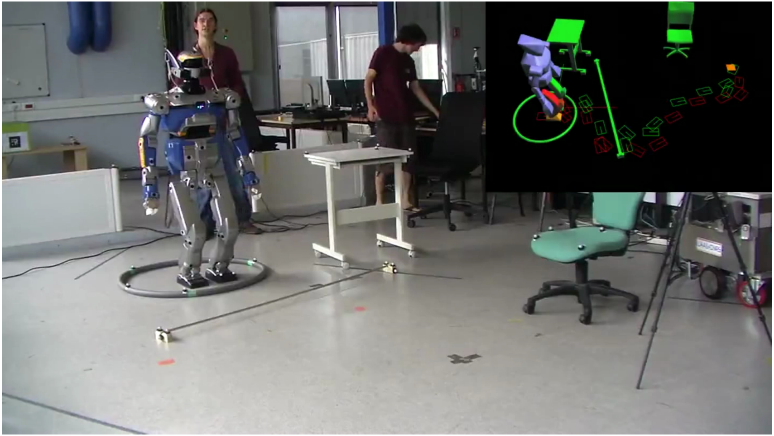
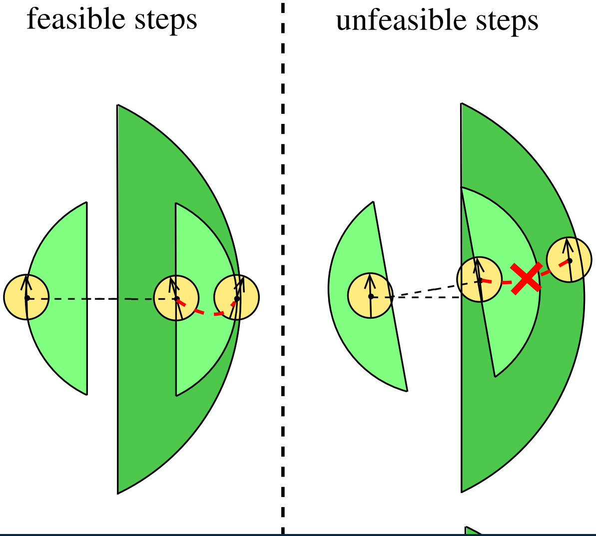
$$

Experiments

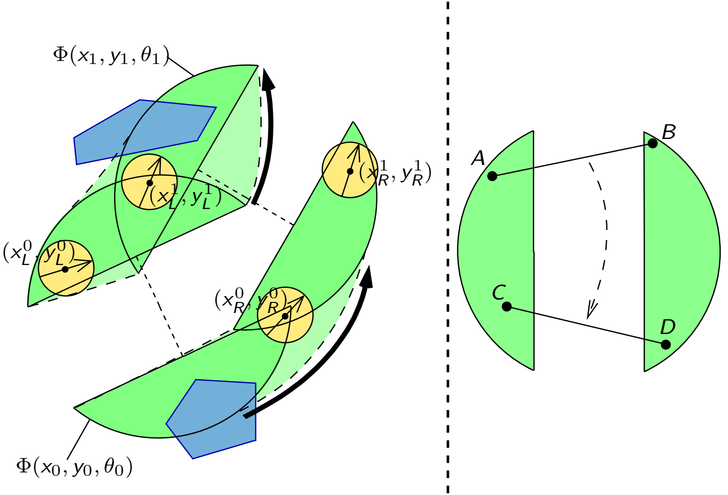
[Perrin, TRO,2012]



Description of the feasible foot-steps

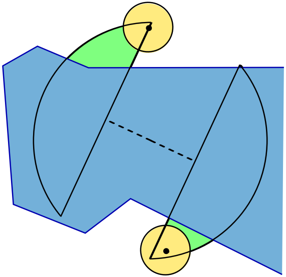


Weak collision

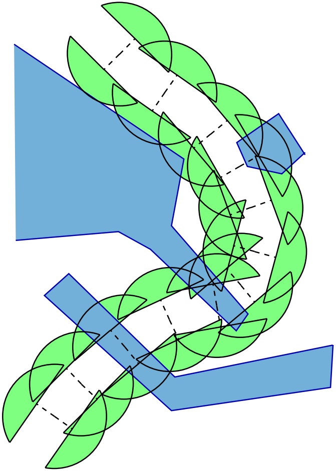


Planning

a weakly collision-free configuration of Φ



a continuous weakly collision-free path



Experiments

[Perrin, TRO, 2017]

Climbing stairs

[Kudruss, Humanoids 2015]
[Carpentier, ICRA 2016]

Previous work
[Luo, ICRA 2014]
[Vaillant, Humanoids 2014]
[Noda, ICRA 2014]
[Hirukawa, ICRA 2007]

$$\begin{cases} m(\ddot{\mathbf{c}} - \mathbf{g}) = \sum_{i=1}^{N_c} \mathbf{f}_i \\ m\mathbf{c}_\times(\ddot{\mathbf{c}} - \mathbf{g}) = \sum_{i=1}^{N_c} \mathbf{p}_{i\times} \mathbf{f}_i \end{cases}$$

Reactive walking pattern generation

[M. Naveau, RA-L 2016]

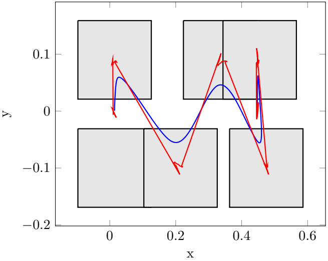
Optimization problem solved:

$$\min_{\mathbf{U}_k} \sum_{i=0}^{j=4} w_i J_i(\mathbf{U}_k)$$

$$\mathbf{X}_{k+1} = \mathbf{A}\mathbf{X}_k + \mathbf{C}\mathbf{U}_k$$

$$\underline{\mathbf{P}} < \mathbf{P}\mathbf{U}_k < \overline{\mathbf{P}}$$

with $\mathbf{U}_k = \left(\dddot{\mathbf{X}}_k \; \mathbf{X}_k^f \; \dddot{\mathbf{Y}}_k \; \mathbf{Y}_k^f\right)^T$



$J_1(\mathbf{U}_k)$ is the linear velocity tracking

$$J_1(\mathbf{U}_k) = \|\dot{\mathbf{X}}_k - \mathbf{X}_k^{ref}\|_2^2 + \|\dot{\mathbf{Y}}_k - \mathbf{Y}_k^{ref}\|_2^2$$

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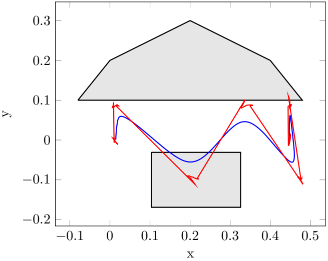
$J_2(\mathbf{U}_k)$ is the control norm

$$J_2(\mathbf{U}_k) = \|\dddot{\mathbf{X}}_k\|_2^2 + \|\dddot{\mathbf{Y}}_k\|_2^2$$



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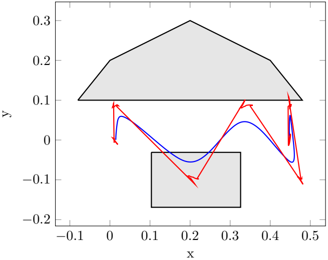

$J_3(\mathbf{U}_k)$ is the distance of the CoP to the most stable trajectory

$$J_3(\mathbf{U}_k) = \|\mathbf{X}^f_k - CoP^x_{k+1}\|^2_2 + \|\mathbf{Y}^f_{k+1} - CoP^y_{k+1}\|^2_2$$

Reactive walking pattern generation w

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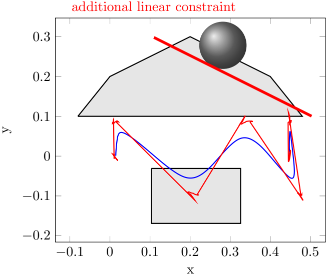
with $\mathbf{U}_k = \left(\dddot{\mathbf{X}}_k \; \mathbf{X}_k^f \; \dddot{\mathbf{Y}}_k \; \mathbf{Y}_k^f \; \theta_k^f\right)^T$



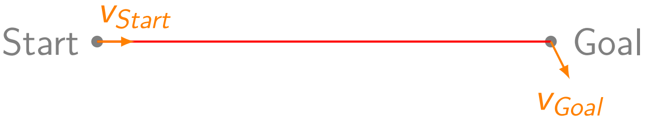
$J_4(\mathbf{U}_k)$ is the angular velocity tracking

$$J_4(\mathbf{U}_k) = \|\theta_k - \int \theta_k^{ref}\, dt\,\|_2^2$$

Power Law

Human moves according to the two-third power-law

$$v = \gamma \kappa^{\beta}$$



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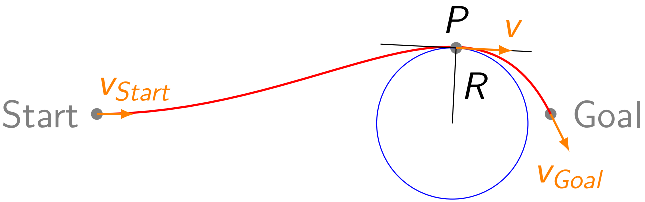
Power Law

Human moves according to the two-third power-law

$$v = \gamma \kappa^{\beta} \qquad \kappa = \frac{1}{R}$$



Power Law

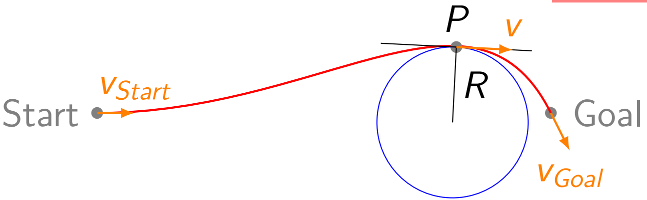
Human moves according to the two-third power-law

$$v = \gamma \kappa^{\beta}$$

$\beta = -1/3$

$\beta = 0$

$\beta = 1/3$



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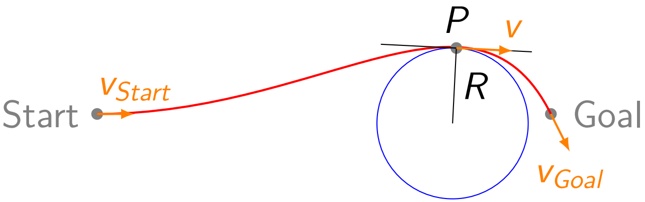
γ such that time from Start to Goal is always the same $\forall \beta$



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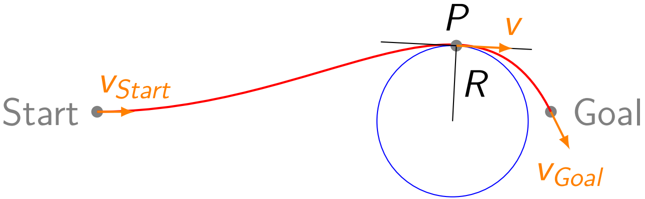

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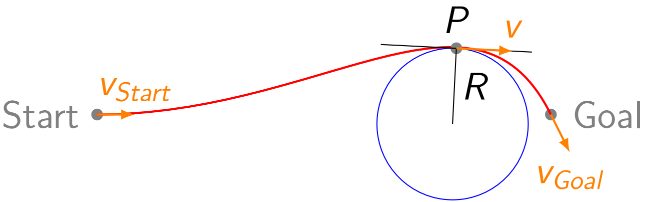
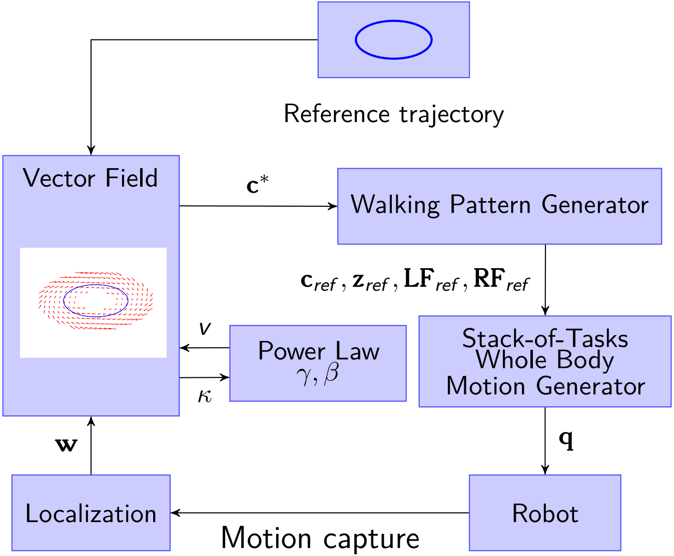


Can humanoid robots benefit from following the same principle ?

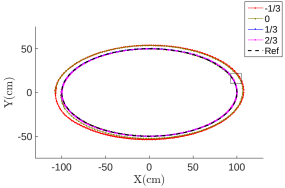
Approach


Reference trajectory
Vector Field
$\mathbf{c}^*$
Walking Pattern Generator
$\mathbf{c}_{ref}, \mathbf{z}_{ref}, \mathbf{LF}_{ref}, \mathbf{RF}_{ref}$
v
Power Law
γ, β
κ
Stack-of-Tasks
Whole Body
Motion Generator
$\mathbf{q}$
$\mathbf{w}$
Localization
Robot
Motion capture

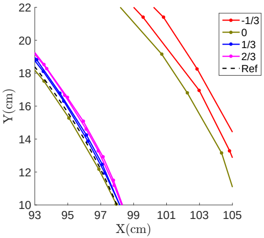
Mixing NMPC walking and Power L

- Simulations on OpenHRP.
- Power law patterns are reproduced (in simulation and experiment).

- Drift correction: better for $\beta = 1/3$ in simulation, the same on the robot.



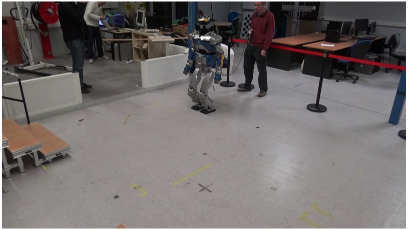
(a)



(b)

Mixing NMPC walking and Power La

- Increase in β exponent decreases duration.
- The amount of correction is far smaller with $\beta = 1/3$.



β	-1/3	0.0	1/3	2/3
Norm	1.416	0.950	0.642	1.124
Orientation	76.83	89.598	60.453	77.217

A replacement to HRP-2

- Pros
  - Highly reliable
  - Very robust (not able to jump ...)
  - Understanding of the software architecture
- Cons
  - Closed access to the low level part
  - DC - Brush motors (unable to achieve fast speed- high torque)
  - Low software support 10.04 LTS $\cdots$

Characteristics for a new humanoid

- Should hold a $10Kg$ tool at strech arm
- Reaction to push recovery (need high speed - high torque)
- Frequency of control at $1KHz$ for OSID
- Low level access needed
- Skin ?

The robots around

- ATLAS - Hydraulic actuation - 2 M$ - Not available
- Valkyrie - SEA - 2.7 M$ - Need a contract agreement with NASA (Edinburgh)
- TORO - Not available - Maybe one day through Kuka
- Proxi SRI - 97 % transmission efficiency - 8 hours continuous walking - 2.2 kWh/19 Kg
- REEM-C - Position control AC motor - HD - 300 k euros

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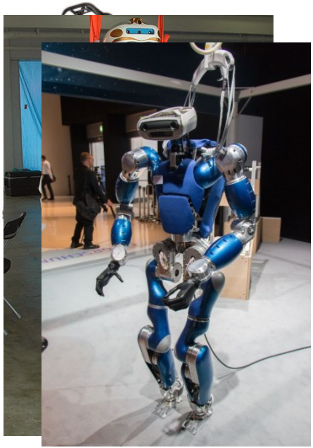

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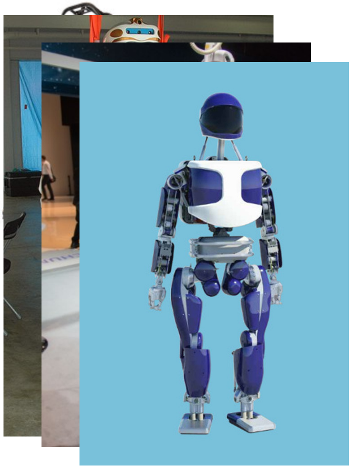
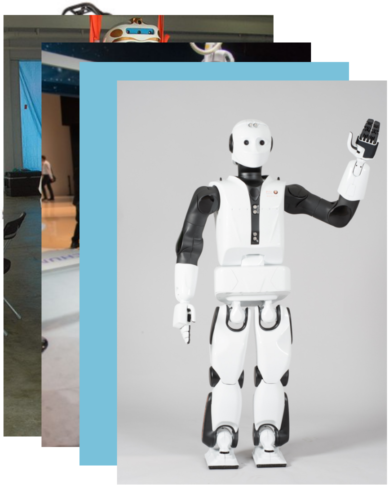


The robots around

- ATLAS - Hydraulic actuation - 2 M$ - Not available
- Valkyrie - SEA - 2.7 M$ - Need a contract agreement with NASA (Edinburgh)
- TORO - Not available - Maybe one day through Kuka
- Proxi SRI - 97 % transmission efficiency - 8 hours continuous walking - 2.2 kWh/19 Kg
- REEM-C - Position control AC motor - HD - 300 k euros

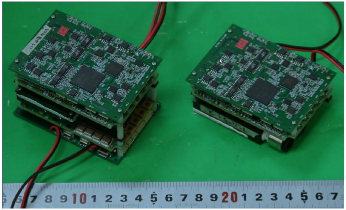


REEM-C

- Pros
  - AC motors - 700 W
  - Xenomai - Ubuntu 12.04 LTS
  - i7 $2.1 GHz$
  - No passivity (facilitate the control)
  - Hand $1 Kg$ payload
- Cons
  - Problem on the hips (too close)
  - No passivity (Increase drift)
  - Low speed - High torque

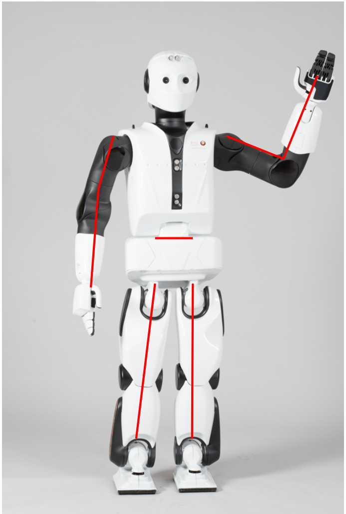
Power electronics

- EM field is created by the commutation of the current
- Lowered by the position of the control board w.r.t the motor
- Control frequency
- Cabling (distributed on REEM-C)



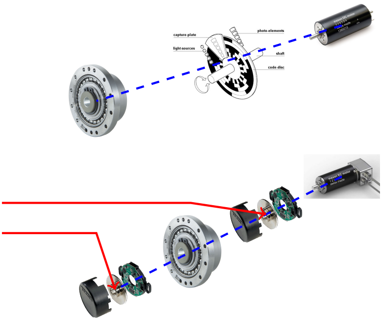
Data network for control

- One CAN network for each limb
- Possible change: EtherCAT
- Access to the PID of the low level board
- Current, Velocity, Position loops.



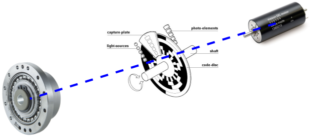
Low-level control

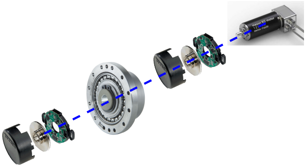
- Encoder before and after the harmonic drive
- Magnetic encoder 16 bits (65536 points)
- Magnetic encoder 18 bits on Hip-Yaw and Knee-Pitch
- Modification of the motor windings to cope with our needs



Low-level control

- Legs
  - Current loop: $10KHz$
  - Velocity loop: $2.5KHz$
  - Position loop: $1KHz$
- Arms
  - Current loop: $10KHz$
  - Velocity loop: $1KHz$
  - Position loop: $500Hz$

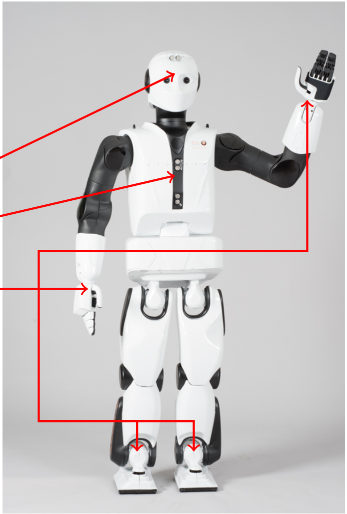




EtherCAT would allow $1KHz$ for the whole robot.

Sensors

- Cameras
- Accelerometer - Gyrometer
- Force sensors
  2 in the feet - 2 in the wrists
- Ultra-sound sensors



Pyrène Talos

Pyrène TALOS from PAL-Robotics

1.75 m

100 kg

RGB-D Camera

Accelerometer - Gyrometer

Force sensors

2 in the feet - 2 in the wrists

Torque sensors in all the actuators

(apart wrist and foot)

Pyrène Talos

EtherCAT: 1KHz control loop

2 i7 hyperthreaded

Cooling system of the CPUs

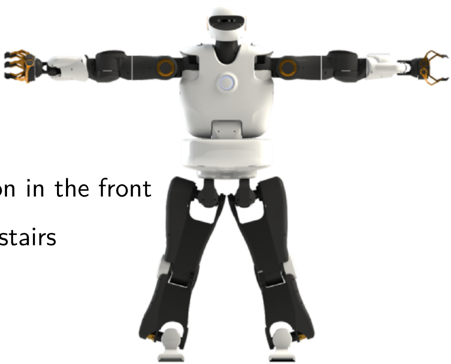
7 DoFs per arm

Kinematics customized for manipulation in the front

Legs are 10cm higher than HRP-2 for stairs

Torque: up to $300\ N\ 56\ RPM$

HRP-2: $168\ N, 38\ RPM$



Conclusions & Perspectives

- We are reaching the limits of our actuators
- They need to be taken into account in our control architecture
- New mechanical design are needed
- Reaching the functionnal level of human may involve robot looking less than human