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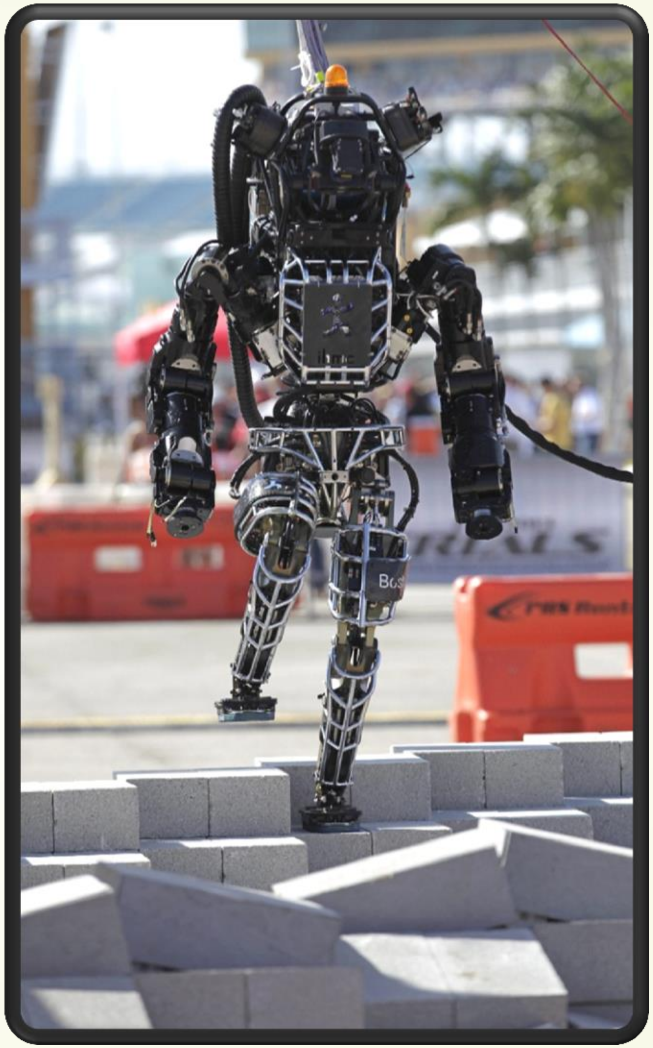
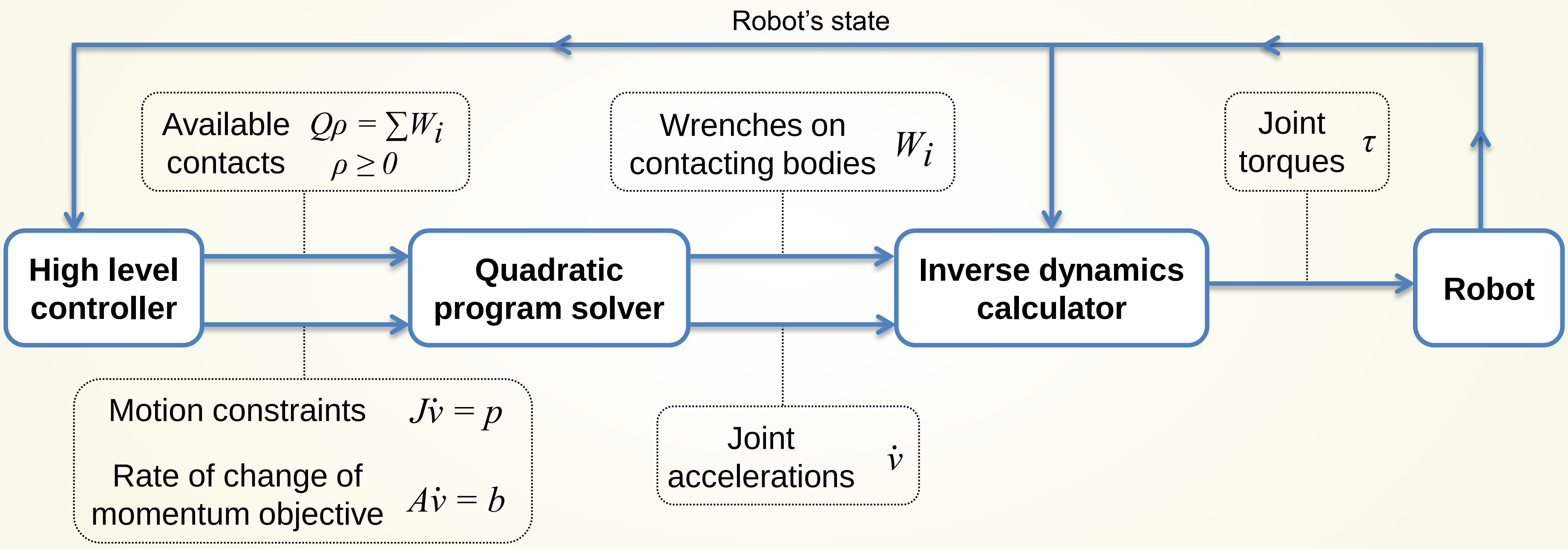
Momentum-based control framework, capturability-based walking control: application to the humanoid robot Atlas

Presented by Tingfan Wu and Sylvain Bertrand


ATLAS

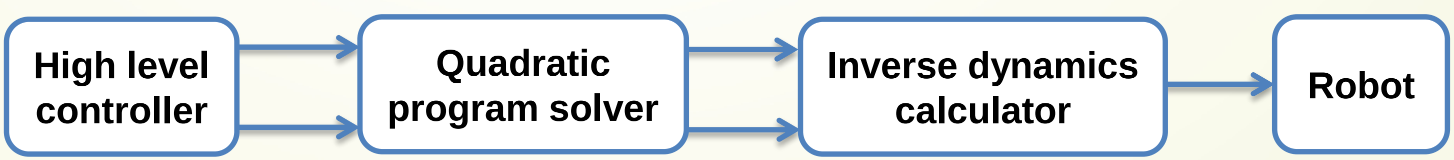


Whole-body motion control framework



Motion Constraints – Instantaneous Goals

- Examples
  - ☺Maintain balance – Keep CoM between feet
  - ☺Move my hand closer to the target
  - ☹Step on rock – instantaneous move!
- Divide long term goal to short ones
  - – Trajectory planner (eg. PID controller, swing planner)



Temporal layers	seconds	166Hz	166Hz	1kHz

Linear Constraints on Joint Acceleration

$$\min_{\dot{v}} \sum w_i \|M_i \dot{v} - p_i\|^2$$

$$s.t \quad M_j \dot{v} = p_j$$

- Connect with desires linearly, e.g.

$$\dot{v}_k = \dot{v_{d,k}}$$

- Change of reference frame via Jacobian

$$Jv = \dot{x_d}$$

$$\dot{J}v + J\dot{v} = \ddot{x}_d$$

$$J\dot{v} = \ddot{x}_d - \dot{J}v$$

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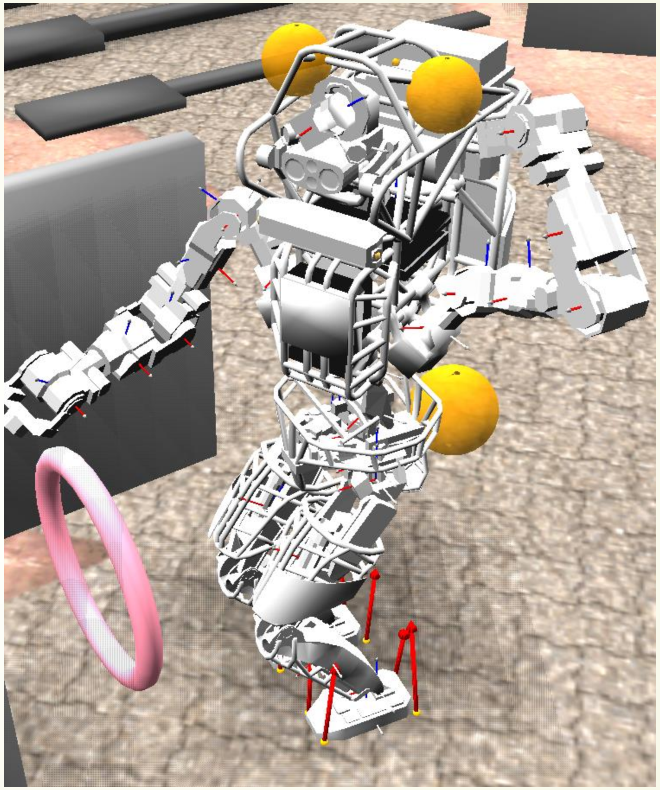
$$J\dot{v} = \ddot{x}_d - \dot{J}v$$

- Link to velocity / position goals with PD controller

$$\dot{v}_k = k_p(x_d - x) + k_d(\dot{x}_d - \dot{x})$$

Constraints / Desires of Atlas

- Chest rotation
  - Joint space goal
- Scratch head
  - Spatial goal in body
- Reach the torus
  - spatial goal in world



Centroidal Momentum

- Single Link- Angular and Linear Momentum

$$h = \begin{bmatrix} k \\ l \end{bmatrix} = \begin{bmatrix} I\omega \\ m\dot{x} \end{bmatrix} = \begin{bmatrix} I & 0 \\ 0 & m\mathbf{1} \end{bmatrix} \begin{bmatrix} \omega \\ \dot{x} \end{bmatrix}$$

- Multiple Links - Centroidal Momentum
  - sum of link momenta expressed in centroidal frame
  - A **linear** function of joint velocities

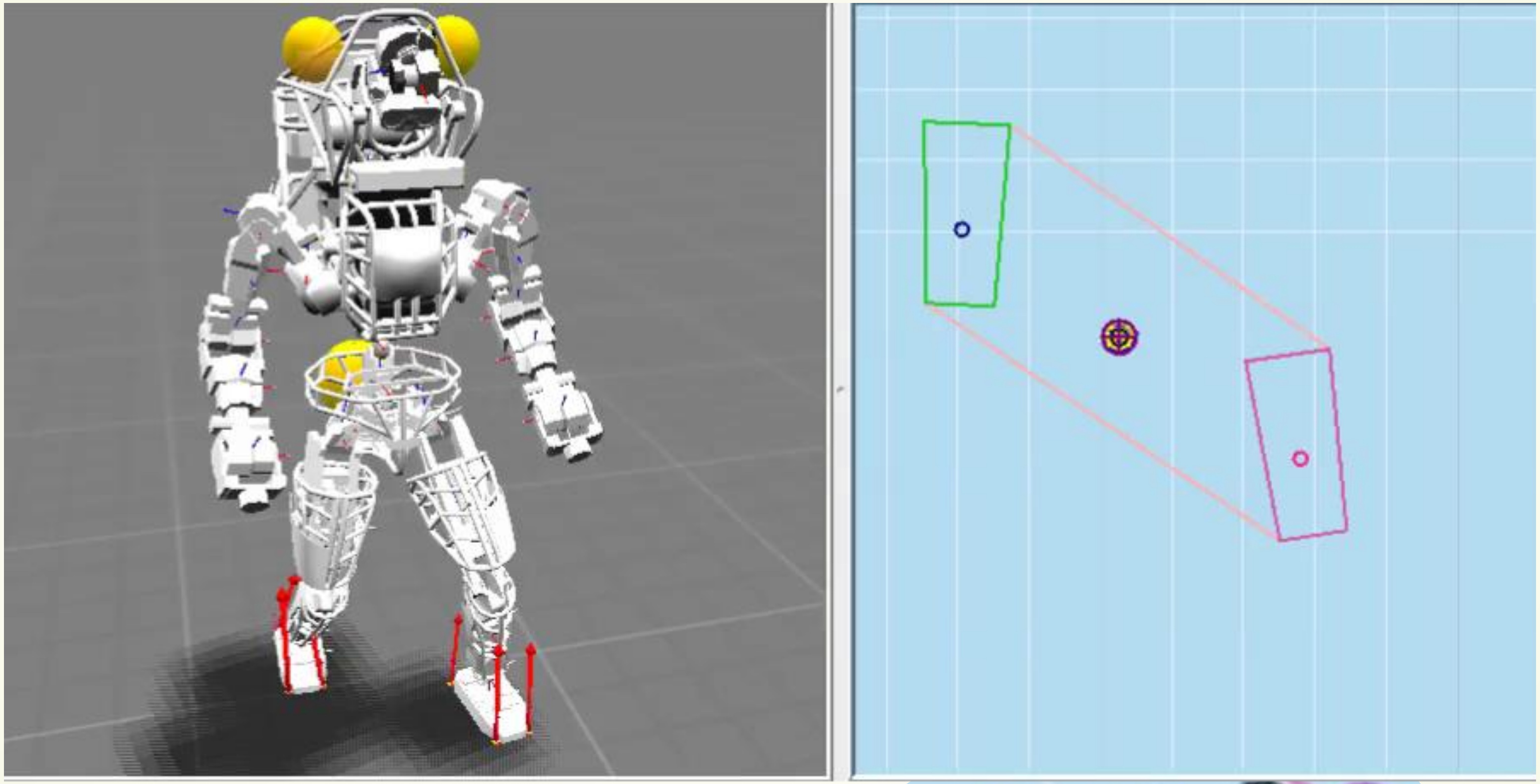
$$h = A(q)v$$

  - Enforce $\dot{h} = \dot{h}_d$ with constraint

$$\dot{A}v + A\dot{v} = \dot{h}_d$$

$$A\dot{v} = \dot{h}_d - \dot{A}v$$

Example of Controlling Centroidal Momentum



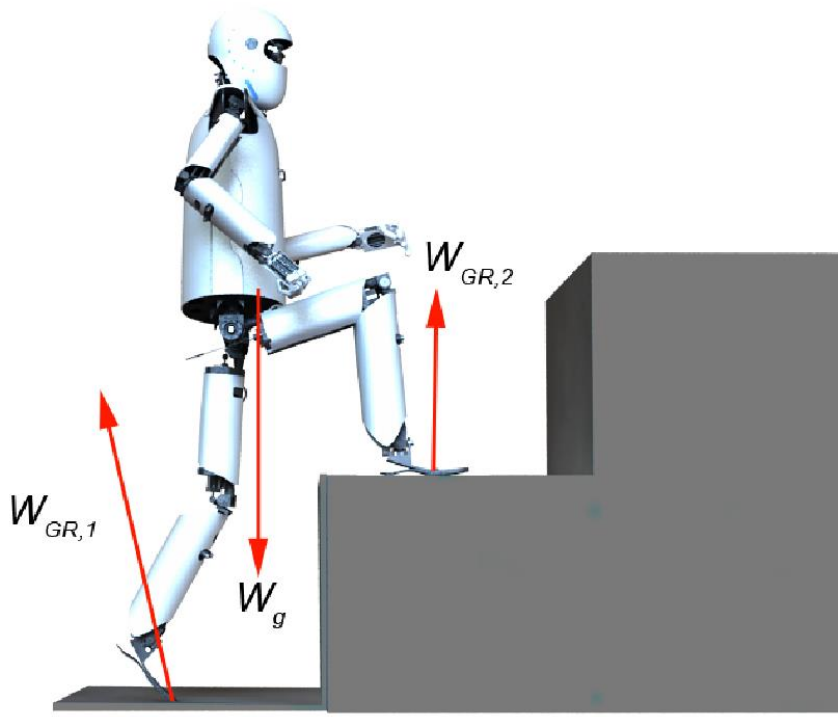
Constraint on External Wrenches

- Newtown/Euler law

$$\dot{h} = \sum external\ wrench$$

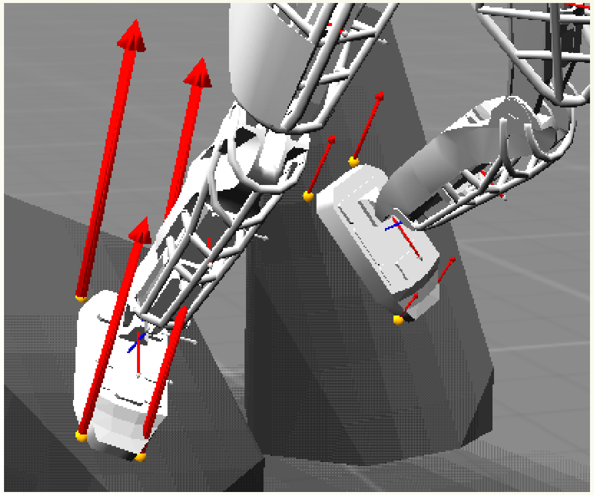
$$\dot{h} = \dot{A}v + A\dot{v} = \sum W_{ext,i}$$

$$A\dot{v} = -\dot{A}v + \sum W_{GR,i} + W_g$$



$$\sum_i W_{\text{ext},i} = \sum_i W_{\text{GR},i} + W_g$$

Constraint on Ground Reaction Wrench



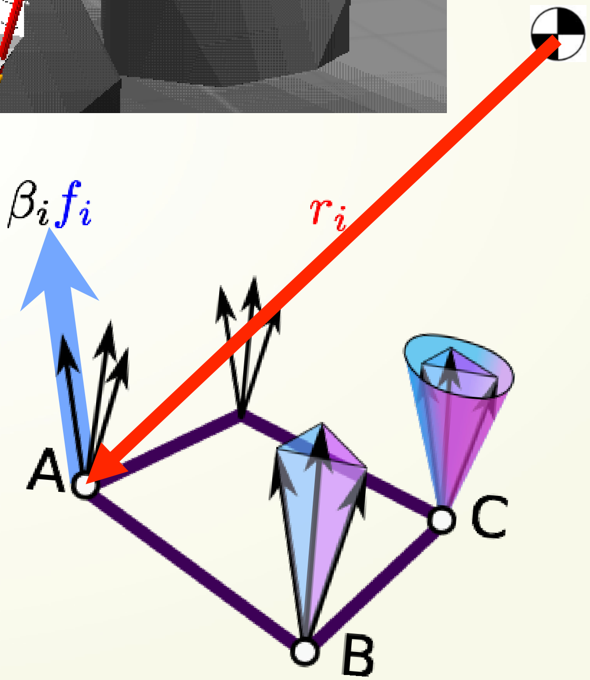
Construct force in pyramid approximation of friction cone [Pollard and Reitsma, 2001]

$$\text{force } f_i = \beta_i \rho_i, \rho_i \geq 0$$

$$\text{torque } \tau_i = r \times f_i$$

$$\text{wrench } w_i = \begin{bmatrix} \beta_i \\ r_i \times \beta_i \end{bmatrix} \rho_i = q_i \rho_i$$

$$w_{GR} = \sum w_i = \sum q_i \rho_i = Q\rho$$



Put It All Together

minimize

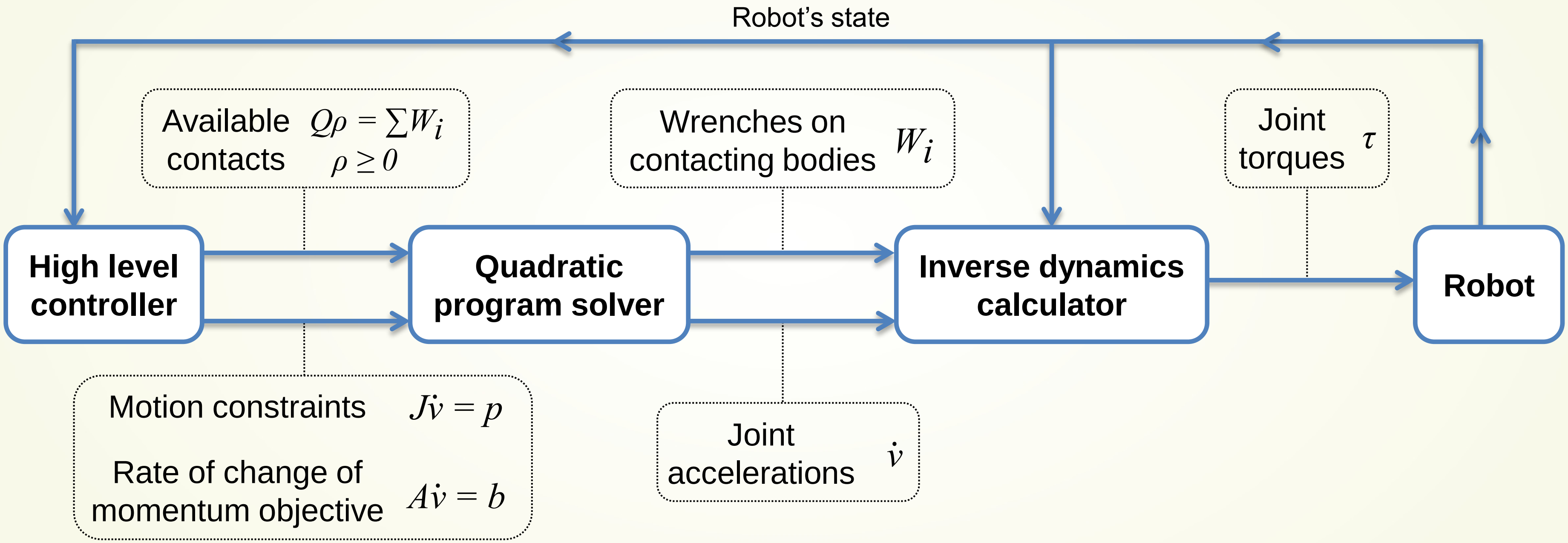
$$\min_{\dot{v},\rho} \sum w_i \|M_i \dot{v} - p_i\|^2 + w_{\dot{v}} \|\dot{v}\|^2 + w_\rho \|\rho\|$$

s.t

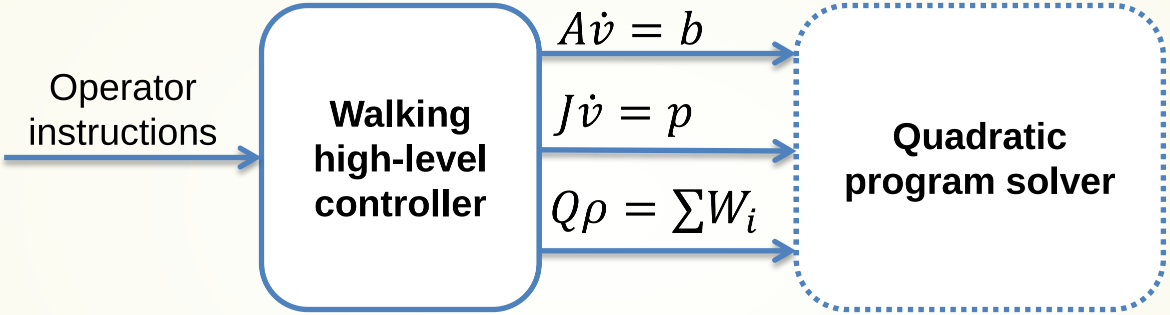
$$\rho \geq 0$$

$$A\dot{v} = -\dot{A}v + W_g + Q\rho$$

Whole-body motion control framework



Walking high-level controller



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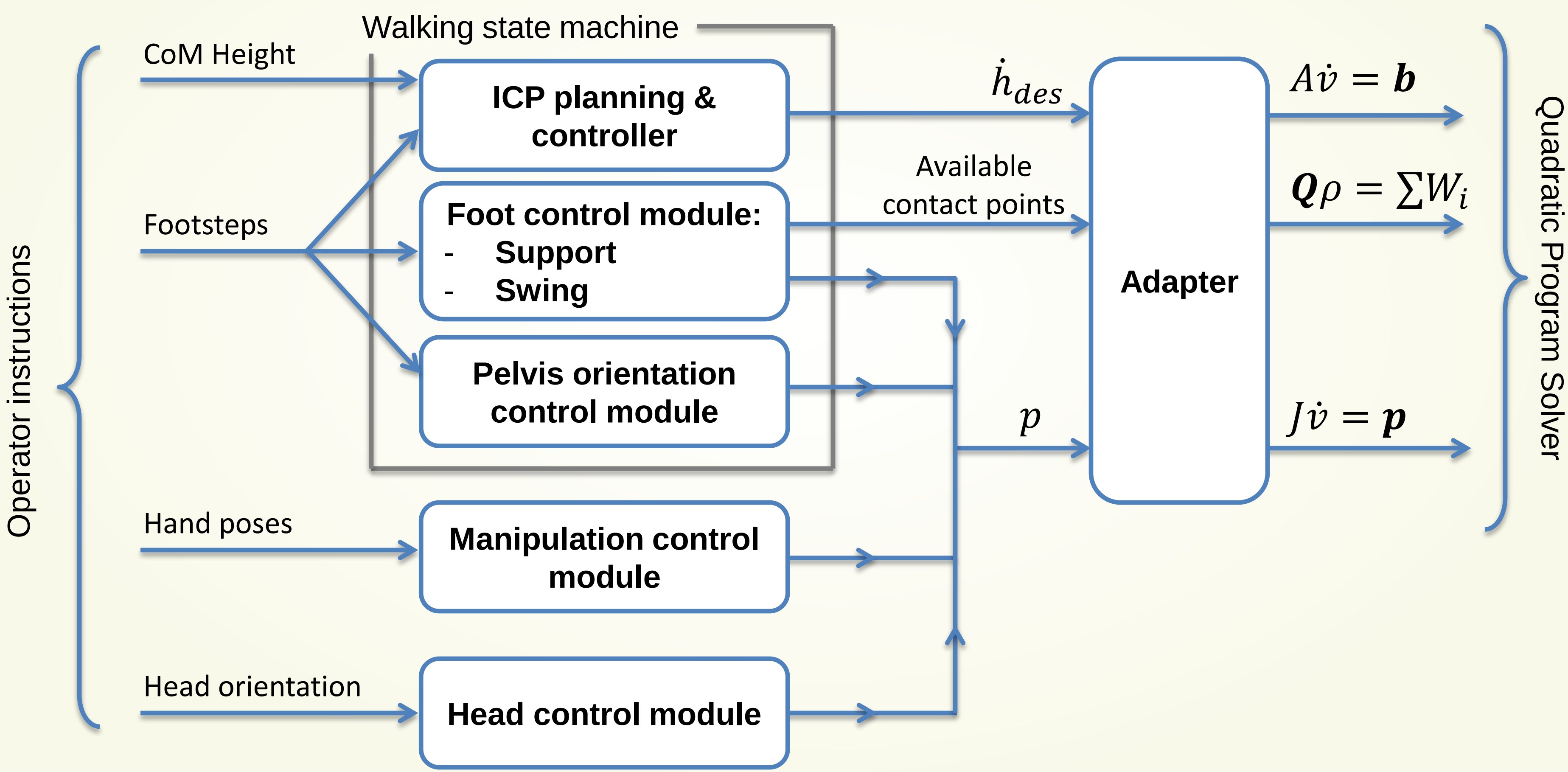


Pelvis Orientation Control Module

- Minimum jerk trajectory generator:

$$\theta_{pelvis}^{ref}, \omega_{pelvis}^{ref}, \dot{\omega}_{pelvis}^{ref}$$

- PD controller:

$$\dot{\omega}_{pelvis}^{des} = \dot{\omega}_{pelvis}^{ref} + K_p\left(\theta_{pelvis}^{ref} - \theta_{pelvis}\right) + K_v\left(\omega_{pelvis}^{ref} - \omega_{pelvis}\right)$$

- Motion constraint:

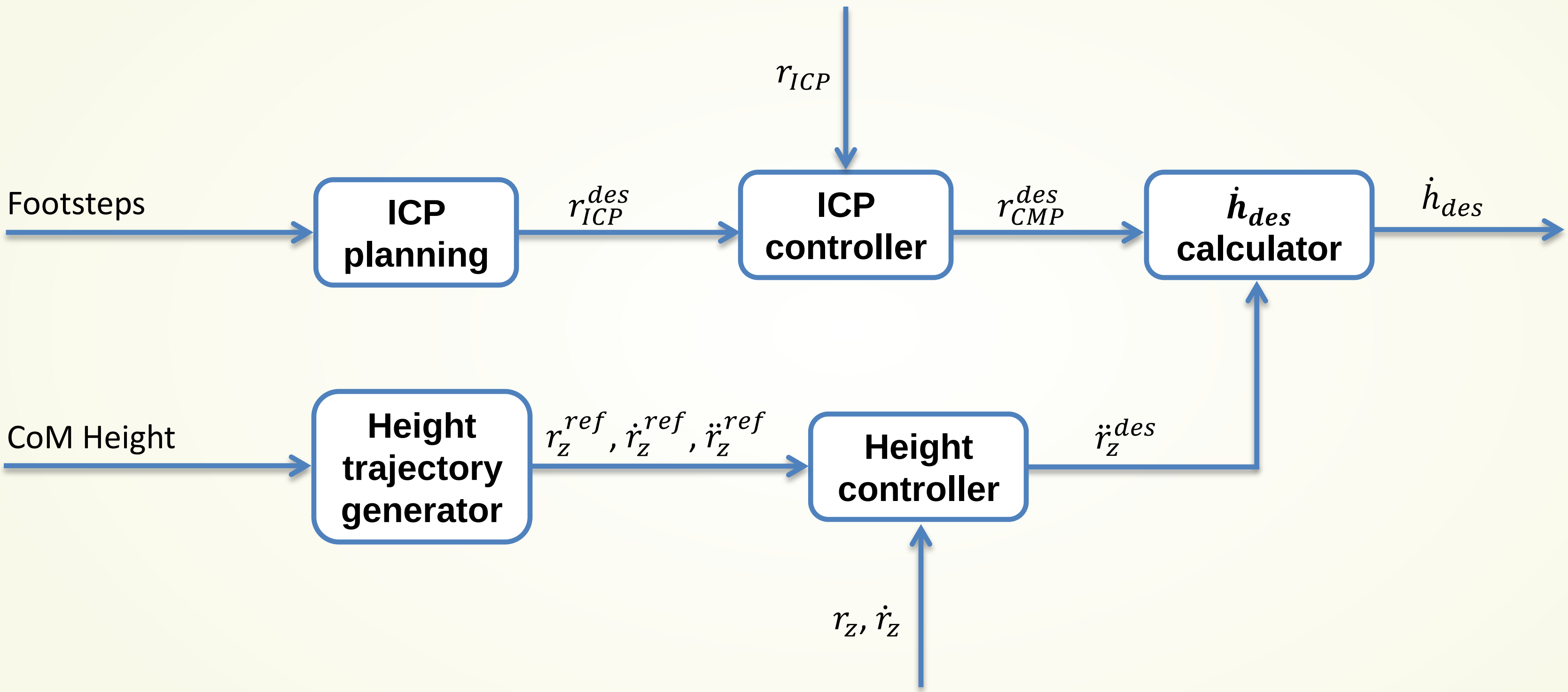
$$SJ\dot{v} = Sp$$

With:

$$p = \begin{bmatrix} \dot{\omega}_{pelvis}^{des} \\ 0_{3\times1} \end{bmatrix} - \dot{J}v$$

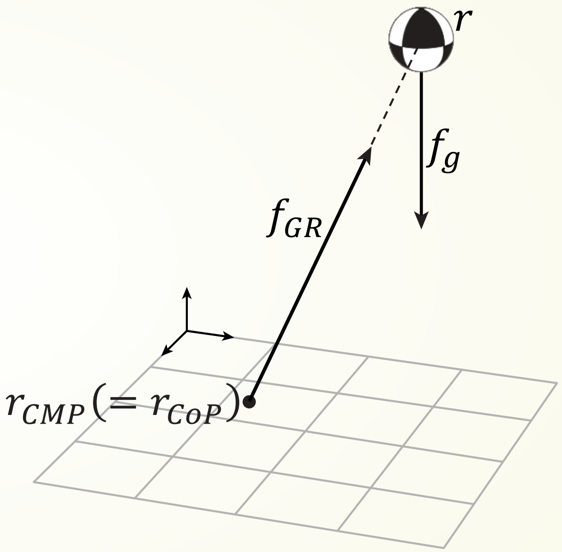
$$S = \begin{pmatrix} I_{3\times3} & 0_{3\times3} \end{pmatrix}$$

ICP Planning & Controller



ICP Overview

- Point mass:
  - $r_{CMP} = r_{CoP}$
  - CoP must be inside support polygon
  - CMP inside the support polygon too



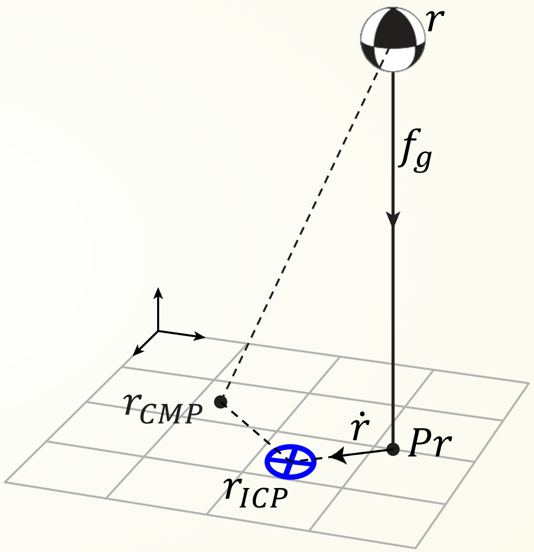
ICP Overview

- Instantaneous Capture Point:

$$r_{ICP} = Pr + \frac{1}{\omega_0}\dot{r}$$

with:

$$\omega_0 = \sqrt{\frac{g}{r_z}}$$



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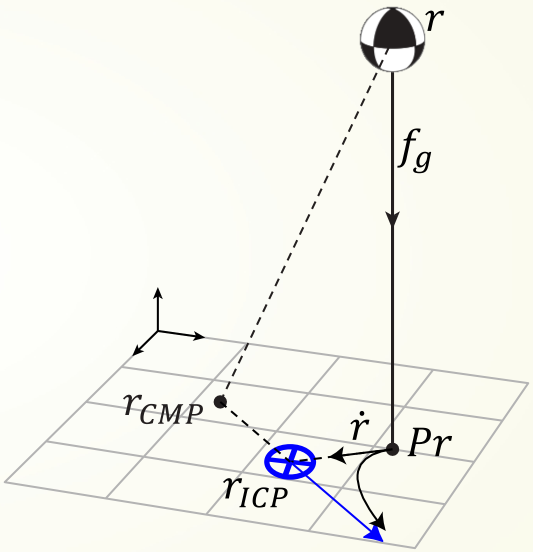
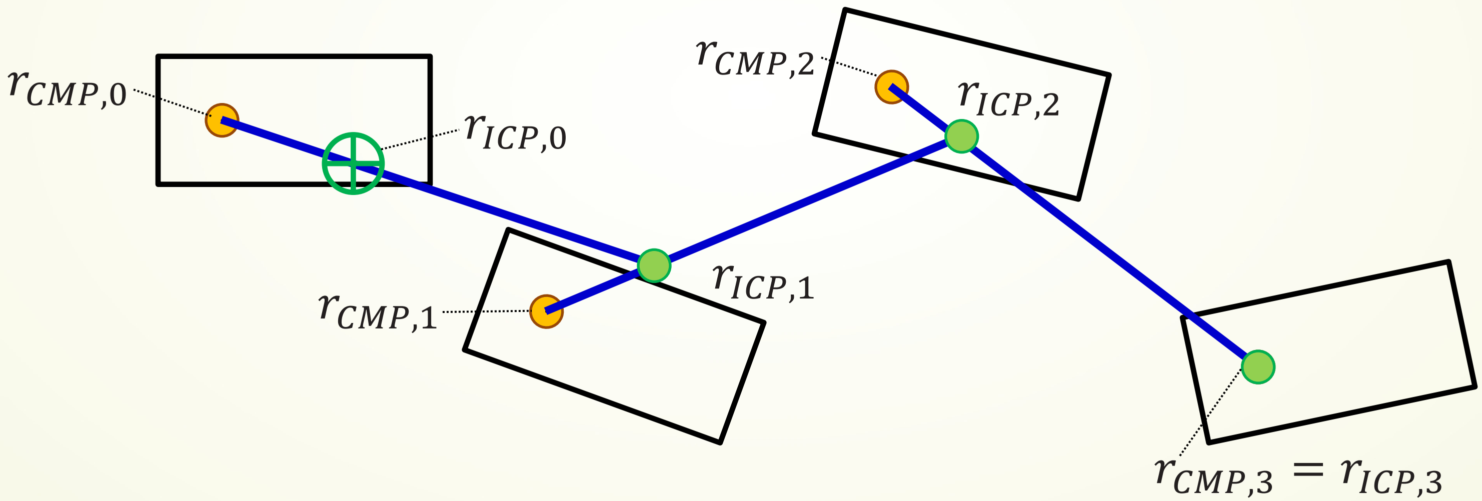


- Dynamics for constant r_z:

$$\dot{r}_{ICP} = \omega_0(r_{ICP} - r_{CMP})$$

ICP Planning (Simpler case)

- Plan r_{CMP} for single supports (shift instant. In double support)
- Find with a recursion r_{ICP} at the beginning of single support
- Generate desired trajectory for the ICP



Englsberger, J. et al. "*Three-dimensional bipedal walking control using Divergent Component of Motion*", *IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), 2013*, 2600-2607

ICP Controller & $\dot{h}_{des}$ Calculation

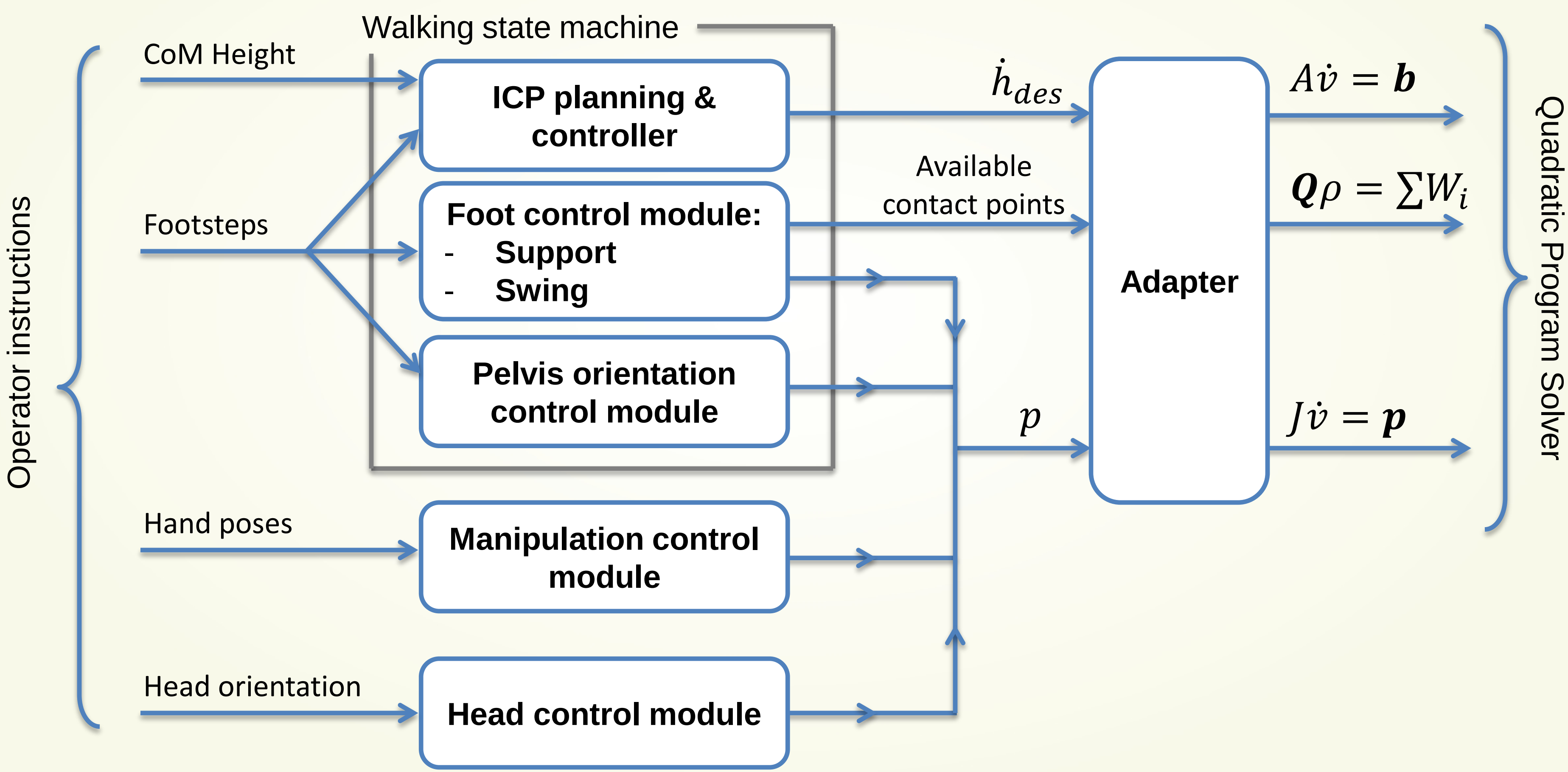
- ICP controller:

$$r_{CMP}^{des} = r_{ICP} + \frac{K_p}{\omega_0}\left(r_{ICP}^{des} - r_{ICP}\right) - \frac{1}{\omega_0}\dot{r}_{ICP}^{des}$$

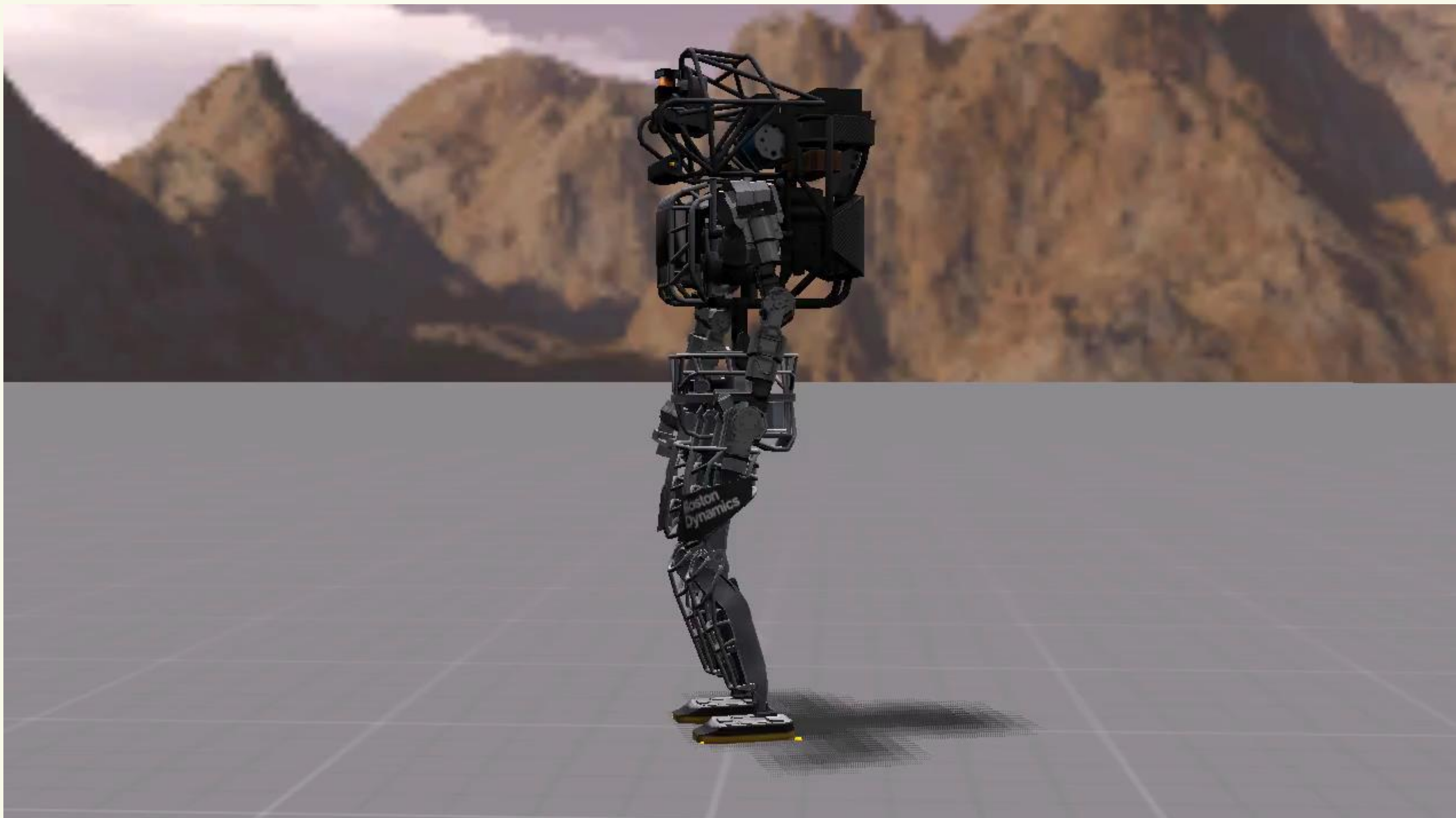
- Compute $\dot{h}_{des}$ ():

$$\dot{h}_{des} = m\begin{bmatrix} \omega_0^2\left(r_x - r_{CMP,x}\right) \\ \omega_0^2\left(r_y - r_{CMP,y}\right) \\ \ddot{r}_z^{des} \end{bmatrix}$$

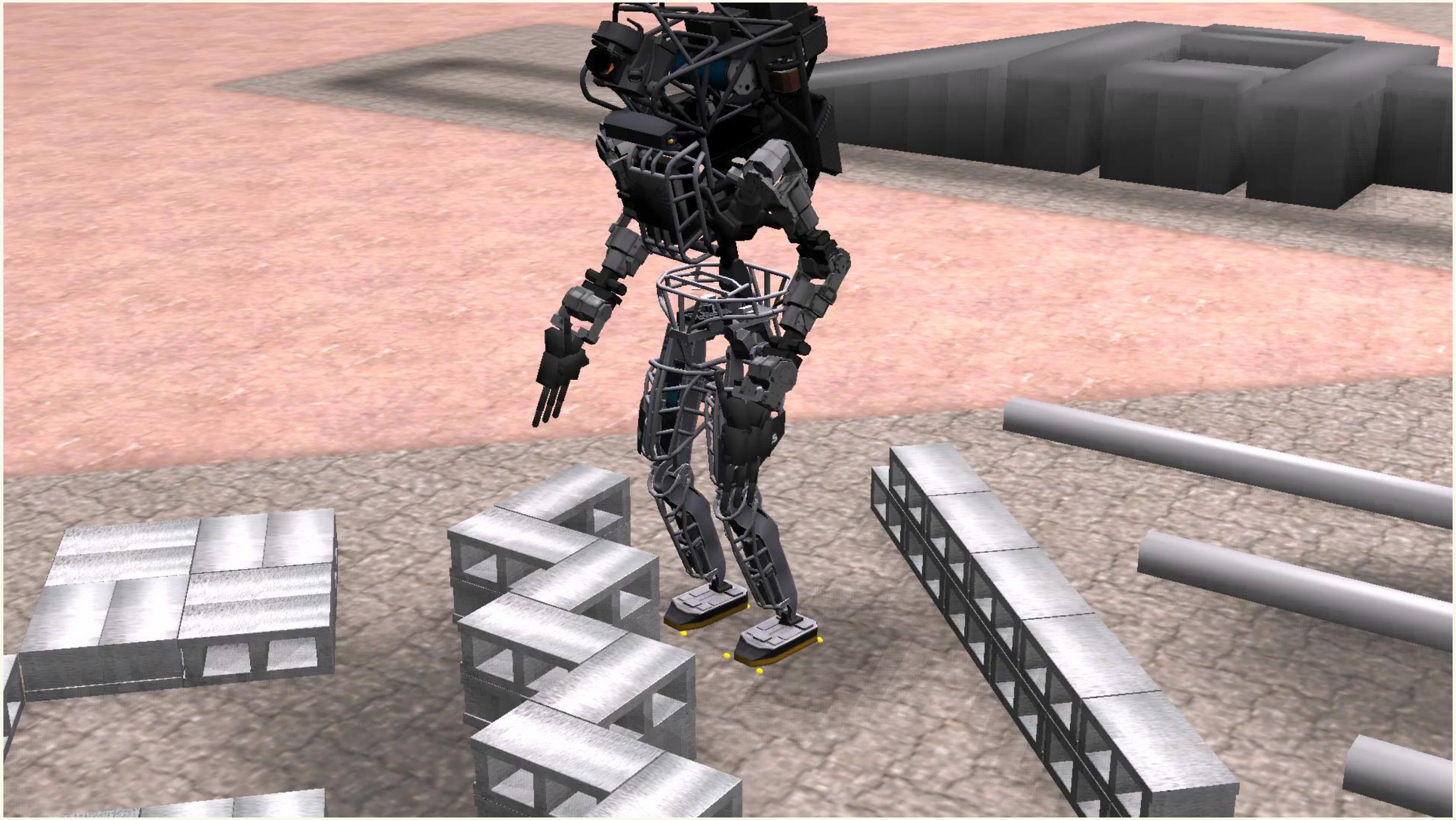
Walking high-level controller

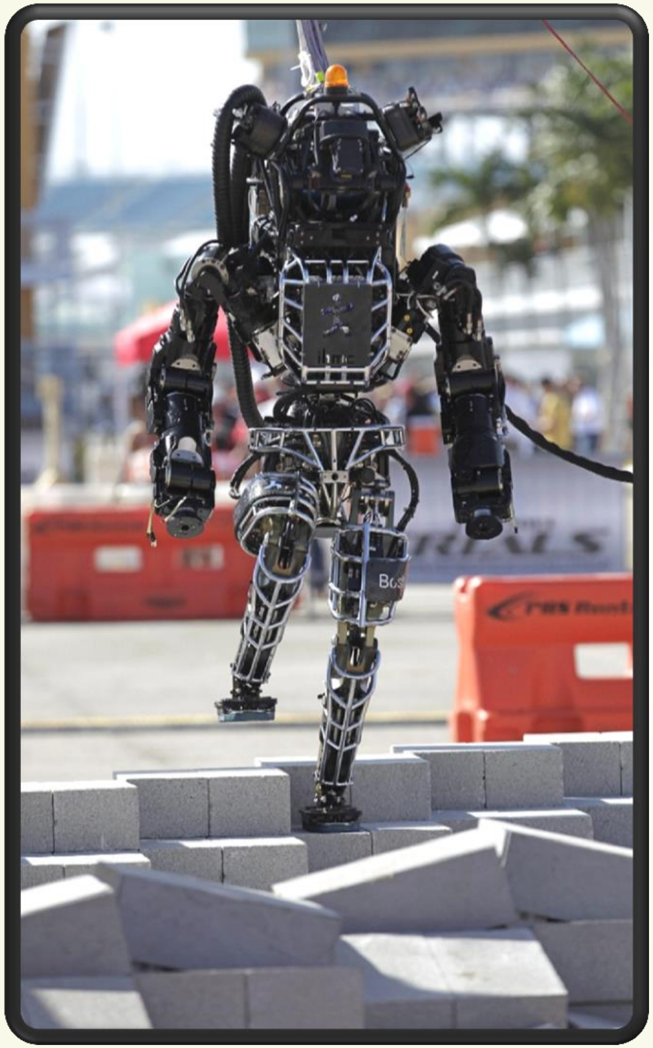


Virtual Atlas Walking



Virtual Atlas Walking





IMPLEMENTATION ON THE REAL ROBOT

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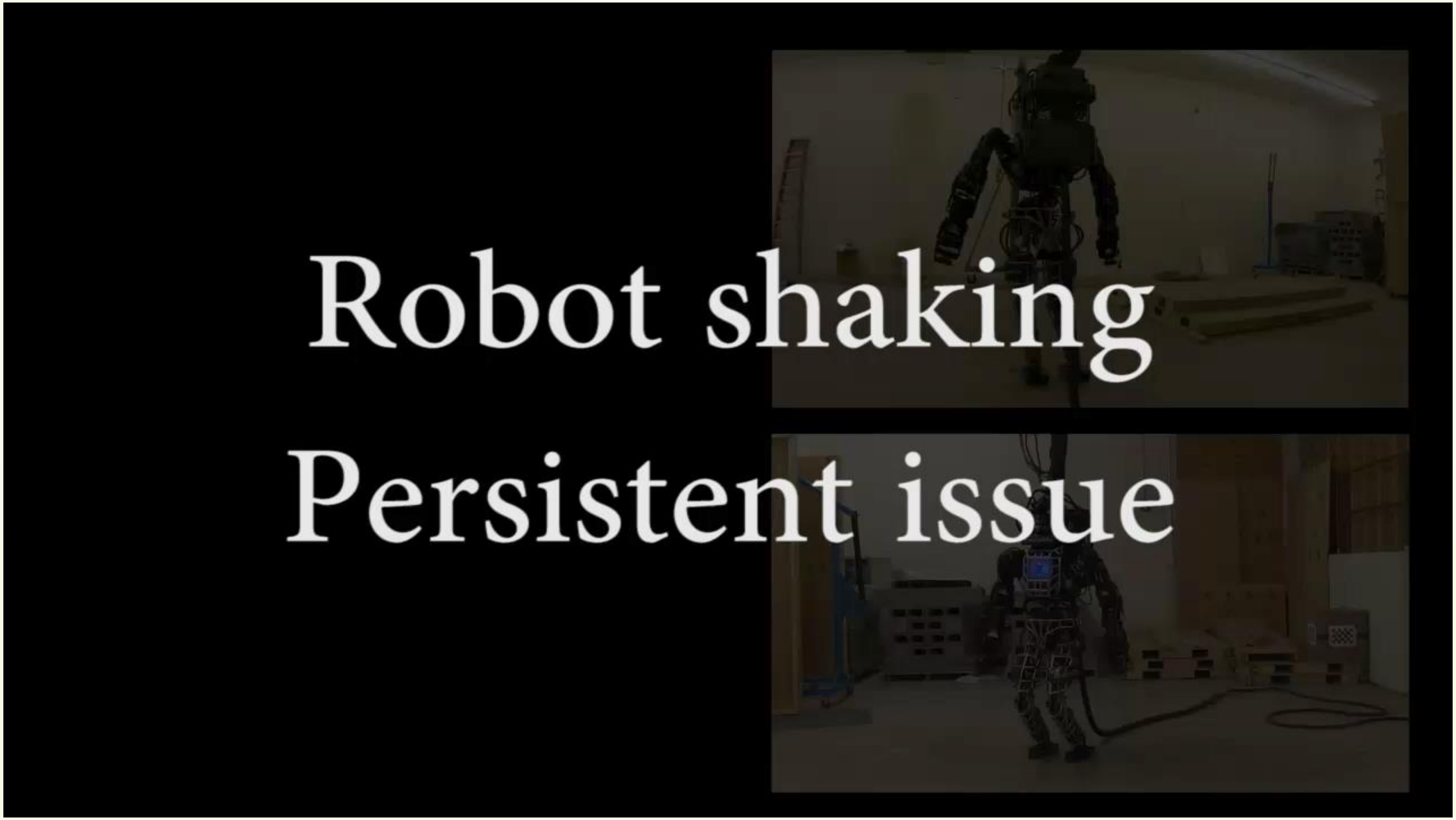
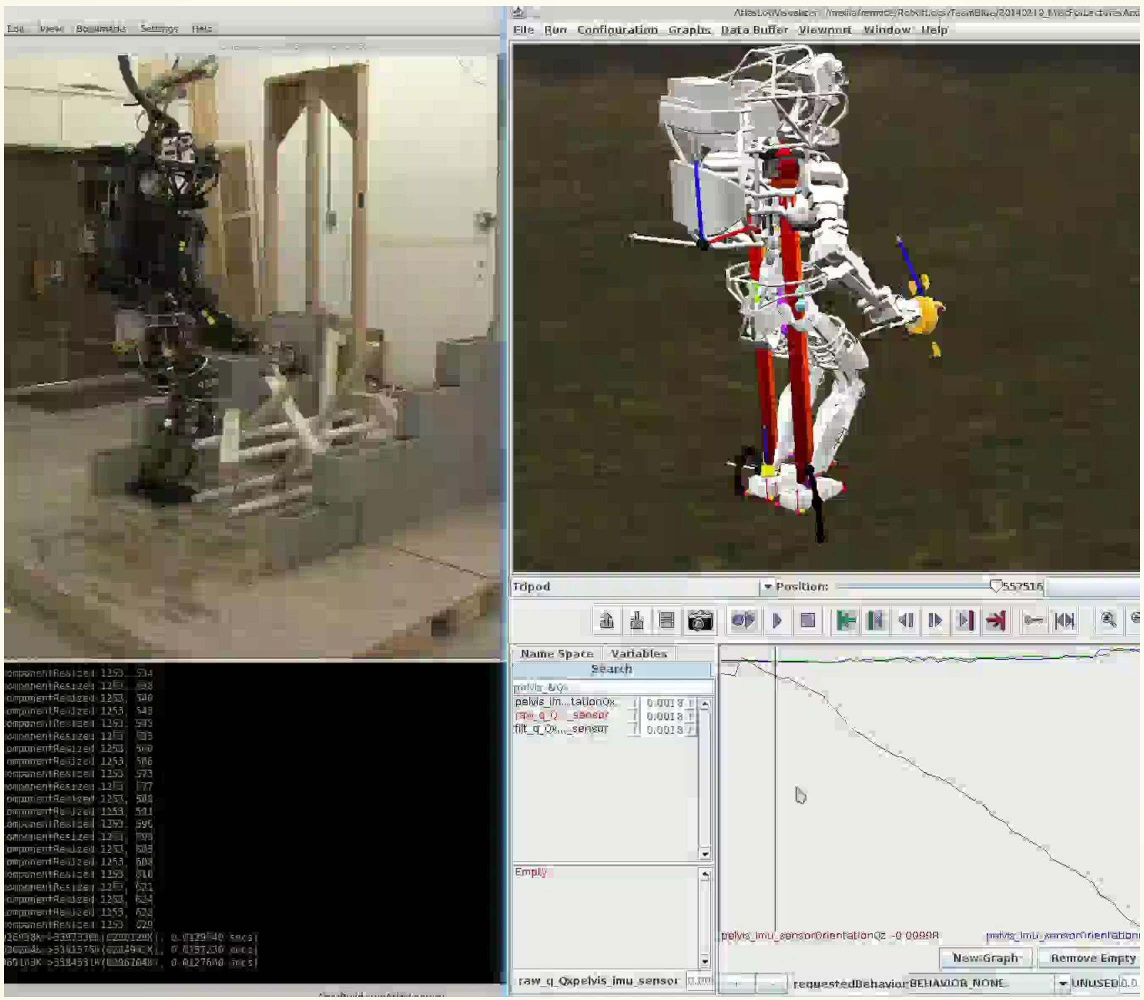
Issues: Shakies

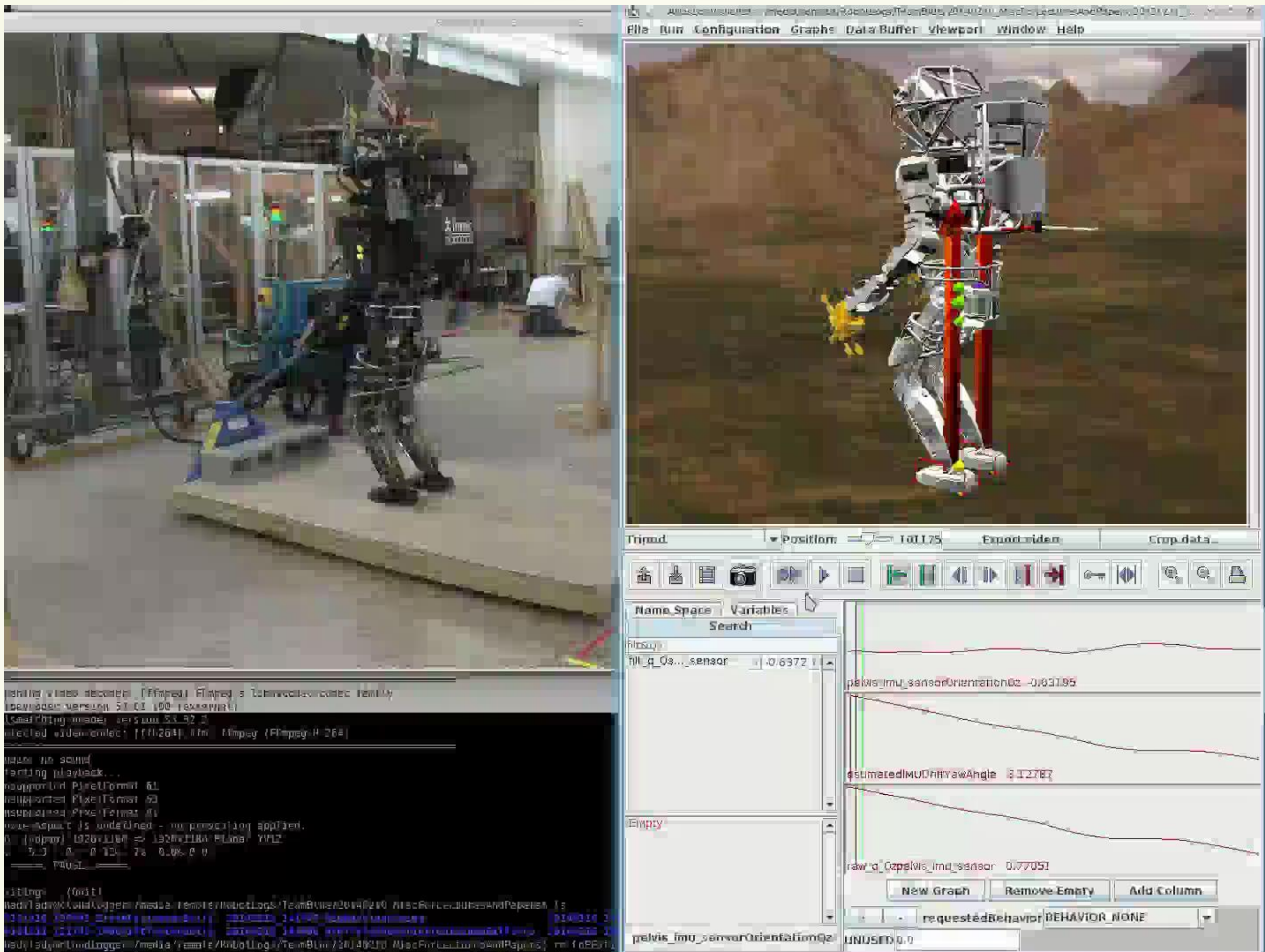


Issues: Foot slipping

Issues: IMU drift



Issues: IMU drift



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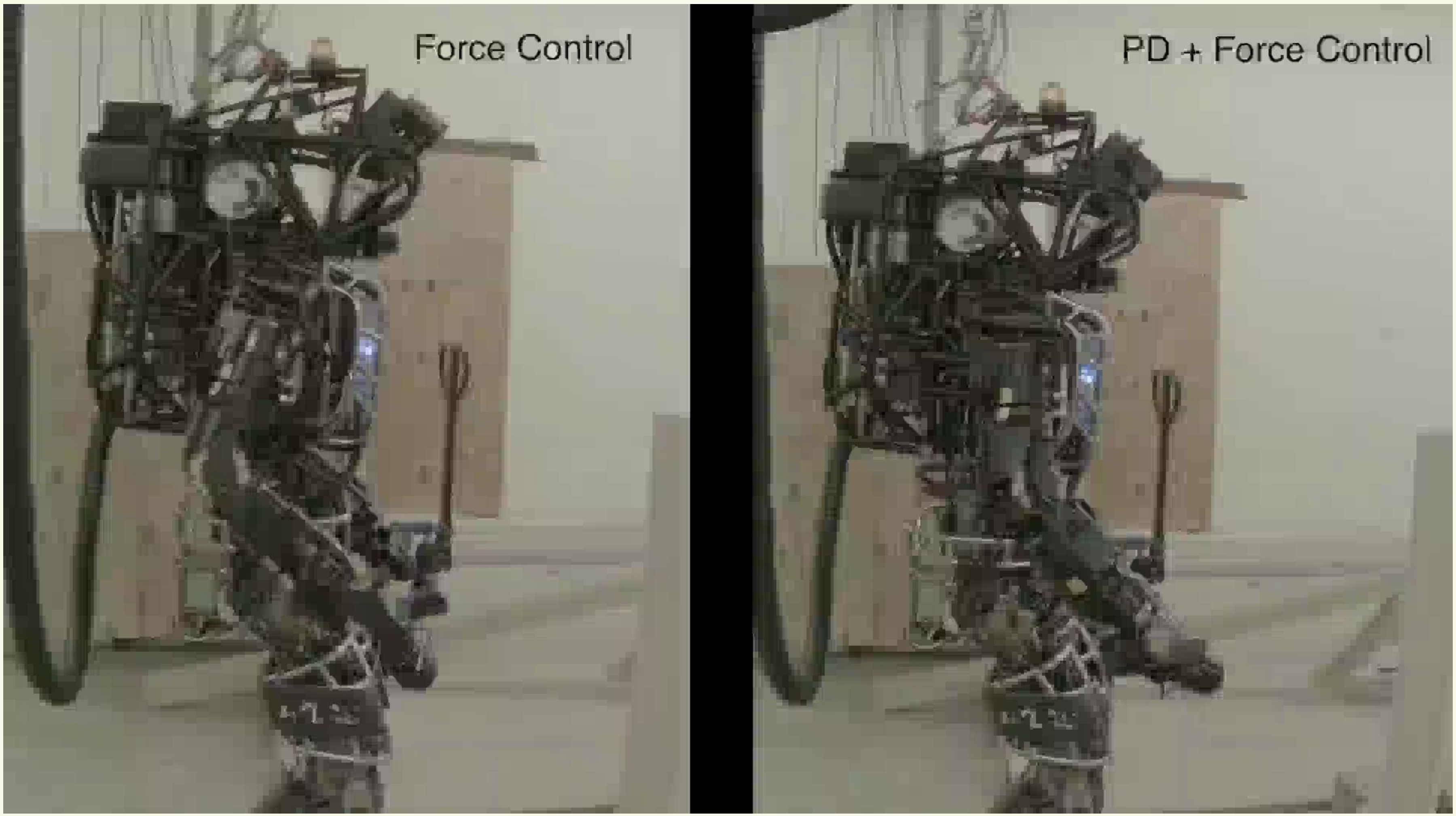
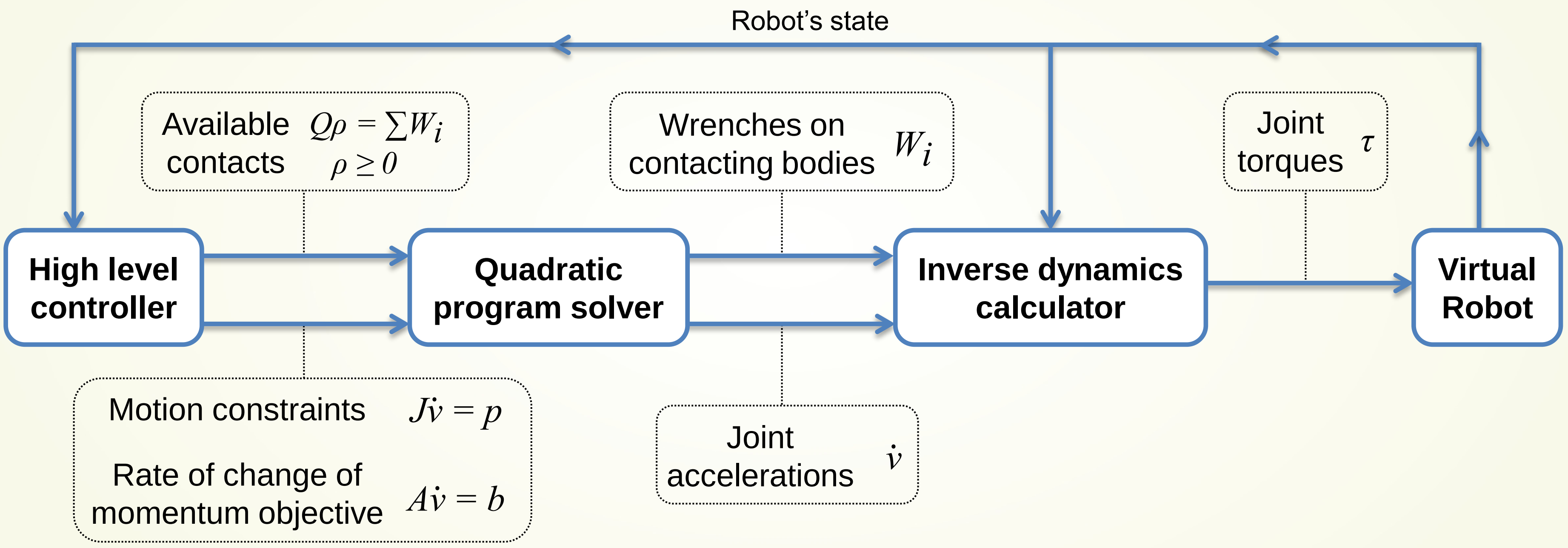
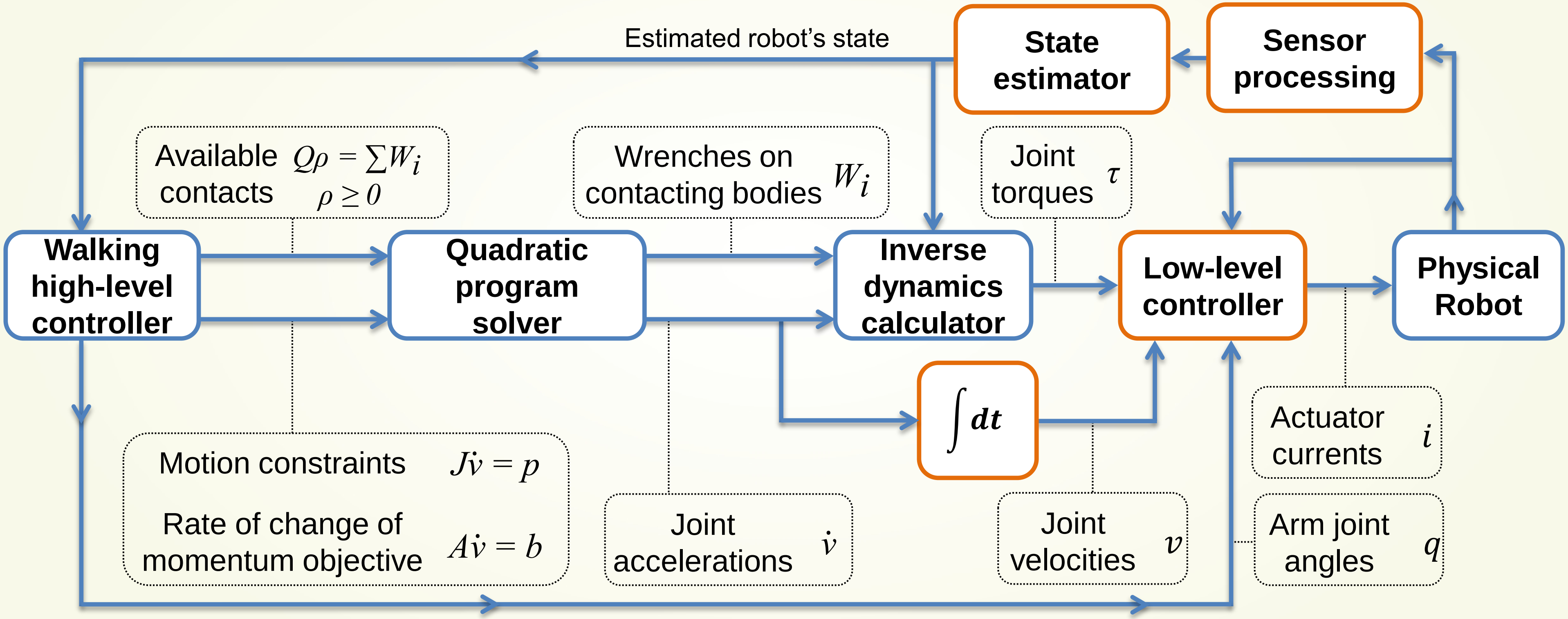
Issues: Joint stiction



Whole-body motion control framework Before



Whole-body motion control framework
After



Sensor processing

- Sensor noise: low-pass filters
- Link elasticity:

$$q_{proc} = q_{raw} + \frac{\tau}{k}$$

- Joint backlash:

$$\dot{q}_{proc}^{t} = \alpha \dot{q}_{proc}^{t-1} + (1-\alpha)\dot{q}_{raw}\eta$$

with: $\eta = \begin{cases} \frac{t-t_0}{\Delta t} & if\ (t-t_0) < \Delta t \\ 1 & else \end{cases}$

$t_0 = t$ when $\dot{q}_{proc}$ crosses zero

State Estimator (IMU drift)

- Built new state estimate for Atlas:
  - Trusts IMU for orientation and angular velocity
  - Fuses data for position and linear velocity:

$$\dot{x}^t = \alpha_{\dot{x}}(\dot{x}^{t-1} + \ddot{x}^t_{IMU}\Delta t) + (1 - \alpha_{\dot{x}})\dot{x}_{kin}$$
$$x^t = \alpha_x(x^{t-1} + \dot{x}^t\Delta t) + (1 - \alpha_x)x_{kin}$$

- Compensator for IMU drift in orientation and angular velocity
- State estimator error:
  - $\sim 1 inch/step$ on the horizontal position
  - $\sim 0.2 inch/step$ along the vertical

Walking controller (chatter/shakies)

- Chatter:
  - Reduced PD controller gains (especially damping)
  - Motion constraints: limited to a maximum acceleration and maximum jerk
- Model inaccuracies:
  - System ID (for the chest mass)
  - Added integral term to the ICP controller:

$$r_{CMP}^{des} = r_{ICP} + \frac{K_p}{\omega_0}\left(r_{ICP}^{des} - r_{ICP}\right) + \frac{K_i}{\omega_0}\int\left(r_{ICP}^{des} - r_{ICP}\right)dt - \frac{1}{\omega_0}\dot{r}_{ICP}^{des}$$

Low-level controller (joint stiction)

- Hybrid controller to fight stiction:

$$i = k_{ff_{qd}}\dot{q} + i_\tau + i_{\dot{q}} + i_q$$

$$\text{with:} \begin{cases} i_\tau = k_{\tau,p}(\tau_d - \tau) + k_{\tau,d}(\dot{\tau}_d - \dot{\tau}) + k_{\tau,i}\int(\tau_d - \tau)dt \\ i_{\dot{q}} = k_{\dot{q}}\left(\int \ddot{q}_d dt - \dot{q}\right) \\ i_q = k_{q,p}(q_d - q) + k_{q,v}(\dot{q}_d - \dot{q}) + k_{q,i}\int(q_d - q)dt \end{cases}$$

  - i_τ: PID controller on joint torque
  - $i_{\dot{q}}$: P controller on joint velocity
  - i_q: PID controller on joint position

- Arm joints: torque + position controller $\left(i = k_{ff_{qd}}\dot{q} + i_\tau + i_q\right)$
- Other joints: torque + velocity controller $\left(i = k_{ff_{qd}}\dot{q} + i_\tau + i_{\dot{q}}\right)$
  - Joint desired velocity obtained from joint desired acceleration (QP solver output)
  - Support ankle joints: only torque controller $\left(i = k_{ff_{qd}}\dot{q} + i_\tau\right)$

Good runs

At the end

- Control
  - Wanted a compliant control ended up with high impedance
  - Introduced lots of “hacks” that needs to be cleaned and improved
- Atlas
  - Gave us hard time
  - Pretty repeatable fitting our testing obsession

Future work

- General improvements
  - Modeling
  - State estimation
  - Low-level controller
  - Push-recovery
  - Fast walking

Thank you!

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