Humanoid Balancing and Its Benchmarking

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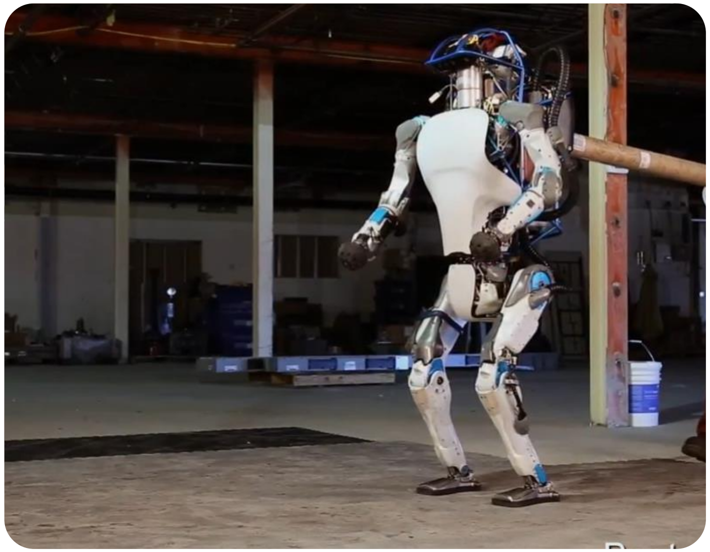
Motivation

Source: Youtube

How about our robots?

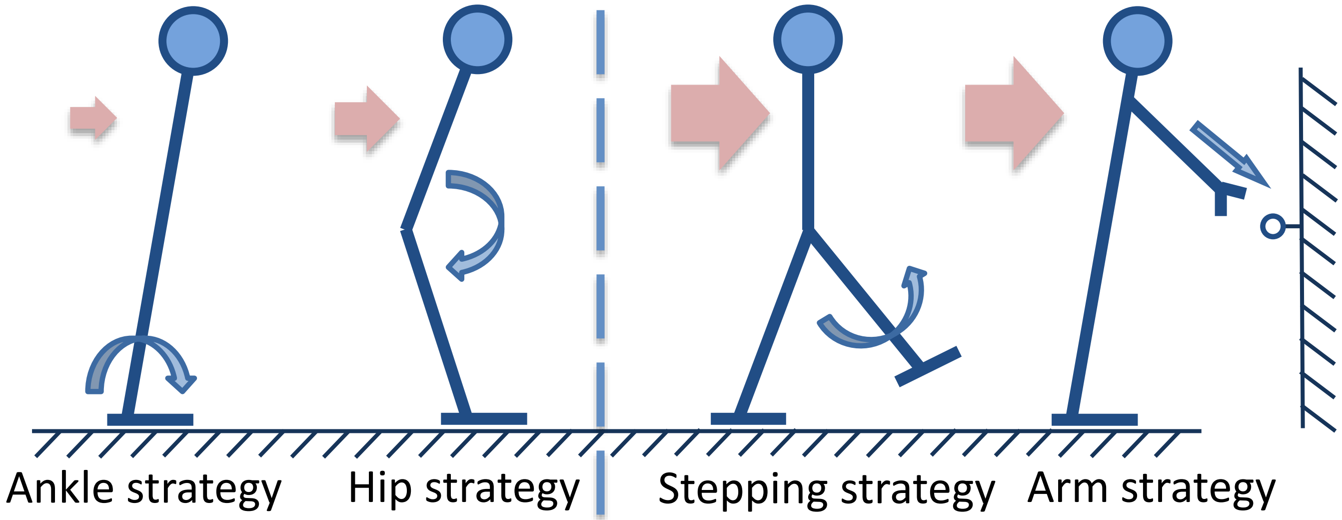


Source: Youtube

After Been Disturbed…

- What Balancing Capabilities?
  - Use its whole-body for balancing
  - Protect itself if a fall is inevitable
  - Recover to stable state
- How to Evaluate?
  - Measure the balancing performance
  - Compare between different HW/SW

Human Balancing Strategies



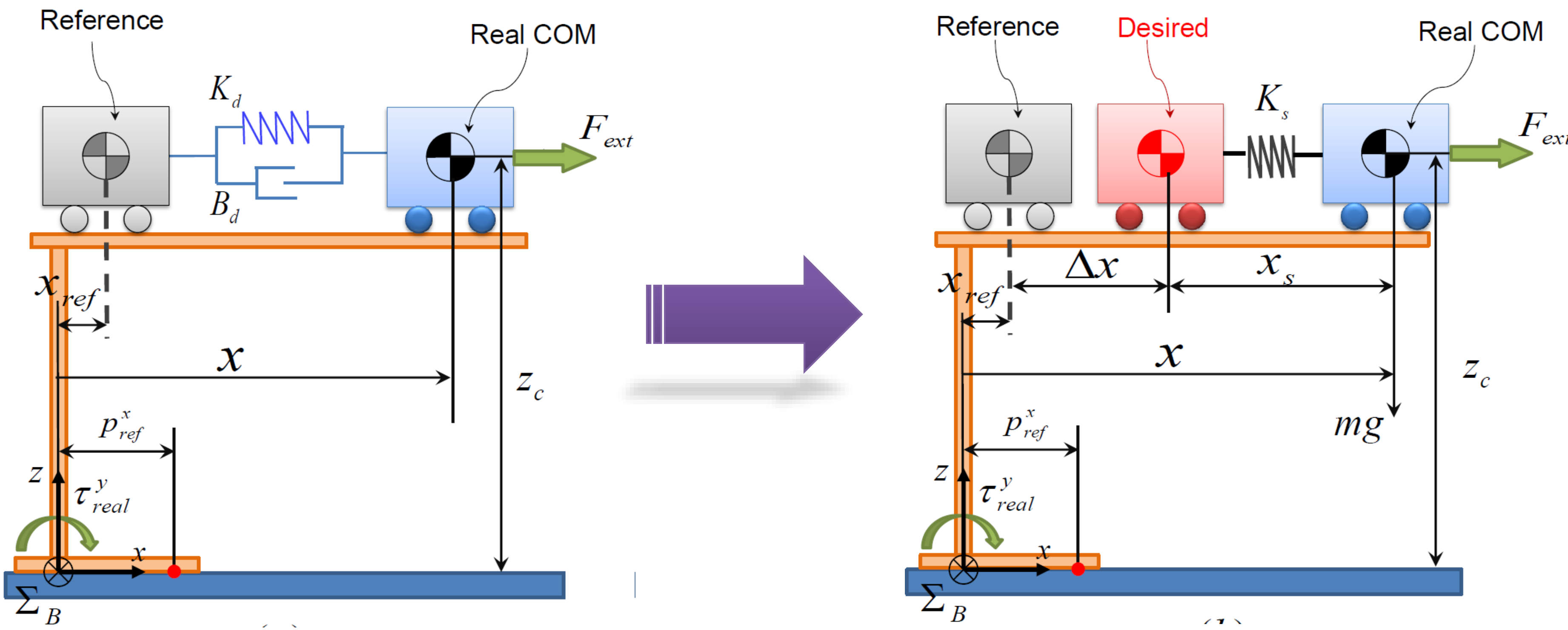
Fixed-support

Change-in-support

$$\sum F_{com} = \sum F_{contact}$$

$$\sum F_{com} > \sum F_{contact}$$

Compliant Stabilizer

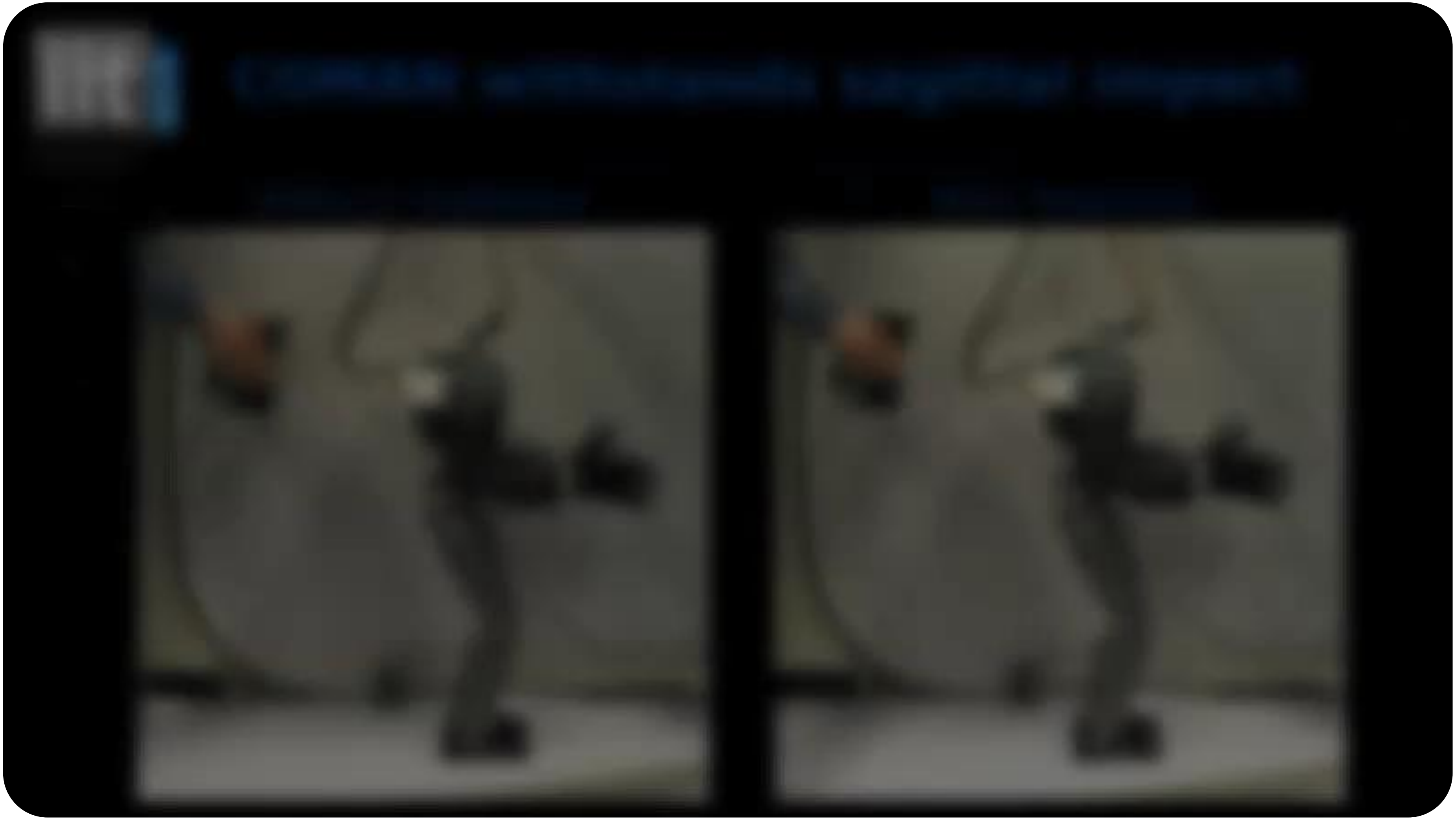


$$\Delta x(i) = \frac{\Delta t}{K_d \Delta t + B_d} A(i) + \frac{B_d}{K_d \Delta t + B_d} \Delta x(i-1)$$

$$A(i) = -\frac{\tau^y_{\mathrm{real}}(i) - \tau^y_d(i)}{z_c} + \frac{B_d \dot{\tau}^y_{\mathrm{real}}(i)}{z_c K_s} + \frac{K_d \tau^y_{\mathrm{real}}(i)}{z_c K_s}$$

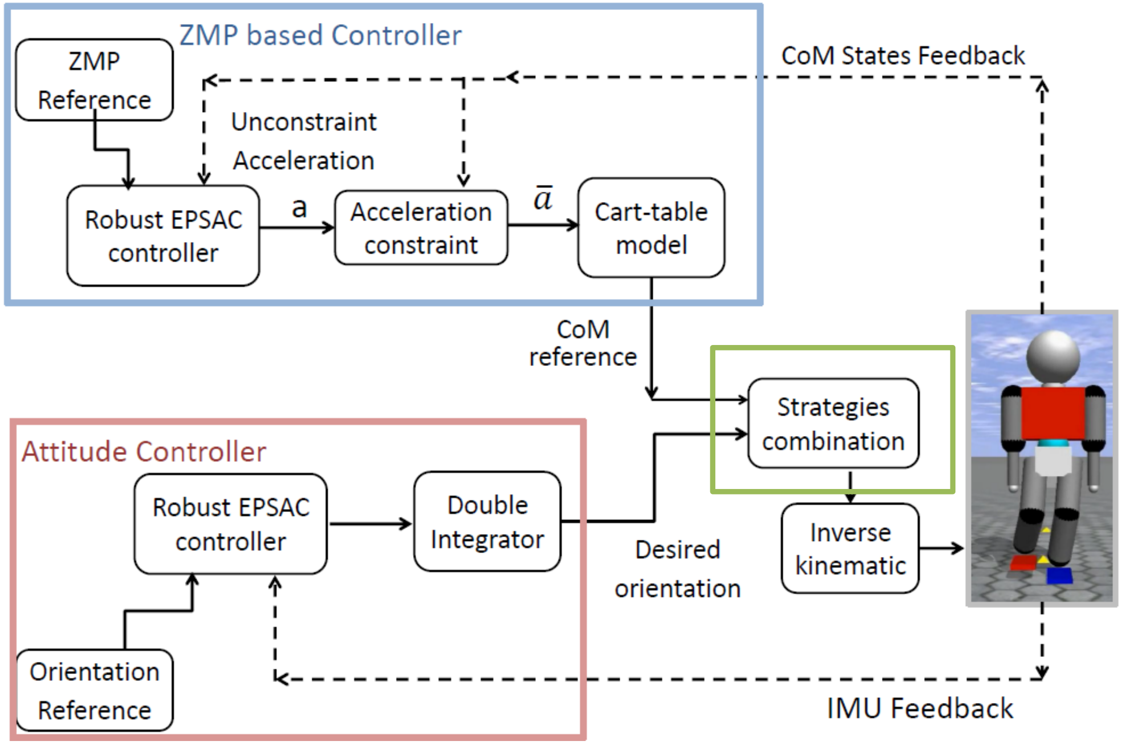
Stiff robot: $K_s \to \infty$

Compliant Stabilizer



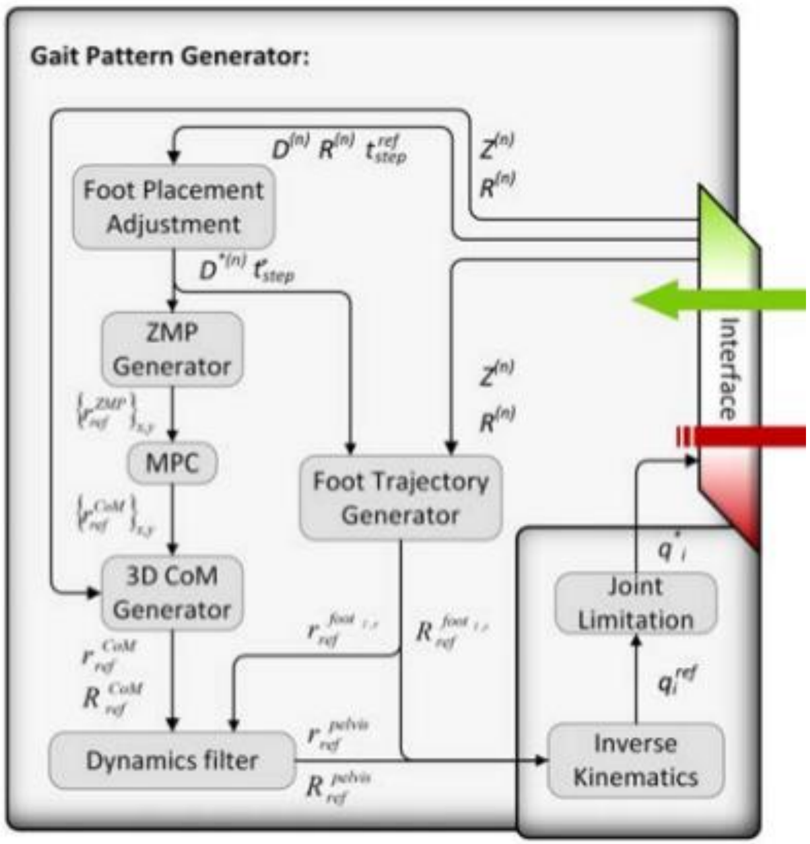
C. Zhou *et al*, "Stabilization of Bipedal Walking Based on Compliance Control," Autonomous Robots, 2016

Integrated Stabilization



J. Castano, **C. Zhou** *et al*, "Robust Model Predictive Control for Humanoids Standing Balancing," IEEE ARM, 2016

Gait Pattern Generator

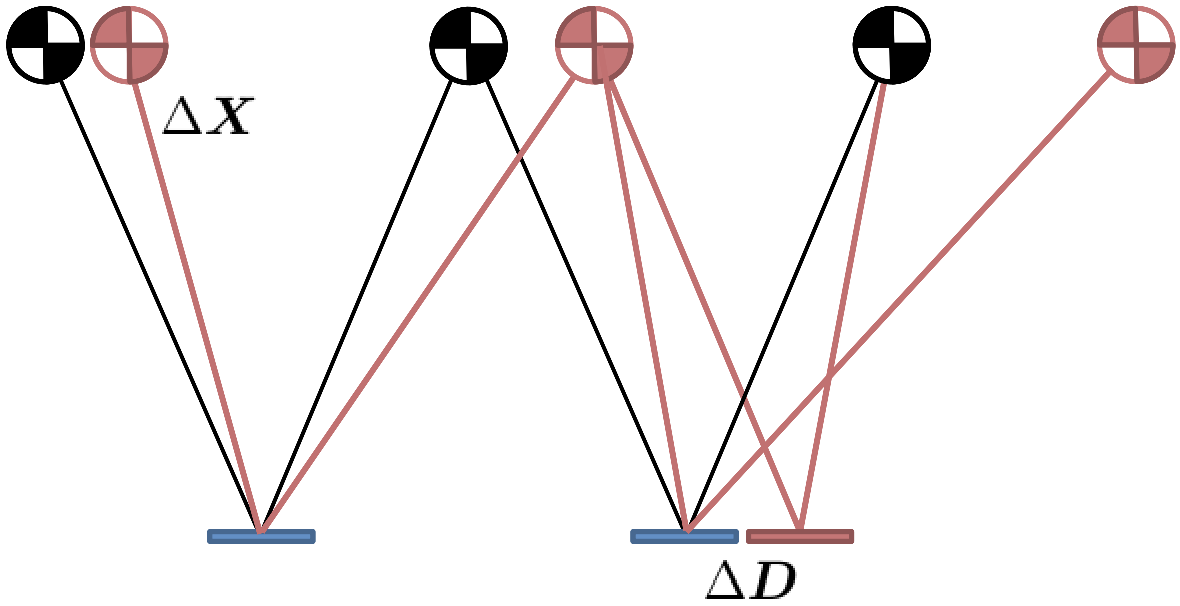


Input : Gait parameters: t_{step}, l_{sl}, l_{sw} and θ_{turn}.
Output: Discrete footsteps $\boldsymbol{D} = [\boldsymbol{d}_x \quad \boldsymbol{d}_y]^T$

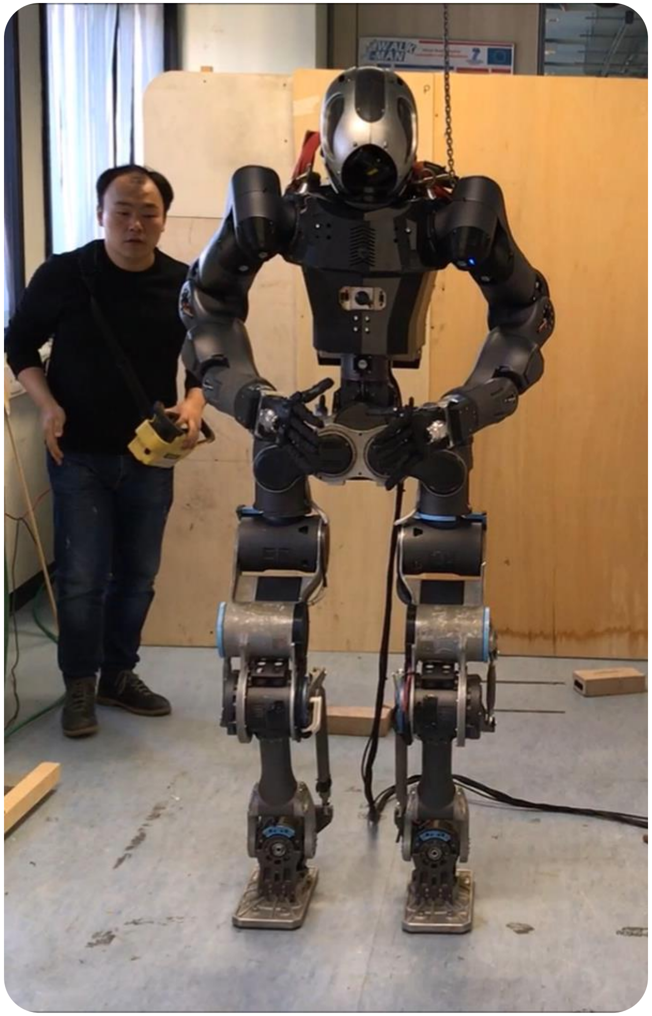
if *command START* **then**
  $\boldsymbol{D}^{(0)} \leftarrow$ initial foot position
else
  $\boldsymbol{D}^{(0)} \leftarrow$ current foot position
end
if *command WALKING* **then**
  for $i \leftarrow 1$ **to** n **do** /
    $\boldsymbol{D}^{(i)} \leftarrow$ update(l_{sl}, l_{sw}, θ_{turn})
  end
end
if *command STOP* **then**
  end($\boldsymbol{D}$) `// add last step to make robo`
end
return $\boldsymbol{D}$

C. Zhou *et al*, "Overview of gait synthesis for the humanoid COMAN," Journal of Bionic Engineering, 2017

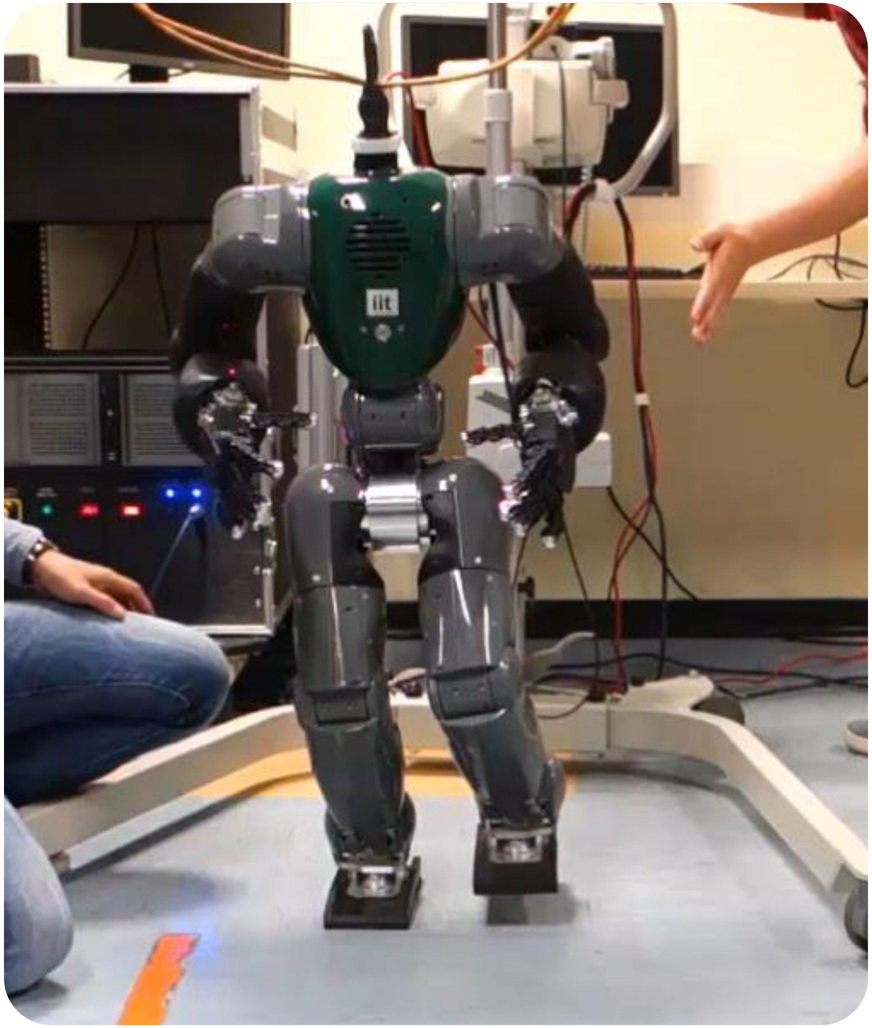
Footstep Modification

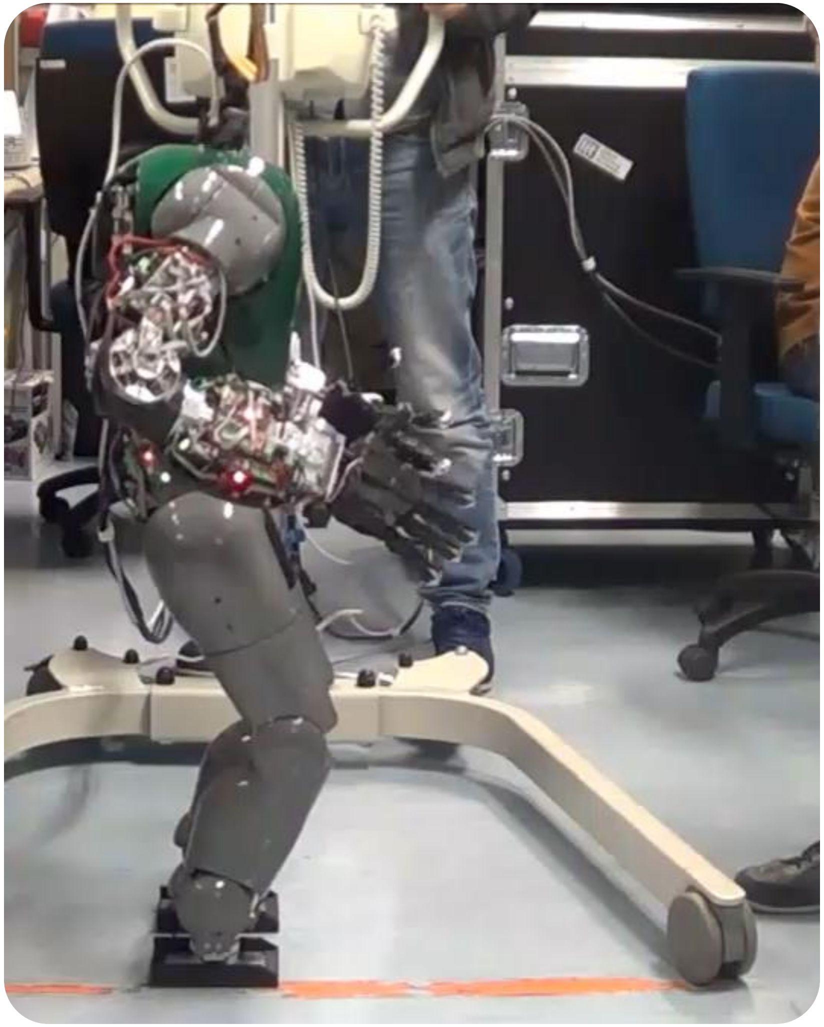


Stepping Strategy - During Standing



Stepping Strategy – During Walking





Whole body balancing using environment constraints

High level planner

Push detected

↓

Choose target wall

↓

Decide contact pose of hands

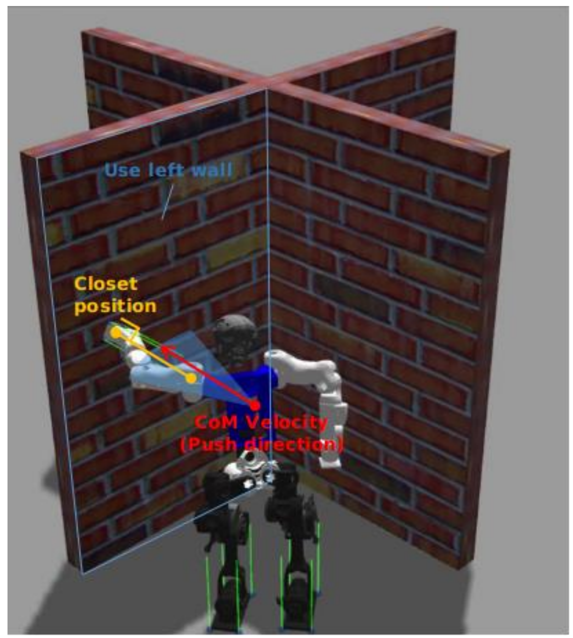
↓

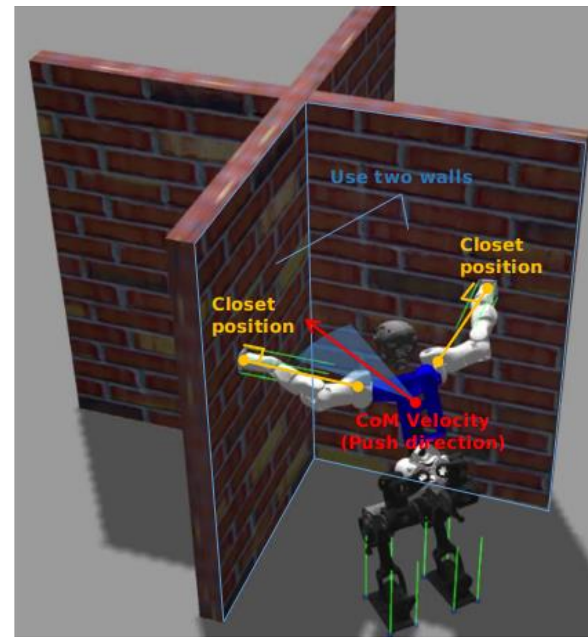
Plan the trajectories of CoM, pelvis and hands

↓

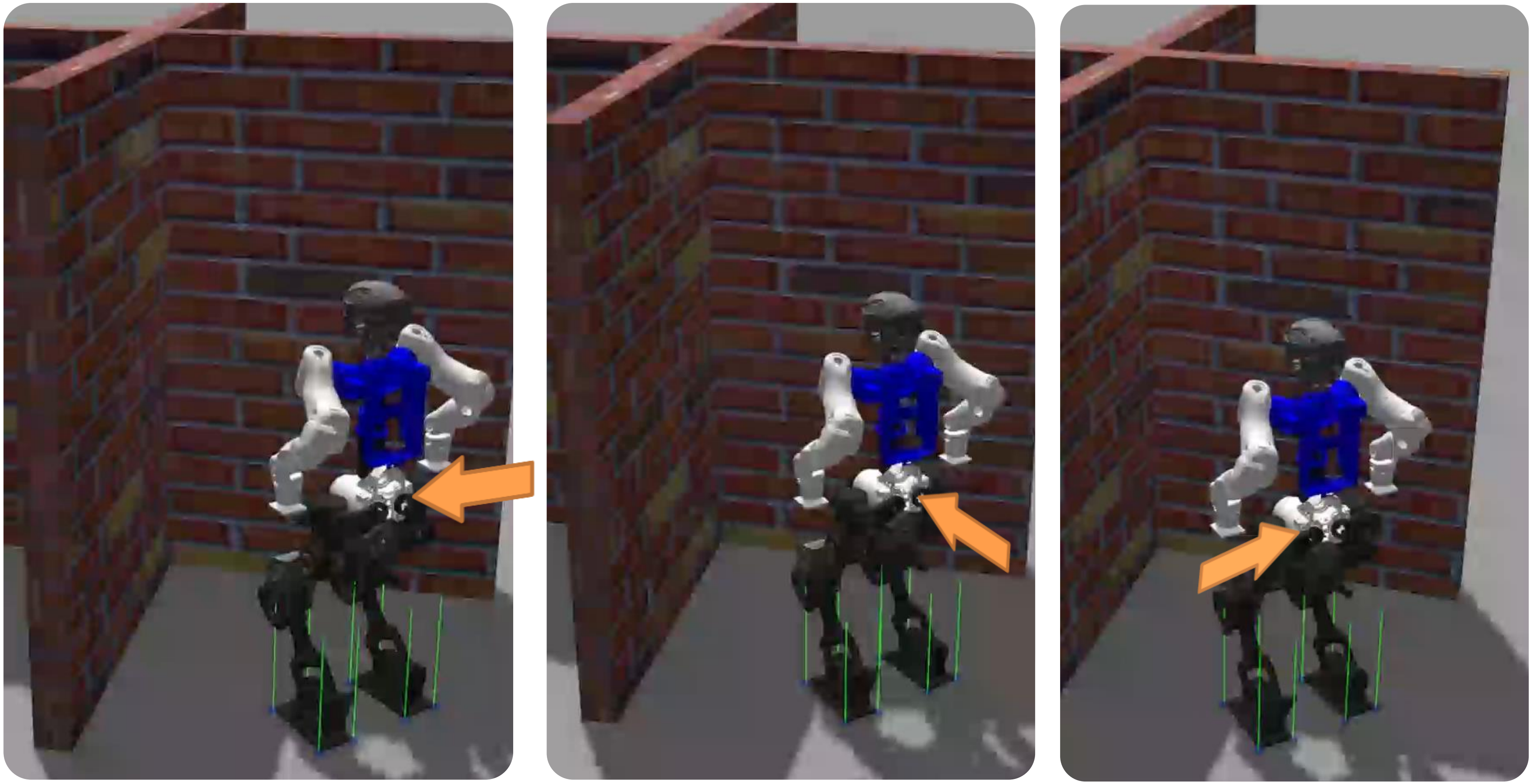
Low level controller

Optimize joint torques and contact forces based on whole body dynamics





Whole body balancing using environment constraints



Whole-body Inverse Kinematics/Dynamics

Formulated as a QP Problem

$$\min_{\mathcal{X}} \quad \frac{1}{2}\left\|\boldsymbol{A}\mathcal{X} - \boldsymbol{b}\right\|^2$$
$$\text{s.t.} \quad C\mathcal{X} \lesseqqgtr c\,,$$
$$\mathcal{X}_{\text{lb}} \leq \mathcal{X} \leq \mathcal{X}_{\text{ub}}\,,$$

- Cartesian Space Tasks

$$\boldsymbol{A}_{cart} = \begin{bmatrix} \boldsymbol{J}_1^T & \boldsymbol{J}_2^T & \cdots & \boldsymbol{J}_m^T \end{bmatrix}^T \qquad \boldsymbol{b}_{cart} = \begin{bmatrix} \dot{x}_1^T & \dot{x}_2^T & \cdots & \dot{x}_m^T \end{bmatrix}^T$$

- Joint Space Tasks
  - Manipulability

$$\boldsymbol{A}_{mani} = \boldsymbol{I} \qquad \boldsymbol{b}_{mani}^{(i)} = \nabla f^{(i)}\left(\sqrt{\det\left(\boldsymbol{J}_i \boldsymbol{J}_i{}^T\right)}\right)$$

  - Direct Joint Tracking

$$\boldsymbol{A}_{joint} = \boldsymbol{S} \qquad \boldsymbol{b}_{joint} = \dot{\boldsymbol{q}}_{des}$$

- Collision Avoidance Constraints

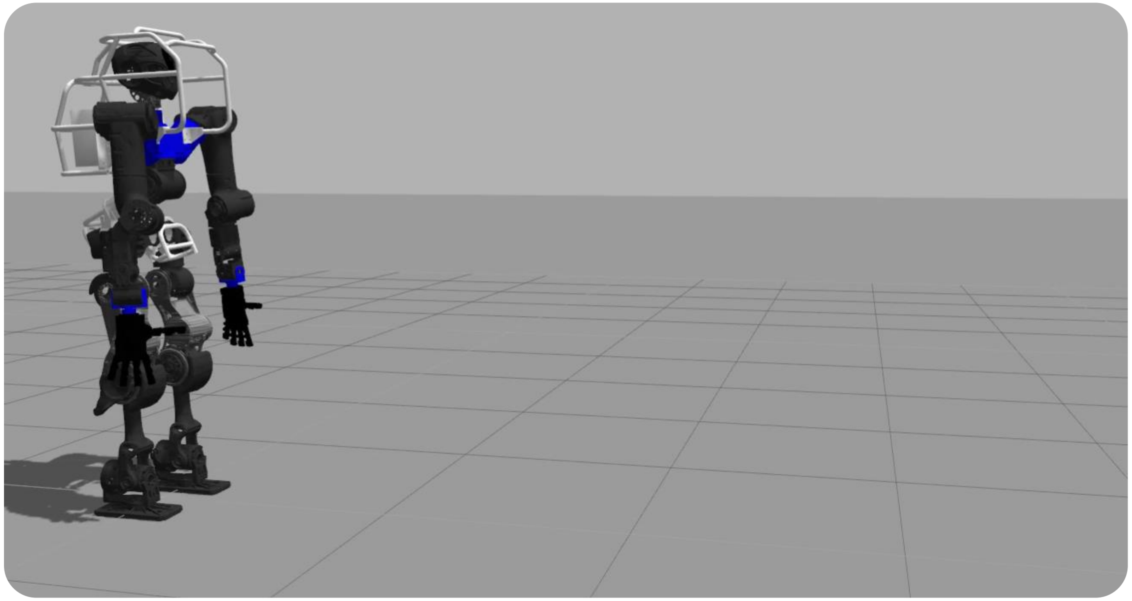
$$\boldsymbol{C}_{collision}^{(i)} = \boldsymbol{n}^T\left(\boldsymbol{J}_{p1} - \boldsymbol{J}_{p2}\right), \qquad \boldsymbol{c}_{collision}^{(i)} = \xi \frac{d - d_s}{d_i - d_s}$$

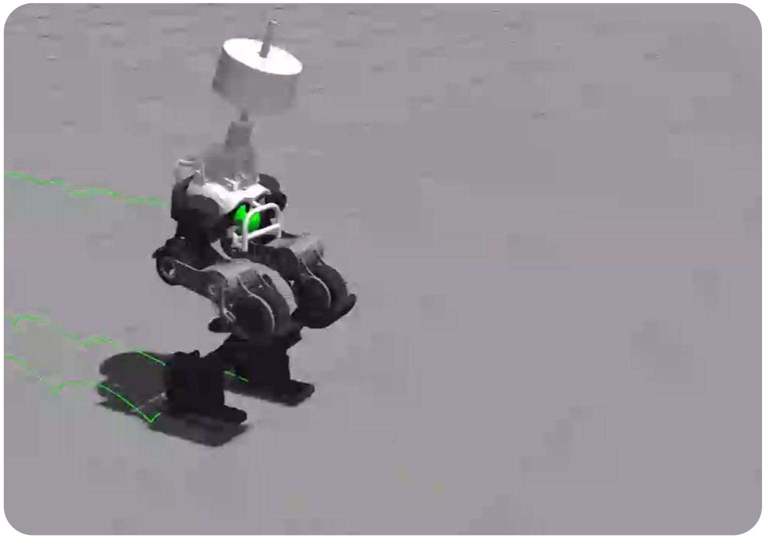
- Bound Constraints

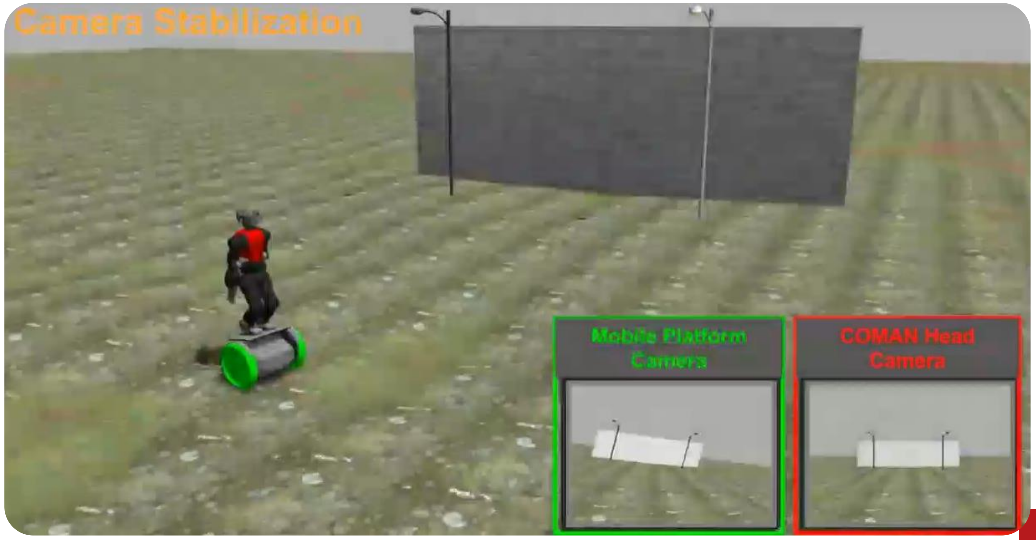
$$\mathcal{X}_{\text{lb}} = -\xi_x \frac{(x - x^-) - x_s}{x_i - x_s} \qquad \mathcal{X}_{\text{ub}} = \xi_x \frac{(x^+ - x) - x_s}{x_i - x_s},$$

C. Zhou et al, "A Generic Optimization-based Framework for Reactive Collision Avoidance in Bipedal Locomotion," IEEE CASE, 2016

Applications of Whole-body Controller







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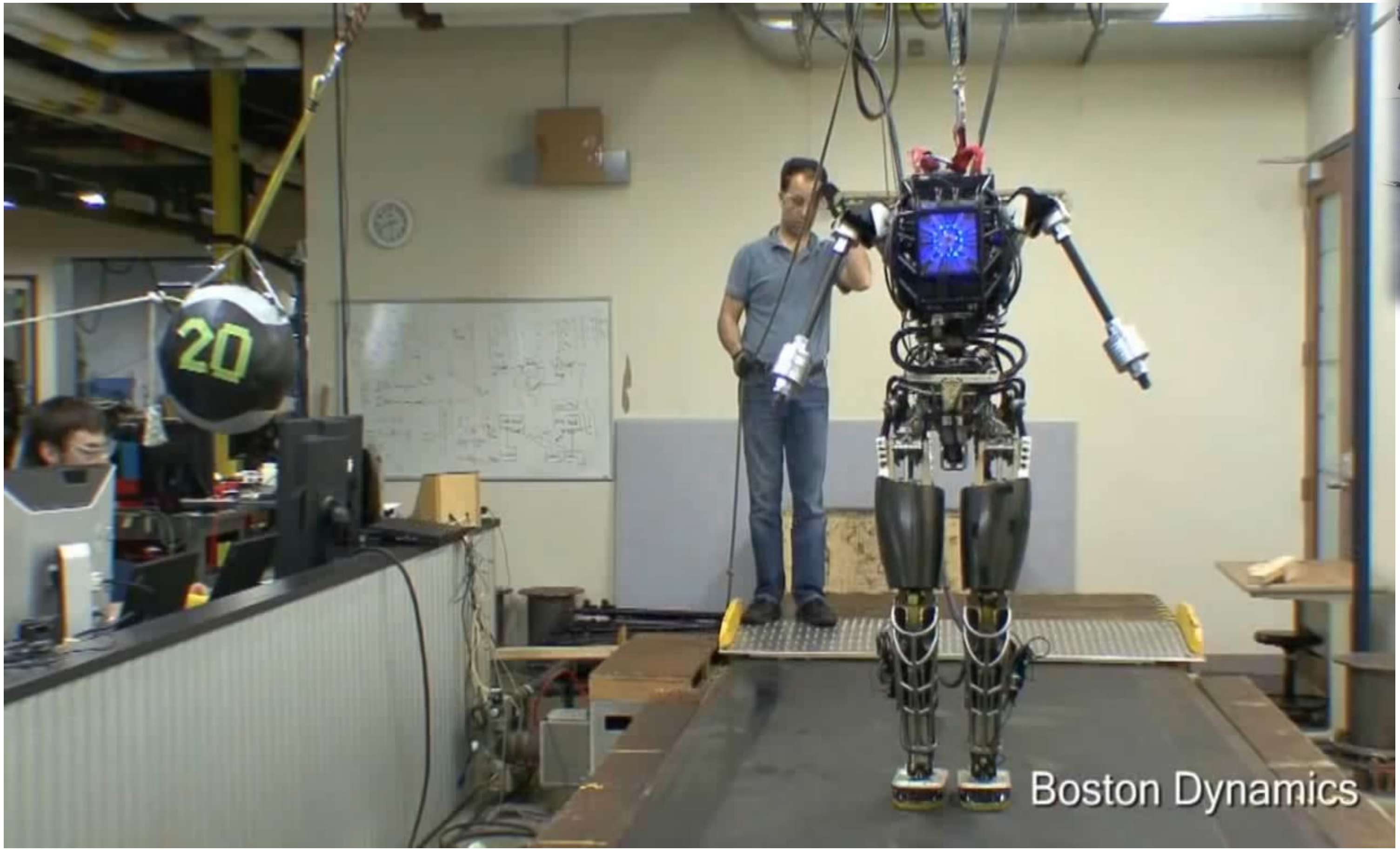
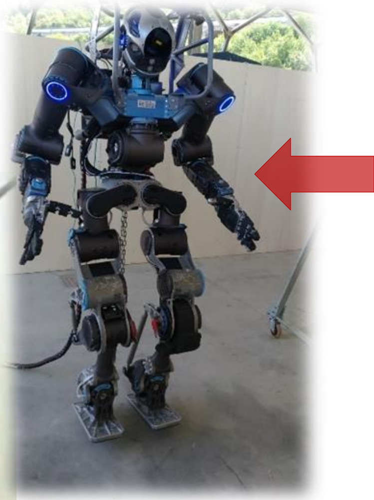
Humanoid resistance to push disturbances

- <u>Metrics: ?</u>





Benchmarking Evaluation Criteria

Stability

Efficiency

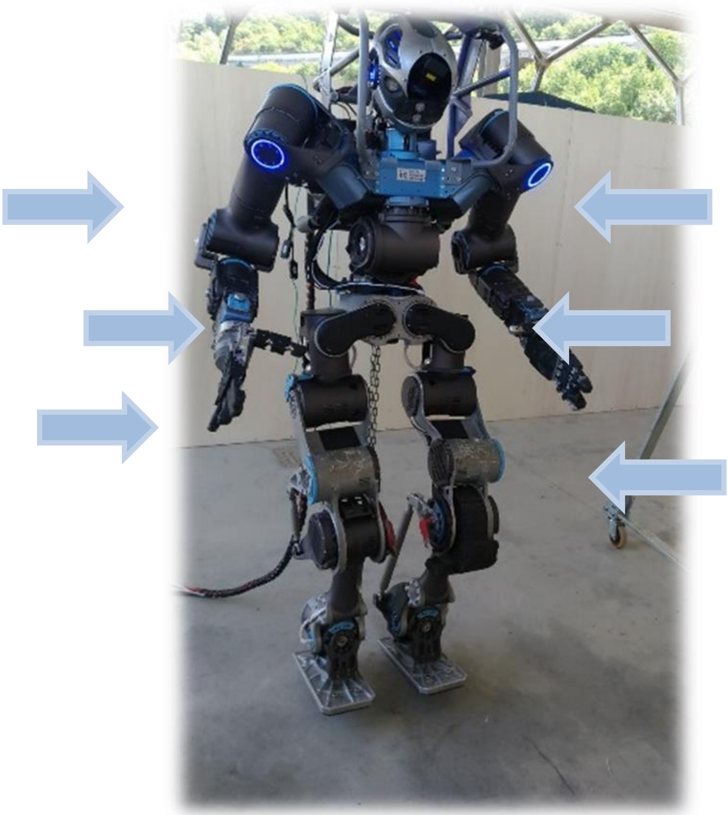
Kinematics

Dynamics

Diego Torricelli, et al, “**Benchmarking Bipedal Locomotion”,** IEEE RAM, 2015

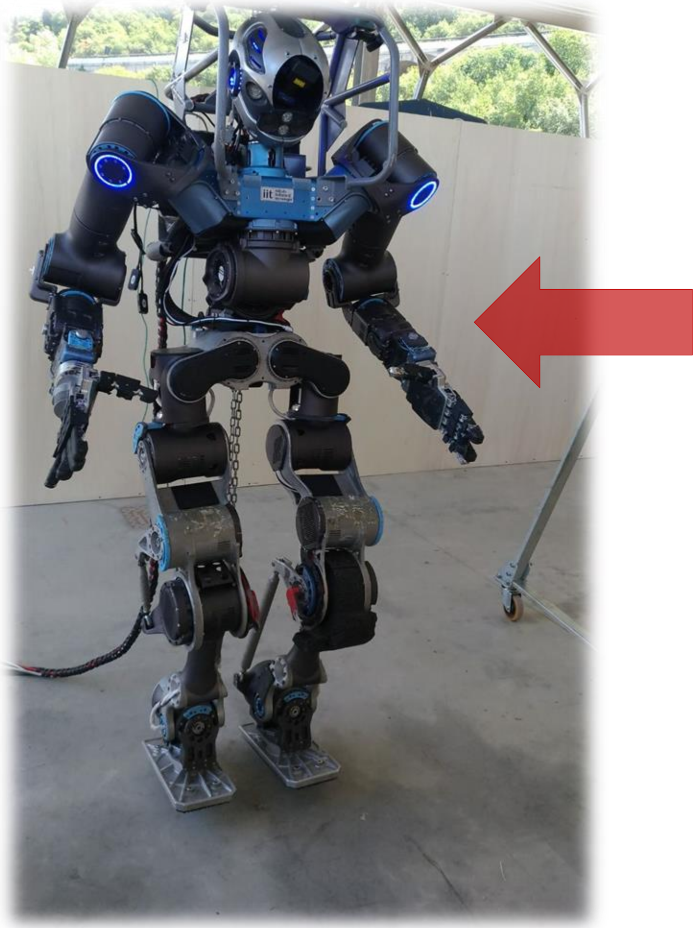
Humanoid resistance to push disturbances

- Metrics:
  - Stability / Success measurement
    - Number/percentage of successful recoveries for each case
    - Balancing recovery classified with respect to the location in the body (three regions are considered)
      - Torso at the level of the shoulder,
      - pelvis area and,
      - along the arms
    - Different directions
      - Frontal, Back
      - and side



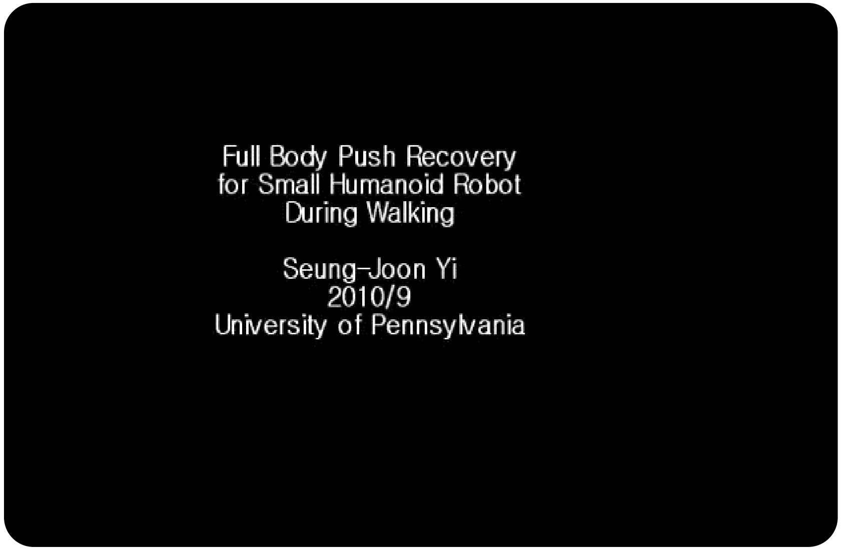
Humanoid resistance to push disturbances

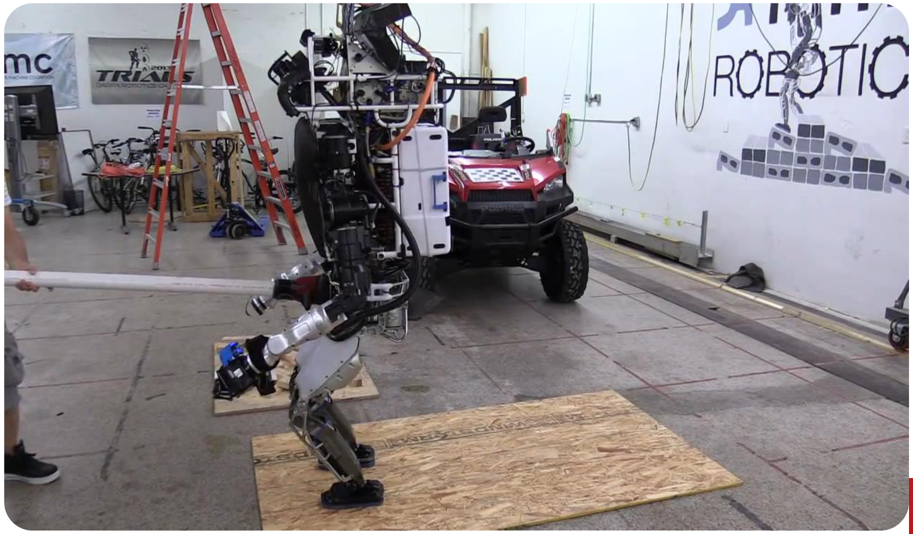
- Metrics:
  - Efficiency / Recovery Effort
    - Control/Joint effort
    - Recovery time
    - Energy consumed / Mechanical work



Benchmarking/Comparison of different hardware

- Direct absolute comparison is not valid
- Normalization
  - Size
  - Dynamics
  - Support polygon
  - …..?

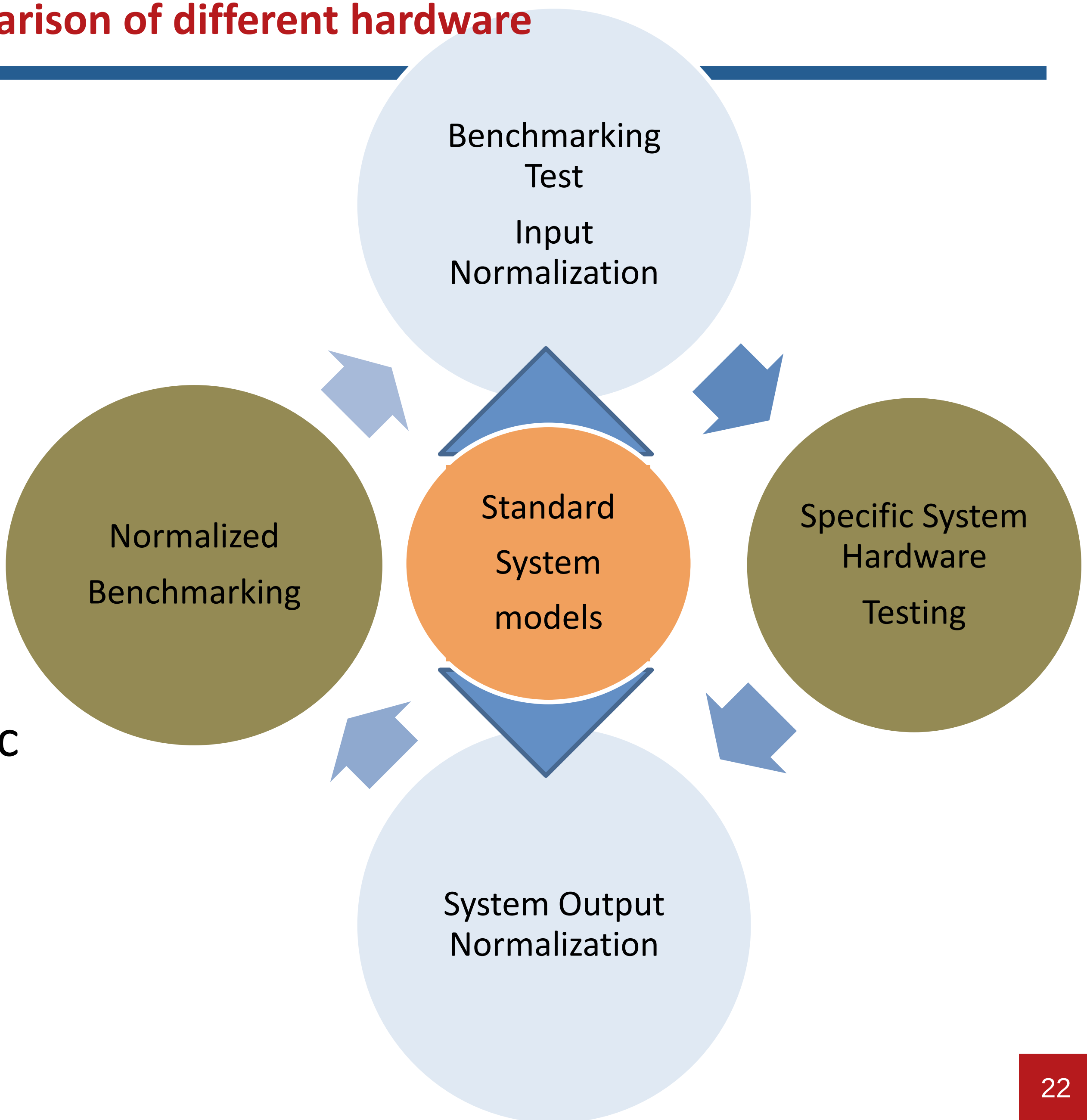




Humanoid resistance to push disturbances

Normalized comparison of different hardware

- Two stages model based normalization process
  - Test Inputs
  - System outputs/mechanical quantities



Normalized Humanoid Resistance to Push disturbance: **Standard model**

- Linear Inverted Pendulum Model (LIPM)
- Default homing pose

Basic constants

M: overall mass

l_0: full leg length

g: gravitational acceleration

z_0: initial COM height

d_0: support polygon dimension

Normalization of mechanical quantities

Quantity	Symbol	Dimension	Normalization by l_0 ($l_0 = l_{leg}$ or z_0)
Mass	m	M	$\hat{m} = \frac{m}{m_0}$
Time	t	T	$\hat{t} = \frac{t}{\sqrt{l_0/g}}$
Frequency	f	T^{-1}	$\hat{f} = \frac{f}{\sqrt{g/l_0}}$
Length	l	L	$\hat{l} = \frac{l}{l_0}$
Velocity	v	LT^{-1}	$\hat{v} = \frac{v}{\sqrt{gl_0}}$
Acceleration	a	LT^{-2}	$\hat{a} = \frac{a}{g}$
Linear Momentum	p	MLT^{-1}	$\hat{p} = \frac{p}{m_0\sqrt{gl_0}}$
Force	F	MLT^{-2}	$\hat{F} = \frac{F}{m_0 g}$
Torque	τ	$\mathrm{ML}^2\mathrm{T}^{-2}$	$\hat{\tau} = \frac{\tau}{m_0 g l_0}$

Quantity	Symbol	Dimension	Normalization by l_0 ($l_0 = l_{leg}$ or z_0)
Inertial	I	ML^2	$\hat{I} = \frac{I}{m_0 l_0^2}$
Angle	θ	(is already dimensionless)	
Angular Velocity	ω	T^{-1}	$\hat{\omega} = \frac{\omega}{\sqrt{g/l_0}}$
Angular Acceleration	$\dot{\omega}$	T^{-2}	$\hat{\dot{\omega}} = \frac{\dot{\omega}}{g/l_0}$
Angular Momentum	L	$\mathrm{ML}^2\mathrm{T}^{-1}$	$\hat{L} = \frac{L}{m_0 g^{1/2} l_0^{3/2}}$
Energy	E	$\mathrm{ML}^{-2}\mathrm{T}^{-2}$	$\hat{E} = \frac{E}{m_0 g l_0}$
Power	P	$\mathrm{ML}^{-2}\mathrm{T}^{-3}$	$\hat{P} = \frac{P}{m_0 g^{3/2} l_0^{1/2}}$

$$\hat{L} = \frac{L}{m_0 g^{1/2} l_0^{3/2}}$$

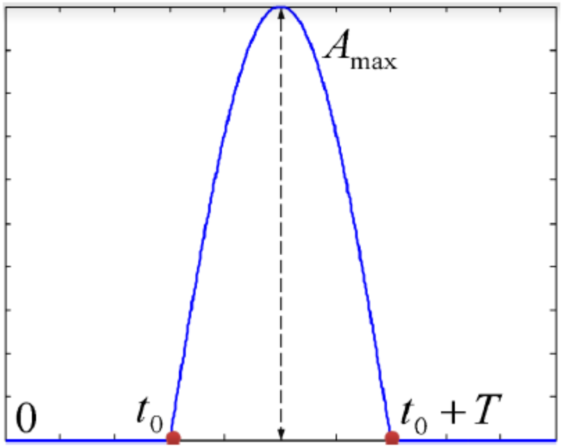
$$\boxed{D_{L_{imp}} = \alpha m_0 l_0 \sqrt{g l_0}}$$

AL Hof, “**Scaling gait data to body size”,** Gait & posture, 1996

Normalized Humanoid Resistance to Push disturbance: **Standard model**

Impulsive Disturbance

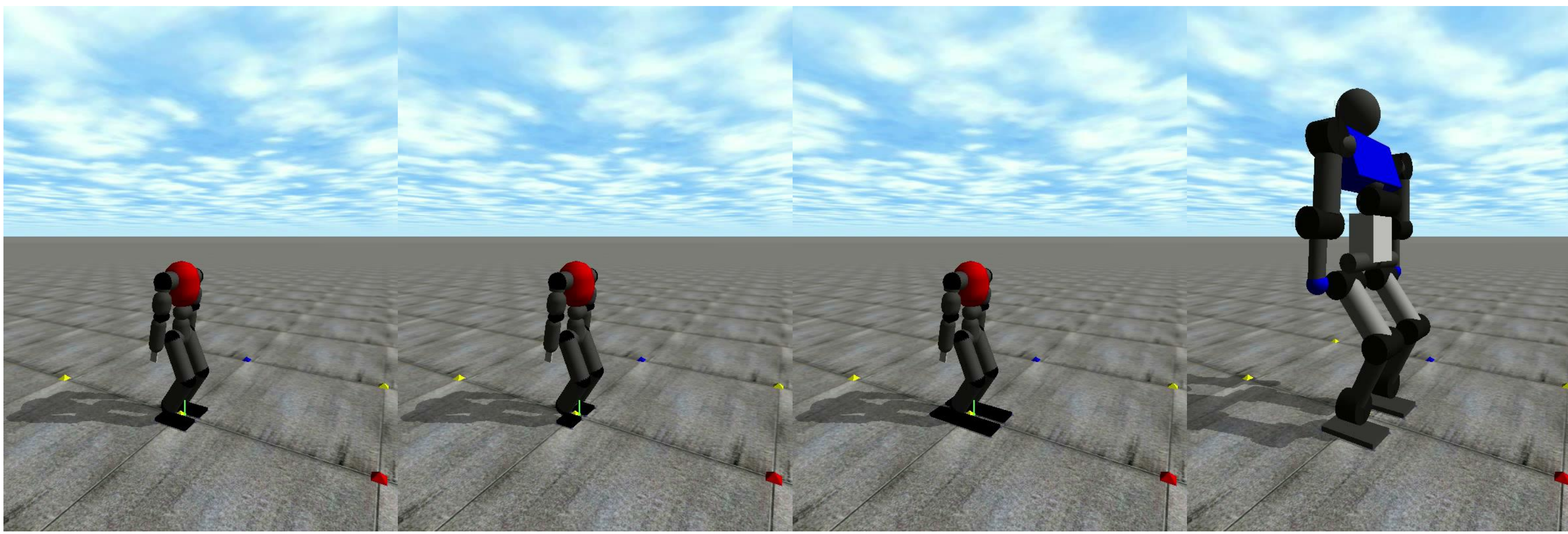
- We define the disturbance as a half sinusoidal impulsive force/torque $F_{imp}(t)$ acting on the robot during a certain period t_{imp}



$$\int_0^{t_{imp}} A_{imp} \sin\left(\frac{\pi t}{t_{imp}}\right) dt = \frac{2 A_{imp} t_{imp}}{\pi}$$

Simulations

Normal COMAN	Half foot length	Double foot length	Walkman
Ang.Mom. : 9.08	Ang.Mom. : 4.34	Ang.Mom. : 18.76	Ang.Mom. : 76.7



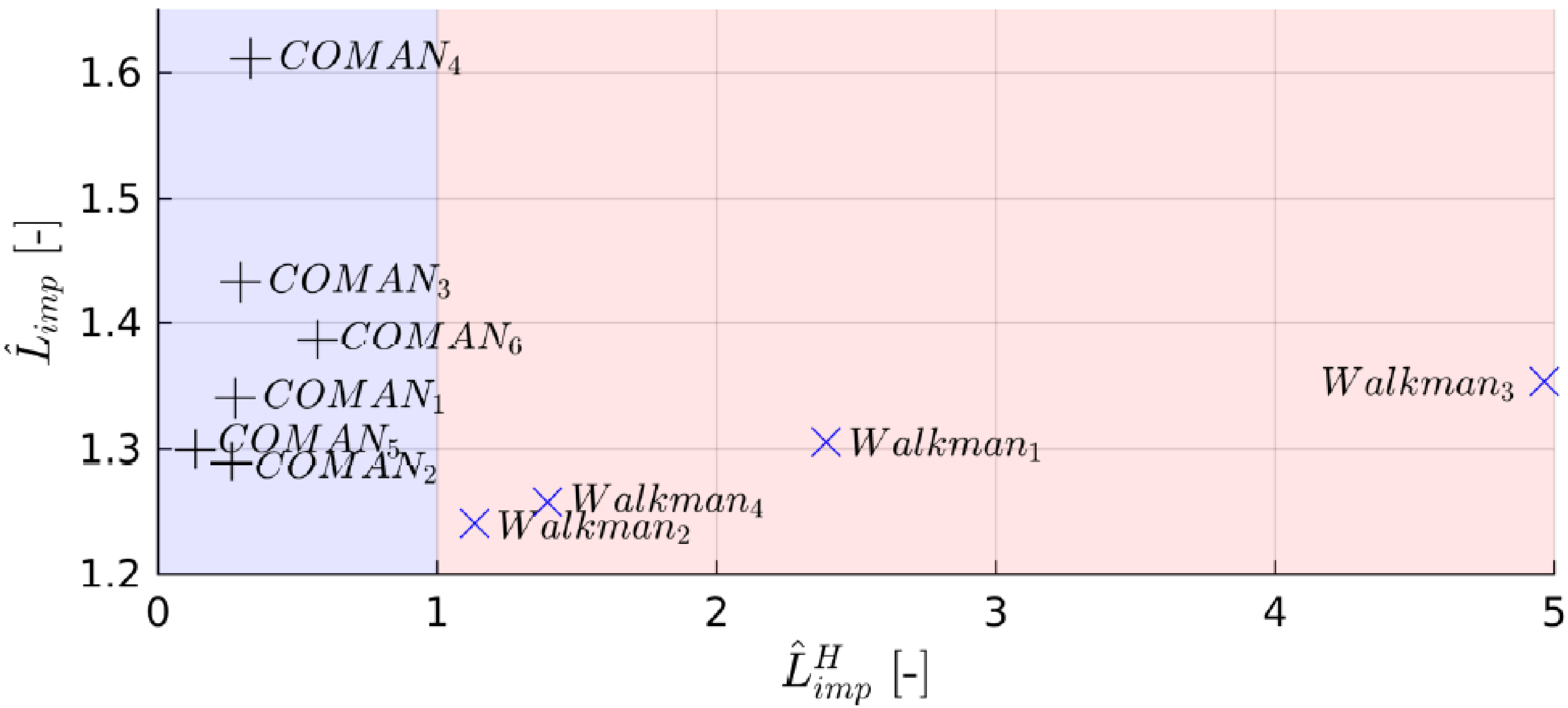
Normalized performance of maximum resistance to push capability

TABLE II: Standing push HBT data of COMAN and Walkman. C_1 is the normal COMAN robot, C_2 is C_1 with stabilizer [6] enabled, C_3 is C_1 with CoM tracking controller enabled, C_4 and C_5 is C_1 with its half and double foot length, respectively. W_1 is the normal Walkman robot, W_2, W_3 and W_4 is W_1 with its half, double foot length and the same α with C_4, respectively.

Quantity	Symbol	Human	C_1	C_2	C_3	C_4	C_5	C_6	W_1	W_2	W_3	W_4
Mass	m_0	70	30.9	←	←	←	←	←	123.375	←	←	←
CoM height	z_0	1	0.492	←	←	←	←	←	0.952	←	←	←
max. CP traveling distance	αz_0	0.15	0.1	←	←	←	0.05	0.2	0.16	0.08	0.32	0.097
max. CP traveling ratio	α	0.15	0.203	←	←	←	0.102	0.407	0.168	0.084	0.336	0.102
Time constant	T_c	0.319	0.224	←	←	←	←	←	0.312	←	←	←
Nominal ang. mom. (11)	$D_{L_{imp}}$	32.887	6.788	←	←	←	3.394	13.576	60.330	30.165	120.660	36.462
Impact applied height	l^*_{imp}		0.498	←	←	←	←	←	1.0712	←	←	←
Impact duration	t_{imp}		0.112	←	←	←	←	←	0.156	←	←	←
Impact force amp.	F^*_{imp}		256.324	246.465	273.823	308.082	124.157	529.909	741.499	351.854	1536.769	430.958
Equi. force at CoM	F_{imp}		259.419	249.441	277.129	311.802	125.656	536.300	834.238	395.860	1728.972	484.858
Impact ang. mom. (4)	L_{imp}		9.099	8.749	9.720	10.936	4.407	18.810	78.733	37.384	163.281	45.789
Normalized ang. mom. to LIPM	$\hat{D}_{L_{imp}}$		**1.340**	**1.289**	**1.432**	**1.611**	**1.299**	**1.386**	**1.305**	**1.239**	**1.353**	**1.256**
Normalized ang. mom. to Human	$\hat{D}^H_{L_{imp}}$	**1.0**	**0.277**	**0.266**	**0.296**	**0.333**	**0.134**	**0.572**	**2.394**	**1.134**	**4.965**	**1**[illegible]

Normalized performance of maximum resistance to push capability

x-axis : Normalized with Human data
y-axis: Normalized with simplified LIP model



Summary of preliminary results

- The distinct bigger size and heavier mass, Walkman
  - could withstand more than 8.5 times absolute angular momentum than COMAN
  - but it is slightly worse in normalized performance.
- Bigger foot size increase the robot’s balancing capability either in terms of absolute or normalized performance.
- With the compliant stabilizer enabled, the robot’s capability decreased.
- Using active balancing controller, the robot’s capability increased.

Acknowledgement

Questions?

WALK-MAN

CoGiMon

eurobench
European robotic framework for bipedal locomotion benchmarking