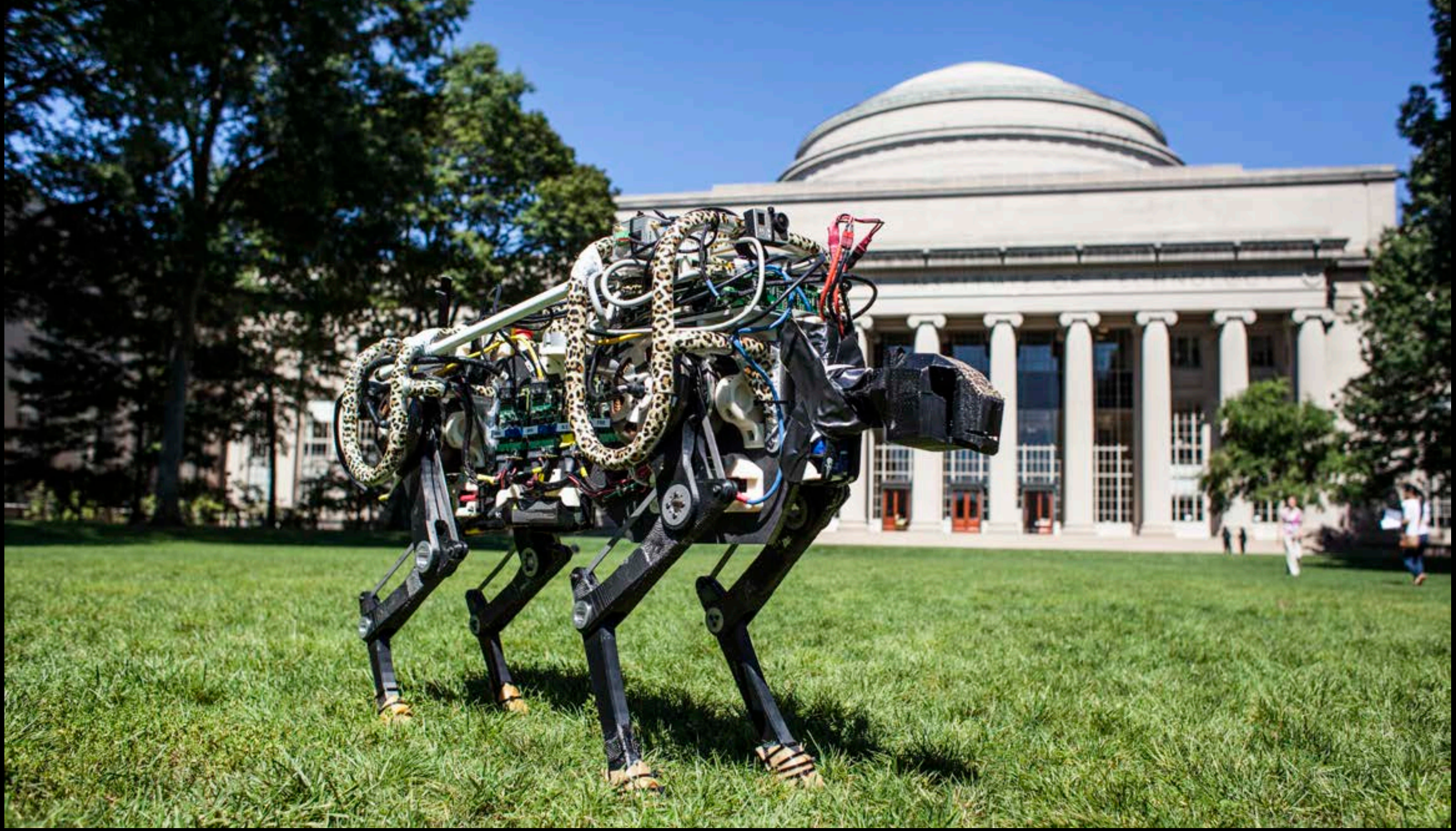


MIT Cheetah : a new design paradigm for physical interaction

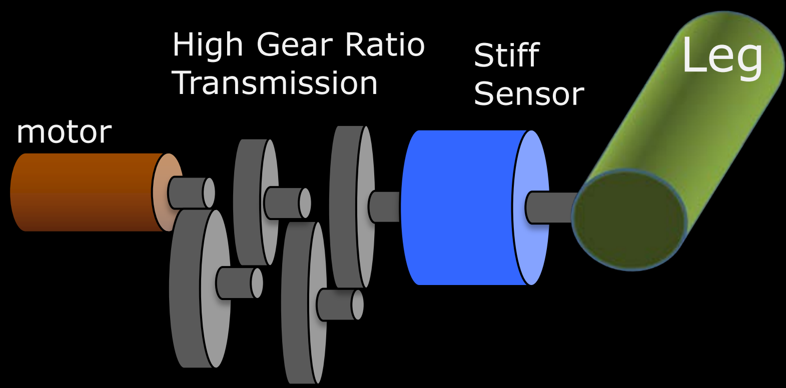
Sangbae Kim
Associate professor
Mechanical Engineering, MIT

Air, Water, and Ground Mobility

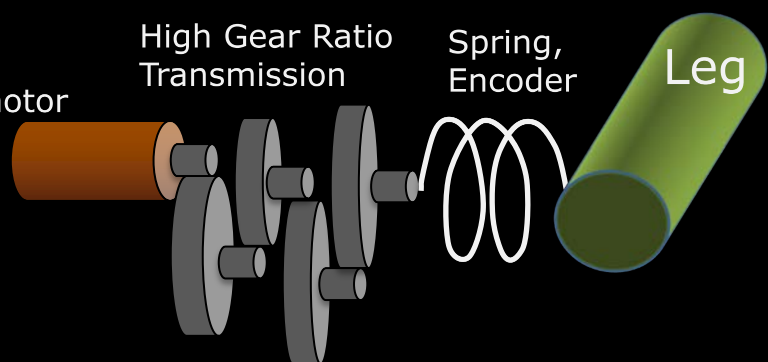
	Air	Water	Ground
Gravity support	Change of air momentum	Buoyancy	Contact force
Propulsion	Change of air momentum	Change of water momentum	Contact force (friction)
Medium	Very low impedance (complex flow)	Low impedance (complex flow)	High impedance (complex geometry)

High Force Proprioceptive Actuation

Maintain force transparency in transmission

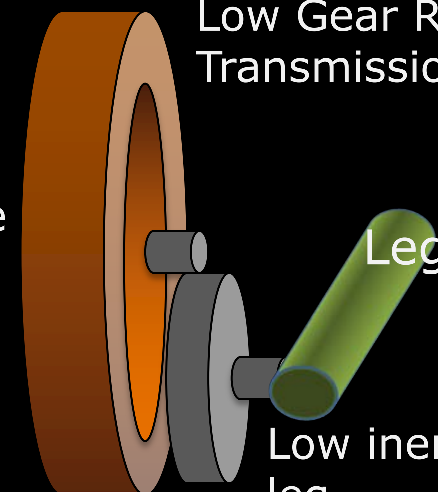


Geared Motor with Torque(Force) Sensor



Series Elastic Actuator

Proprioceptive Actuation



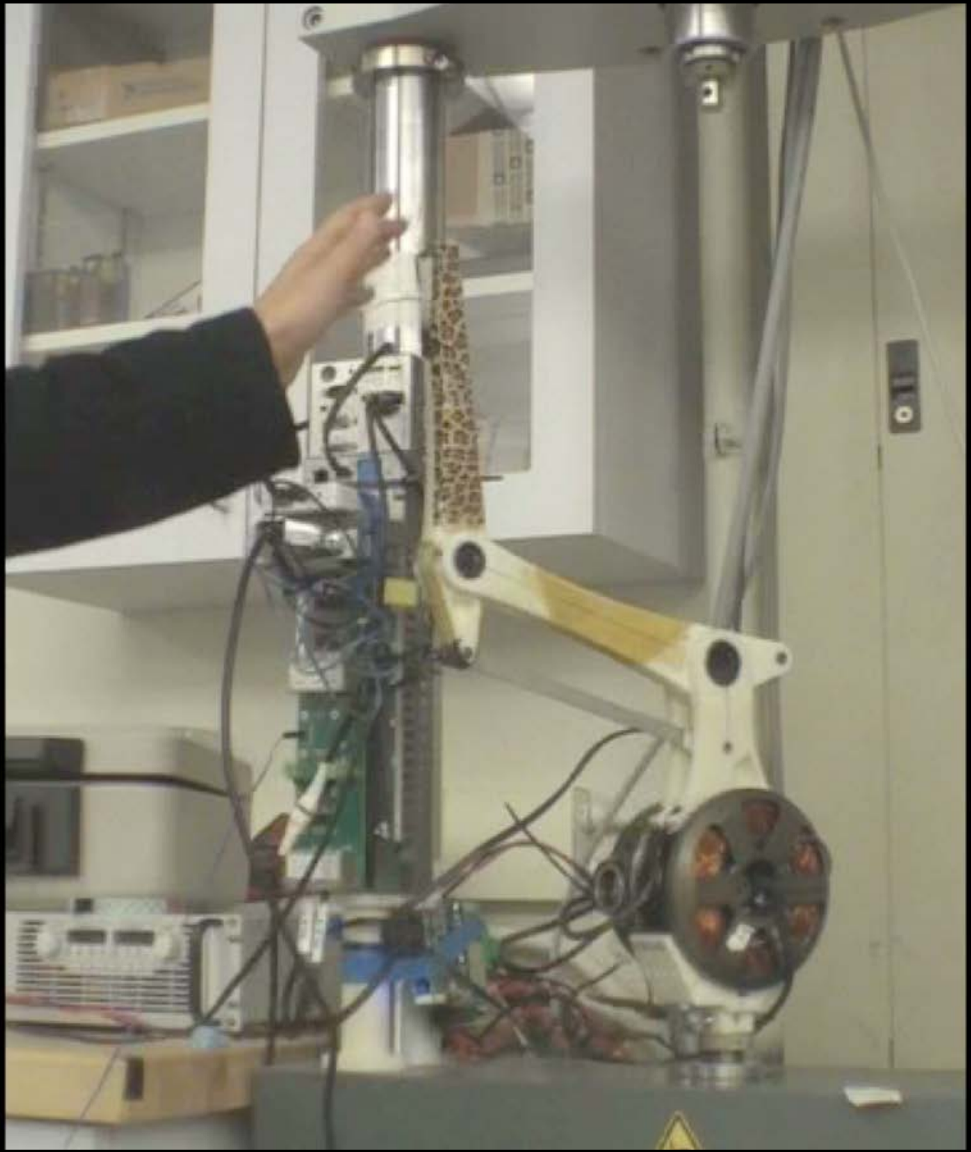
No Force(Torque) Sensor
No Series Elastic

Proprioceptive actuation

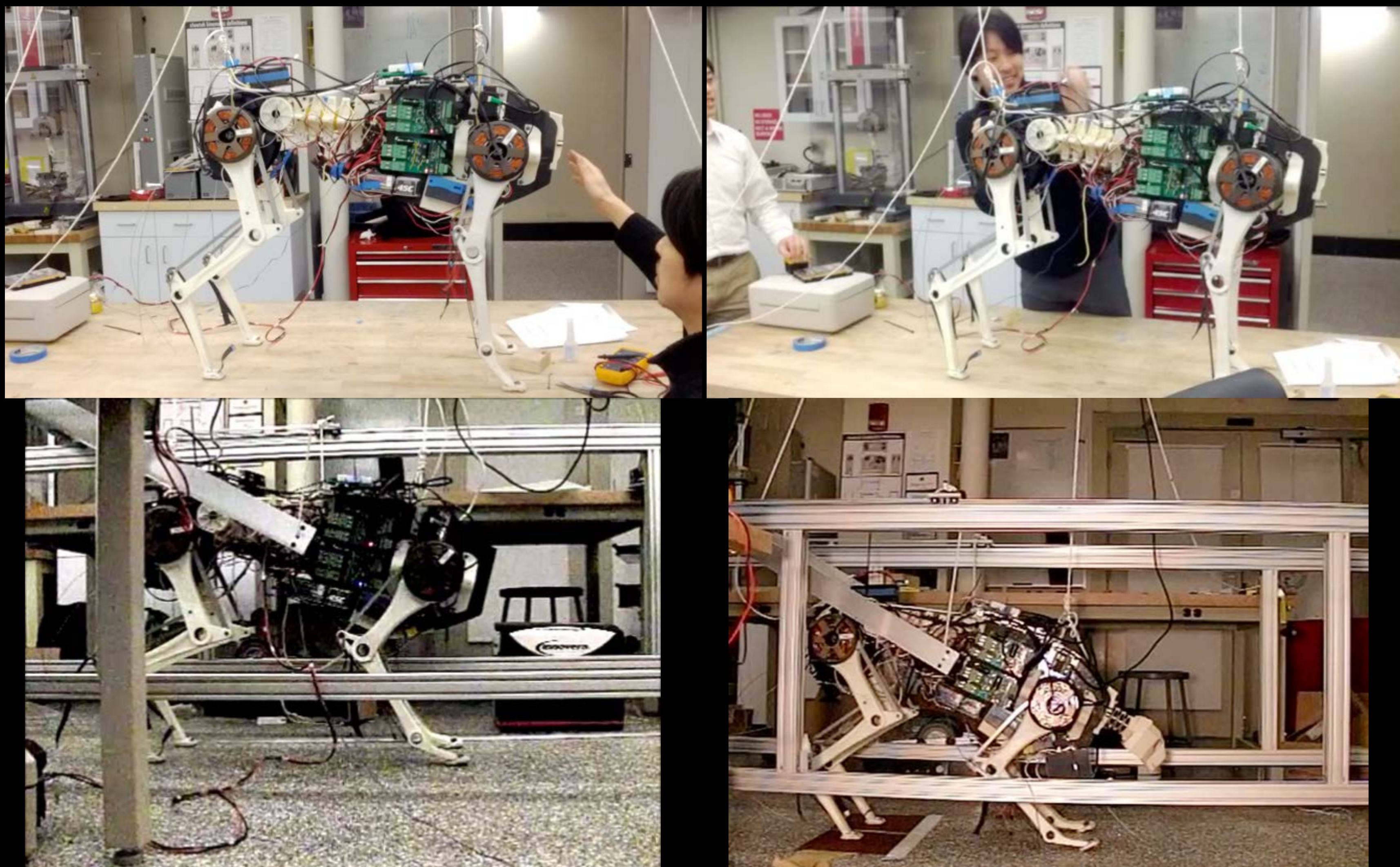
Impedance control for physical-interaction

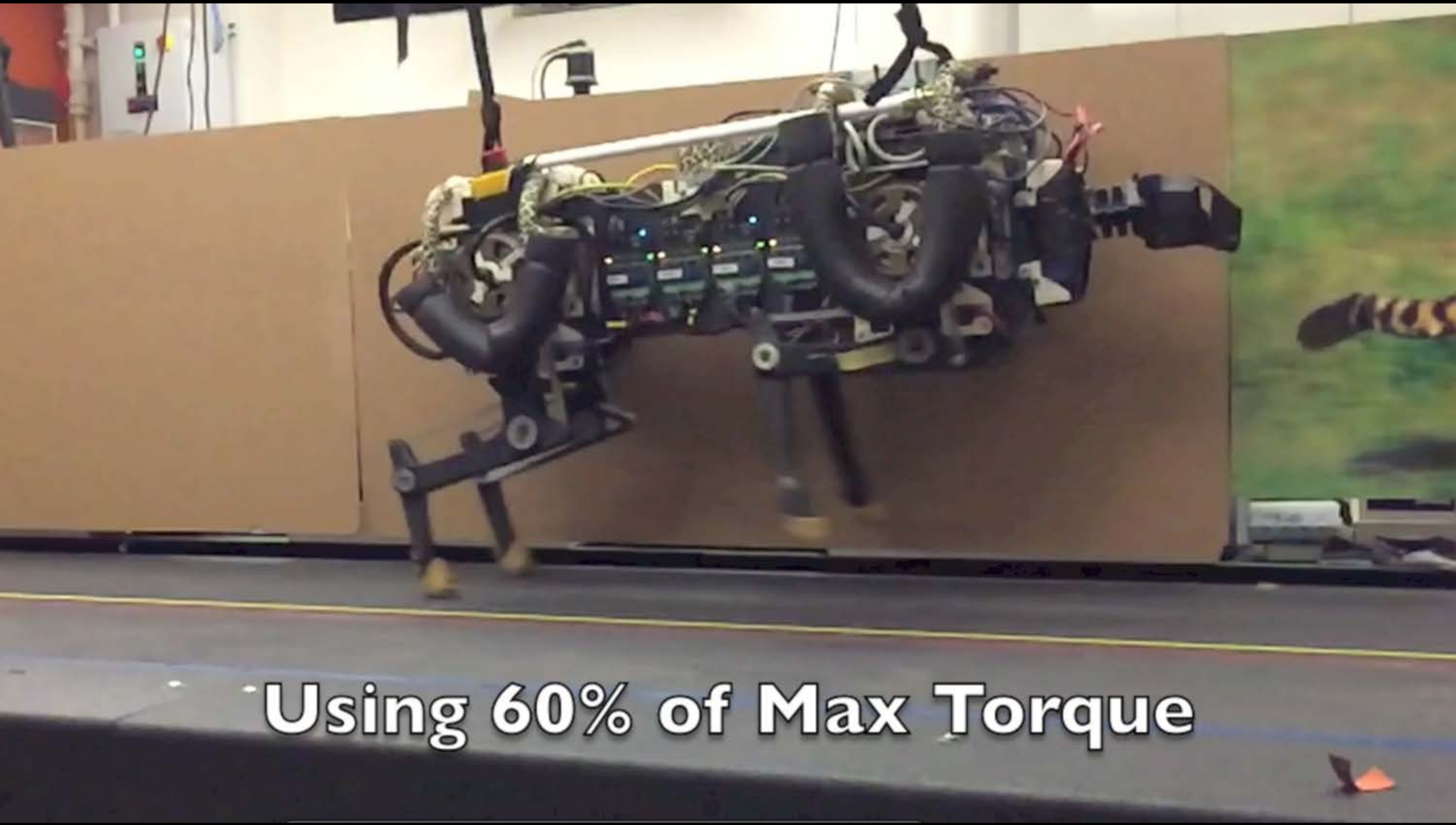
1. Minimum distal mass
2. Max. torque density
   – Min. mechanical impedance
3. Proprioceptive control (collocated sensing, no force sensors)

Phantom – Haptic display device
Kenneth Salisbury



MIT Cheetah I (2010~2013)



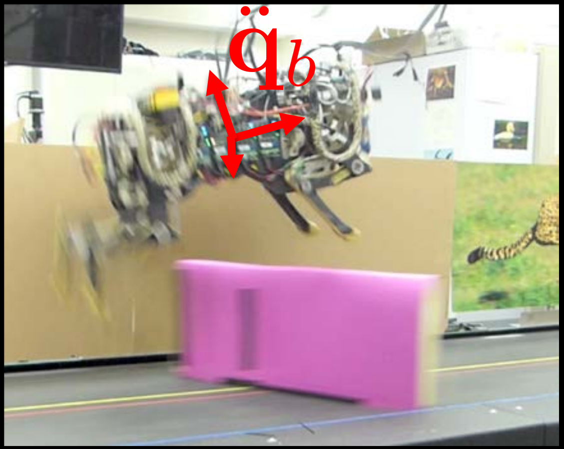

Using 60% of Max Torque

Impact Mitigation Factor (IMF)

- **Equations of Motion**

$$\mathbf{H}\ddot{\mathbf{q}} + \mathbf{h}(\mathbf{q}, \dot{\mathbf{q}}) = \mathbf{S}^T \boldsymbol{\tau} + \mathbf{J}^T \mathbf{f}$$

$$\begin{bmatrix} \mathbf{H}_{bb} & \mathbf{H}_{bj} \\ \mathbf{H}_{jb} & \mathbf{H}_{jj} \end{bmatrix} \begin{bmatrix} \ddot{\mathbf{q}}_b \\ \ddot{\mathbf{q}}_j \end{bmatrix} + \mathbf{h}(\mathbf{q}, \dot{\mathbf{q}}) = \begin{bmatrix} \mathbf{0} \\ \boldsymbol{\tau} \end{bmatrix} + \begin{bmatrix} \mathbf{J}_b^T \\ \mathbf{J}_j^T \end{bmatrix} \mathbf{f}$$



- **Impact:**

$$\hat{\mathbf{f}} = -\left(\mathbf{J}\mathbf{H}^{-1}\mathbf{J}^T\right)^{-1} \mathbf{v}$$

$$= -\boldsymbol{\Lambda}\mathbf{v} \qquad (\boldsymbol{\Lambda}\text{: Operation space mass matrix})$$

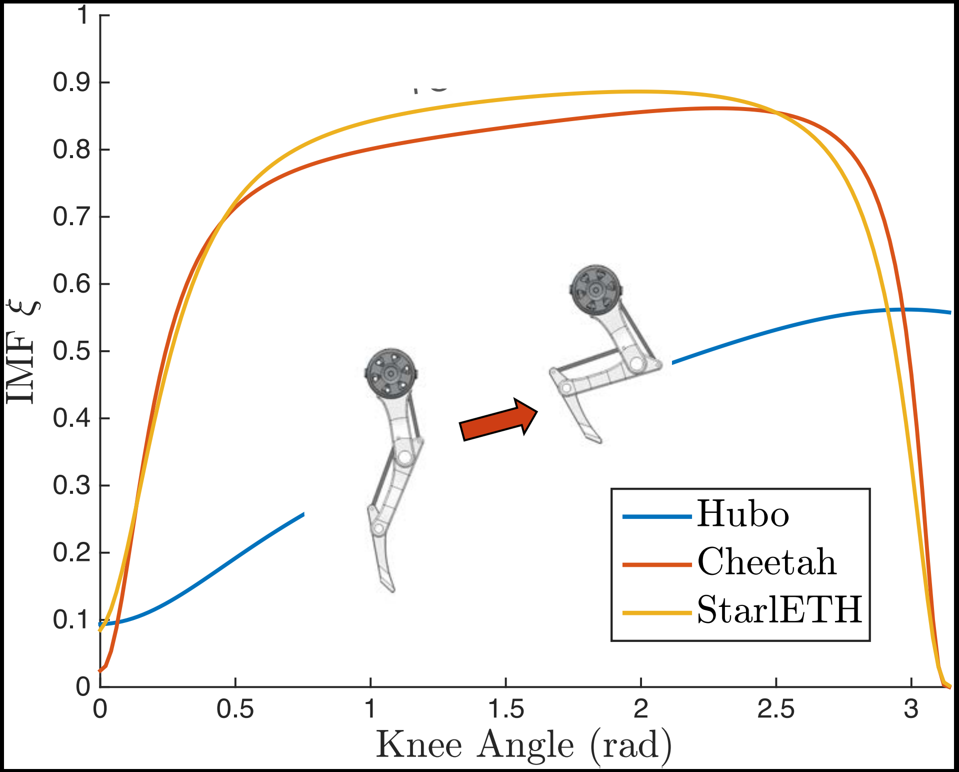
- **Worst Case:** $\boldsymbol{\Lambda}_L = \left(\mathbf{J}_b \mathbf{H}_{bb}^{-1} \mathbf{J}_b^T\right)^{-1}$ $\qquad \boldsymbol{\Lambda}_L \succeq \boldsymbol{\Lambda}$

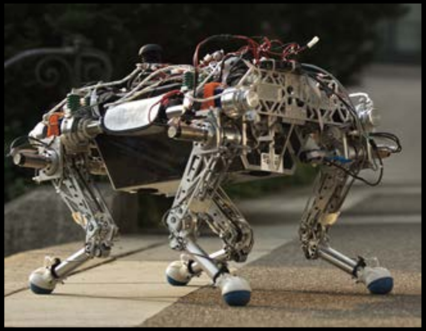
- **IMF =** $\det(\mathbf{I} - \boldsymbol{\Lambda}\boldsymbol{\Lambda}_L^{-1})$ **(0~1)**

[Wensing, et. al *IEEE TRO*]

IMF

- Impact Mitigation Factor: $\xi = \det(\mathbf{I} - \mathbf{\Lambda}\mathbf{\Lambda}_L^{-1})$

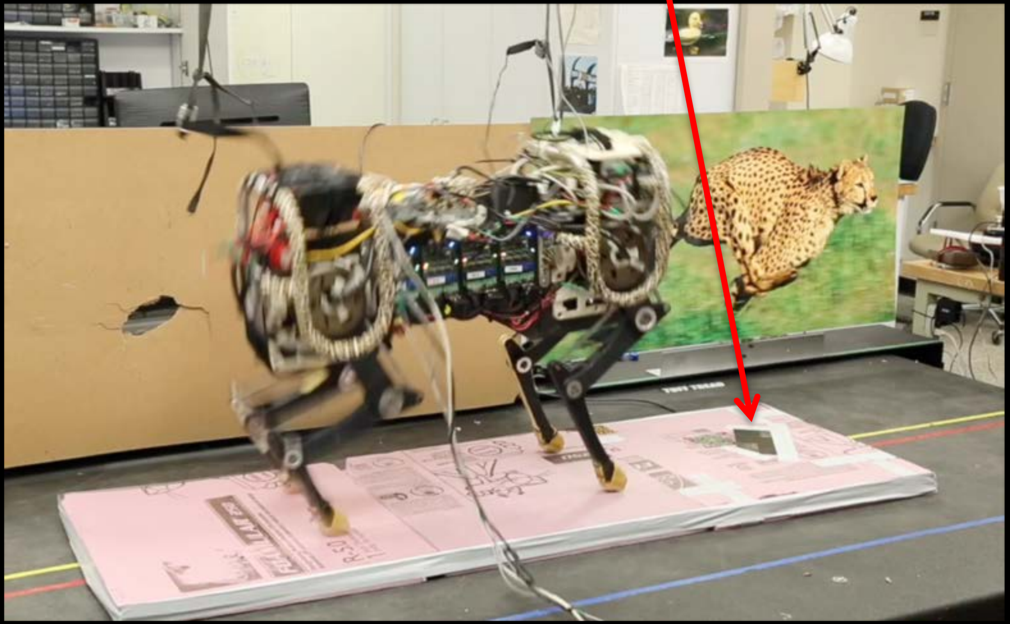


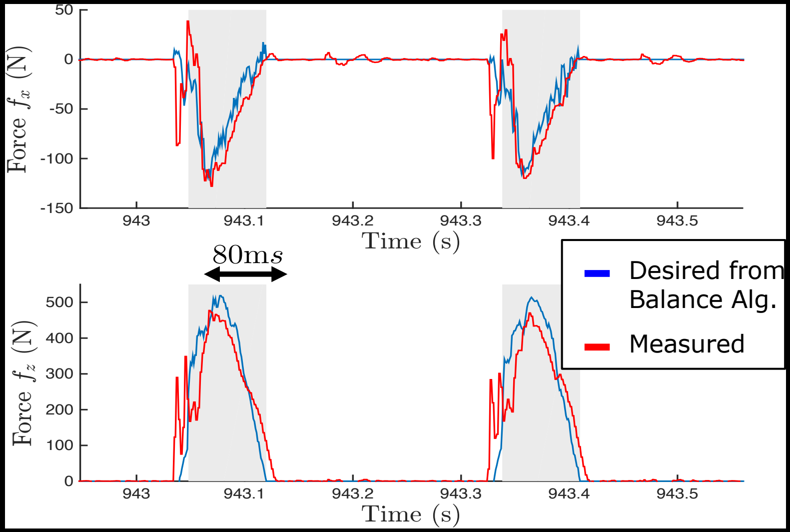


[Wensing, et. al *IEEE TRO*]

High torque/bandwidth actuation

Load Cell

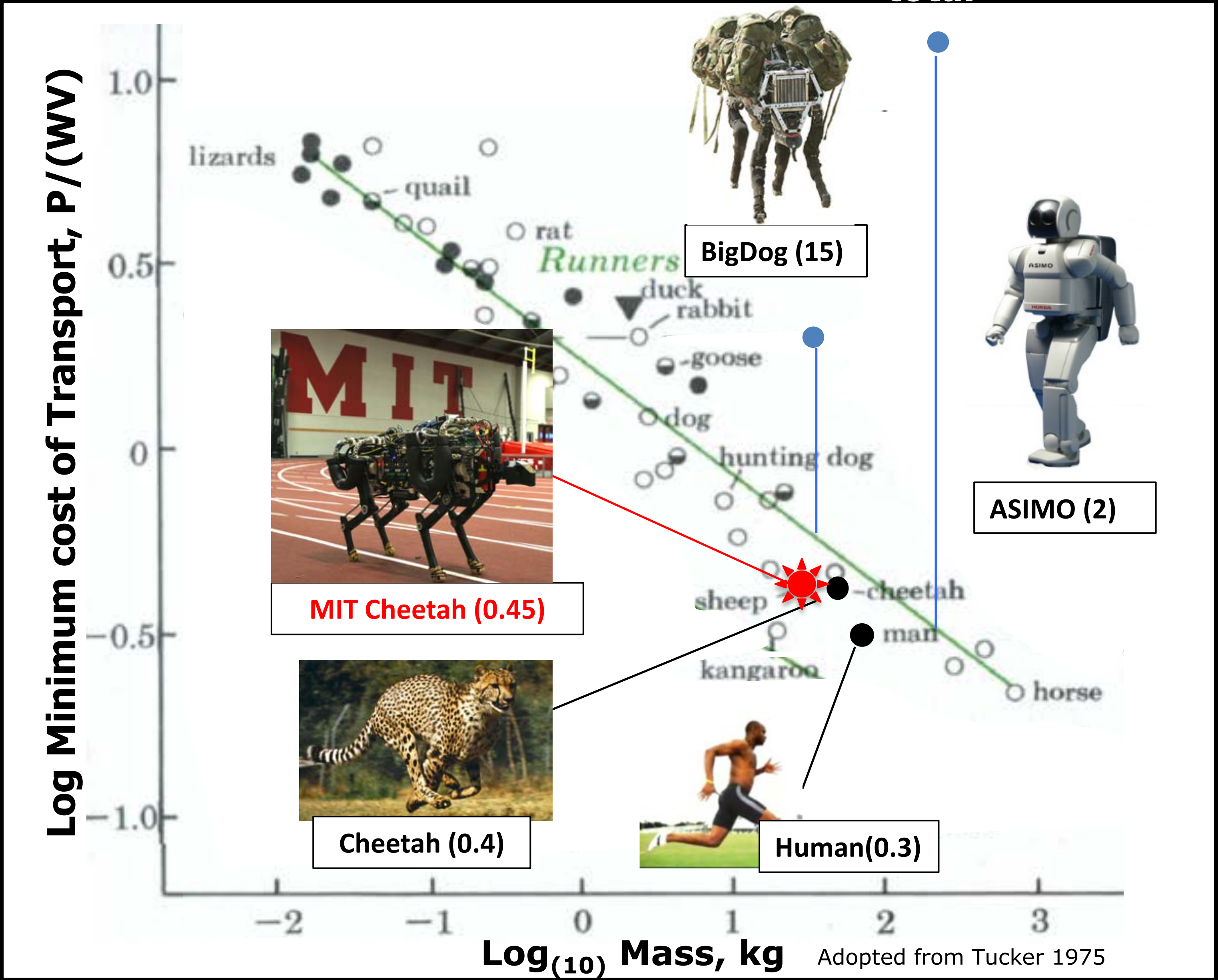




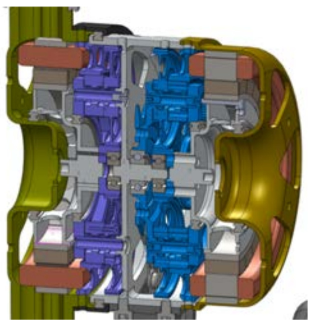
- High Impact Mitigation Factor (IMF)
- High torque density
- Hierarchical software architecture

Custom developed motor in collaboration with Jeff Lang

Total Cost of Transport (P_{total}/WV)



MIT Cheetah 3

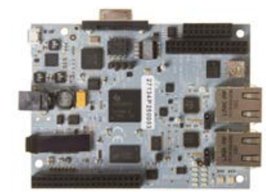


Custom dual power module

Weight : 40kg
Length : 80cm
Leg length : 70cm
Width: 46cm
Max. Torque at joints: 230 – 250 Nm
Transmission: Compound planetary 10.7:1
Payload: 10kg
Power consumption : 150W at 0.5m/s
Vertical jumping height (simulated) : 1.5m

Real sense +jetson board

Motion control module

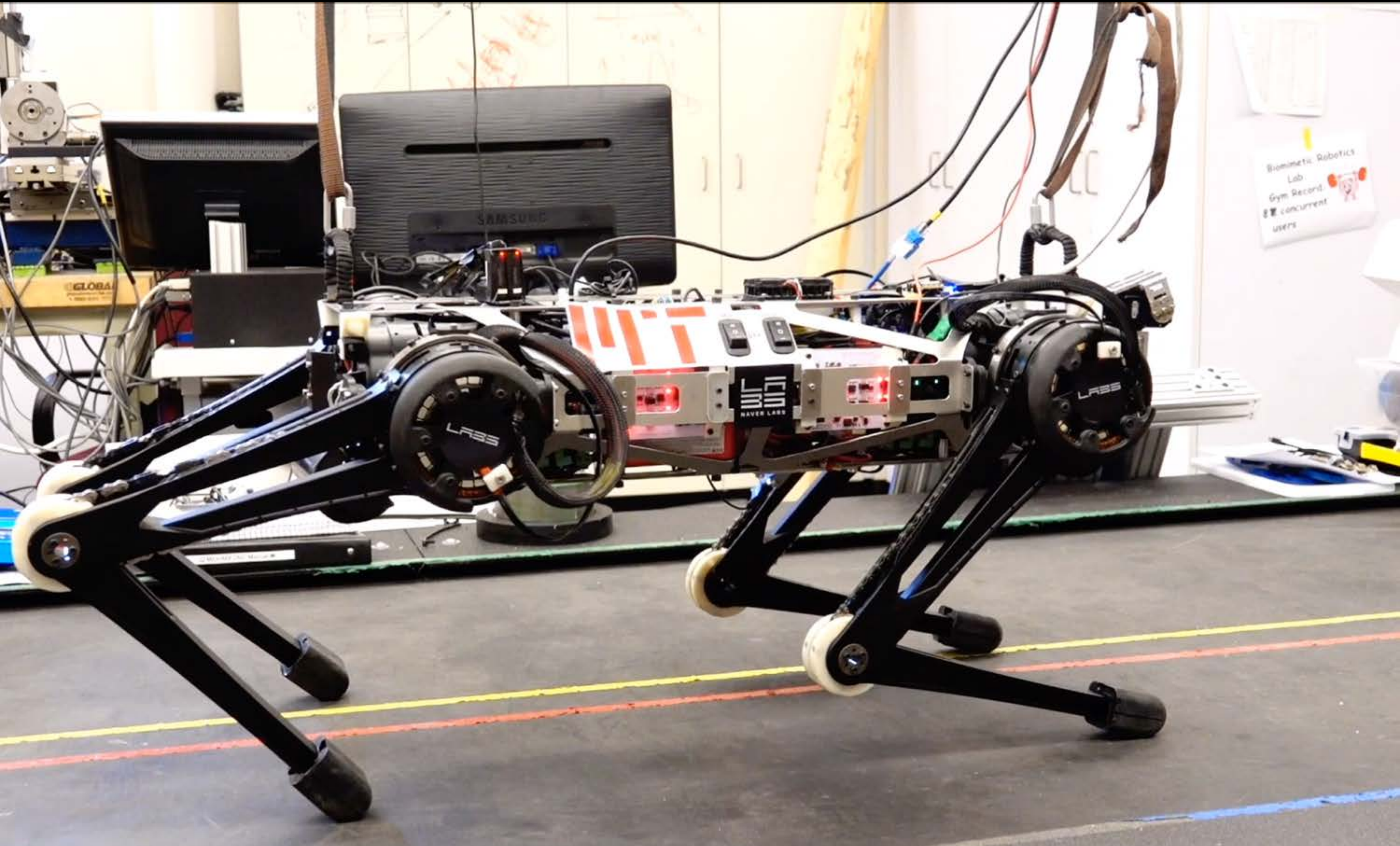


X 4

Leg control module

X 12

Motor module with Custom high torque electric motor


SAMSUNG
NAVER LABS

Probabilistic Contact Motion Model

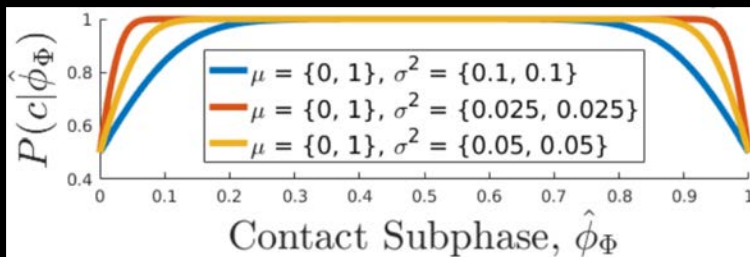
Stance Phase Contact Modell

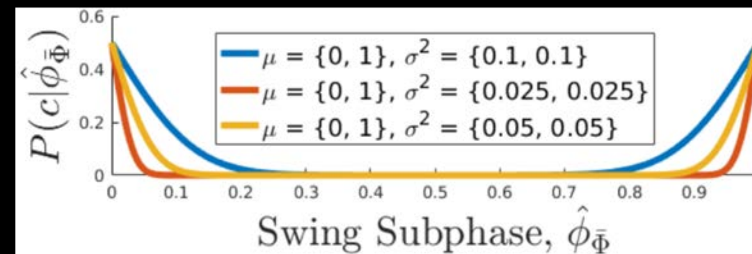
Probabilistic measure of when contact is broken given that it is in stance already

Swing Phase Contact Model

Probabilistic measure of when contact is made given that it is in swing

$$P_f(c|\Phi,\hat{\phi}) = \frac{1}{2}\left(\Phi\left[erf\left(\frac{\hat{\phi}-\mu_{c_0}}{\sigma_{c_0}\sqrt{2}}\right) + erf\left(\frac{(-\hat{\phi})-(-\mu_{c_1})}{\sigma_{c_1}\sqrt{2}}\right)\right] + \bar{\Phi}\left[2 + erf\left(\frac{(-\hat{\phi})-(-\mu_{\bar{c}_0})}{\sigma_{\bar{c}_0}\sqrt{2}}\right) + erf\left(\frac{\hat{\phi}-\mu_{\bar{c}_1}}{\sigma_{\bar{c}_1}\sqrt{2}}\right)\right]\right)$$

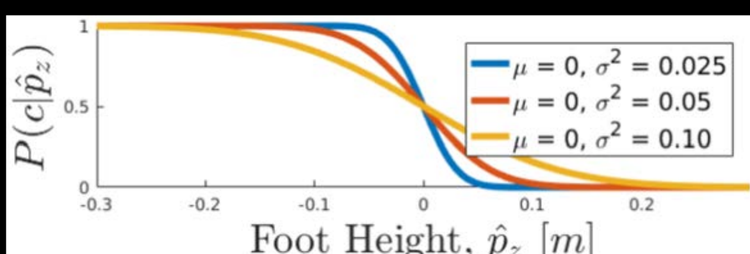




Ground Height Model

Probabilistic measure of ground height with roughness signified by the variance

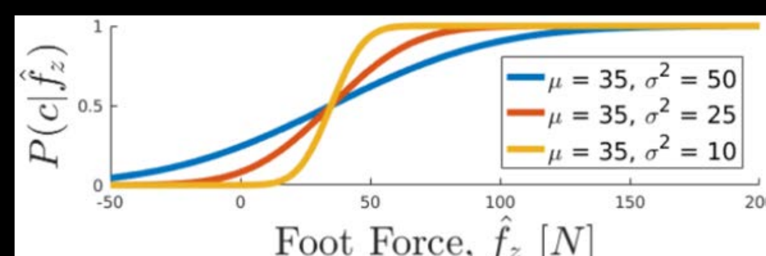
$$P_f(c|\hat{p}_z) = \frac{1}{2}\left[1 + erf\left(\frac{(-\hat{p}_z)-(-\mu_{z_g})}{\sigma_{z_g}\sqrt{2}}\right)\right]$$



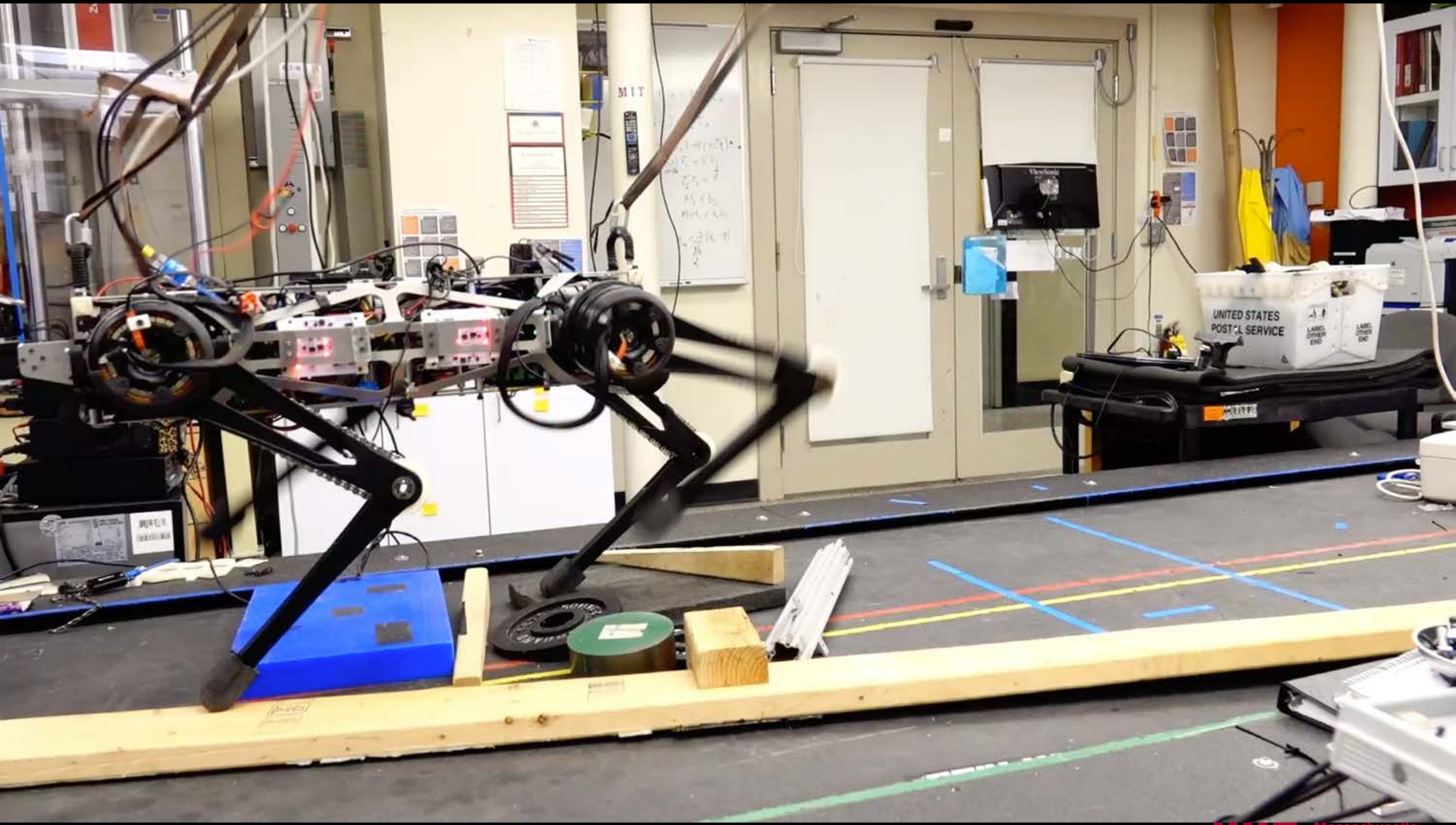
Force of Contact Model

Probabilistic measure of typical sensed force at initial contact

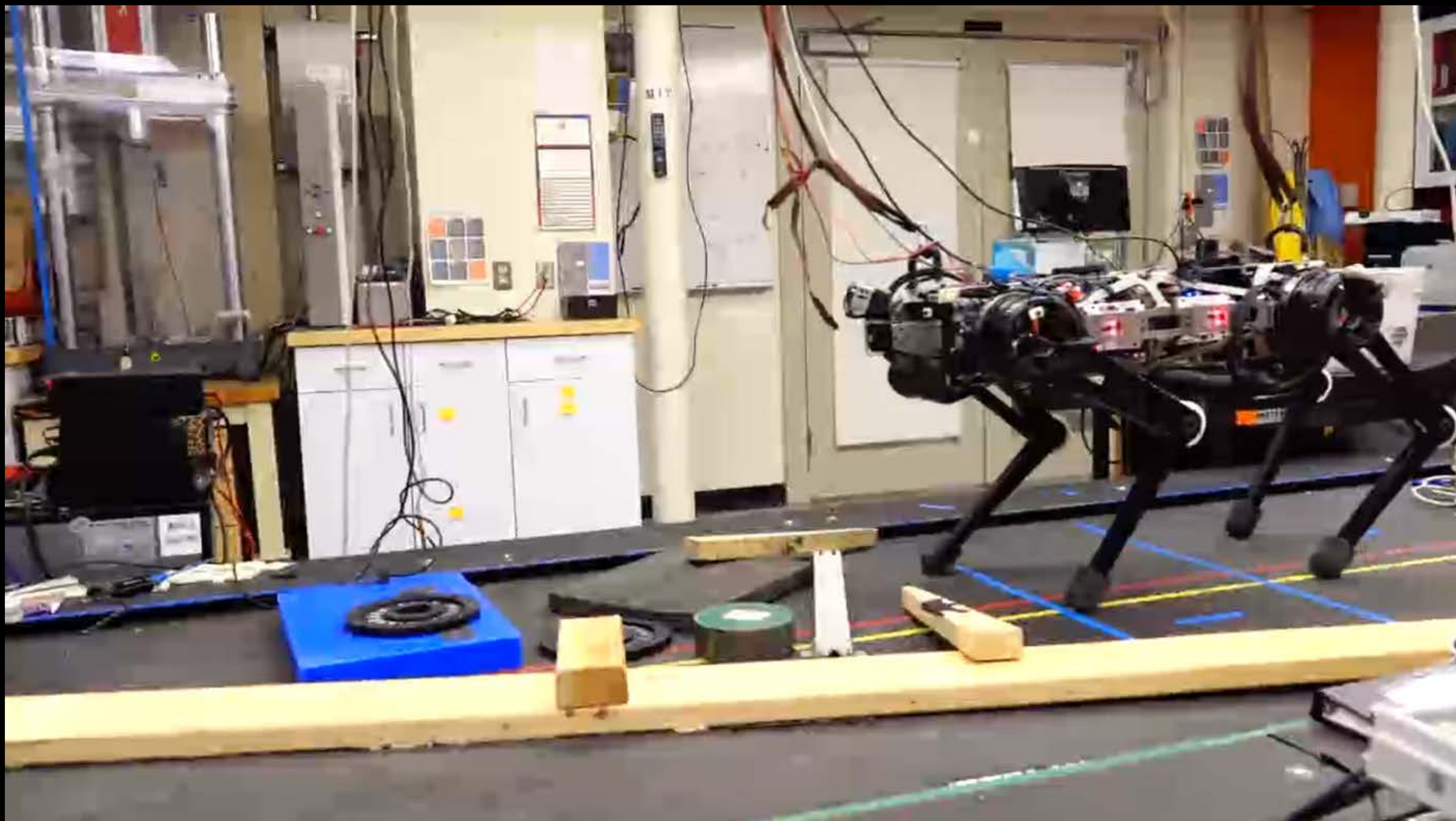
$$P_f(c|\hat{f}_z) = \frac{1}{2}\left[1 + erf\left(\frac{\hat{f}_z-\mu_{f_c}}{\sigma_{f_c}\sqrt{2}}\right)\right]$$

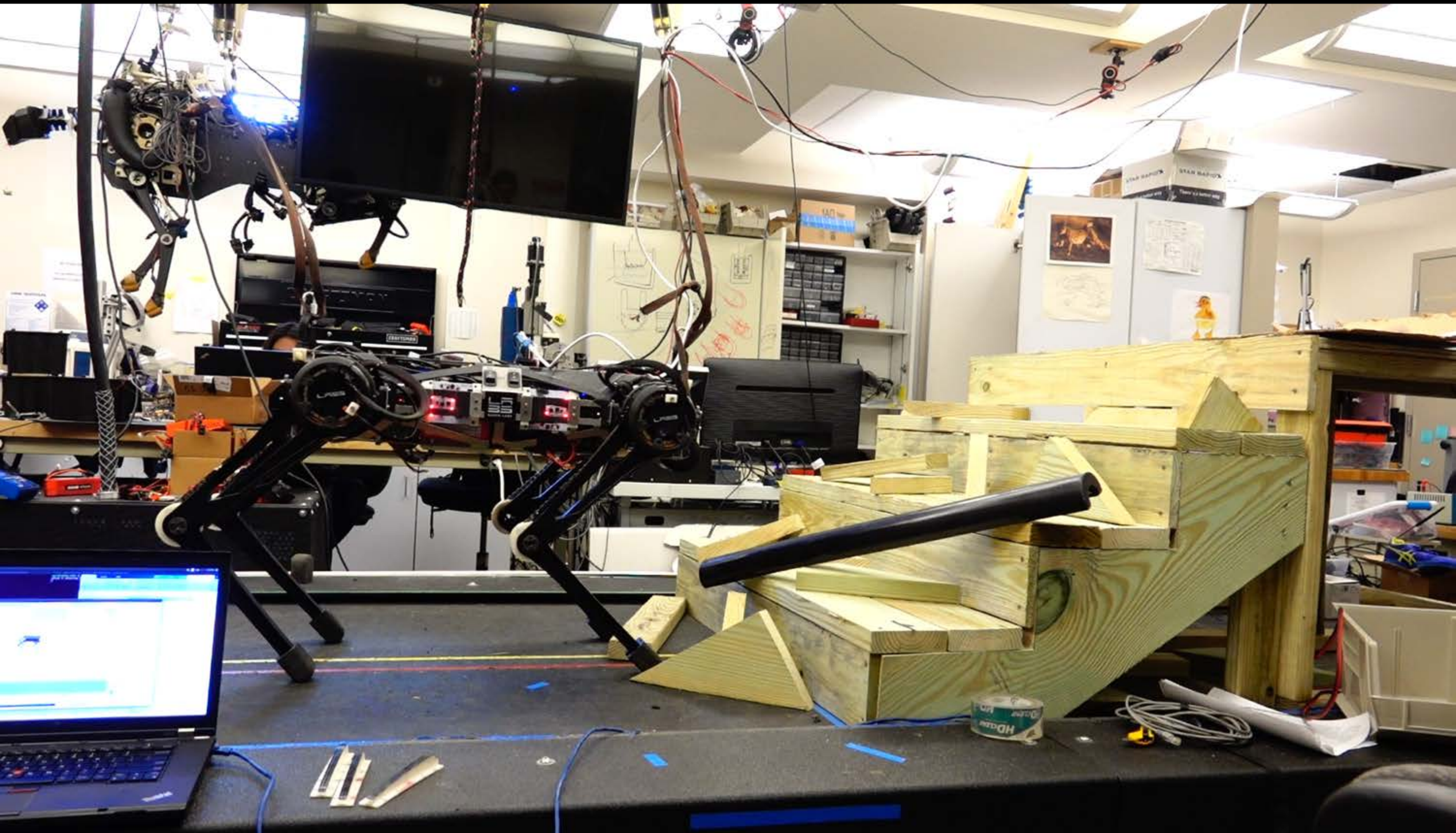


Contact uncertainties

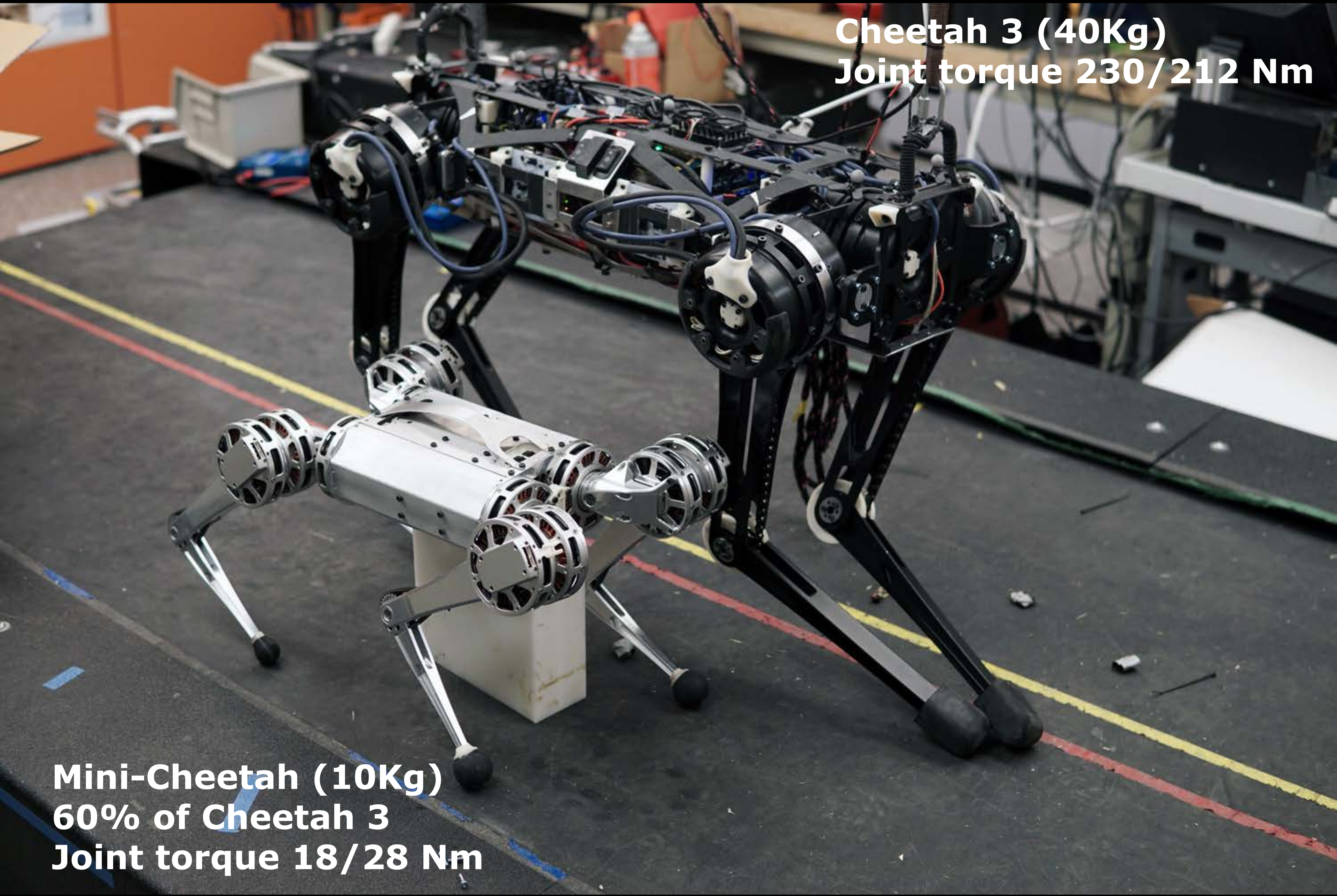


Event-based switching

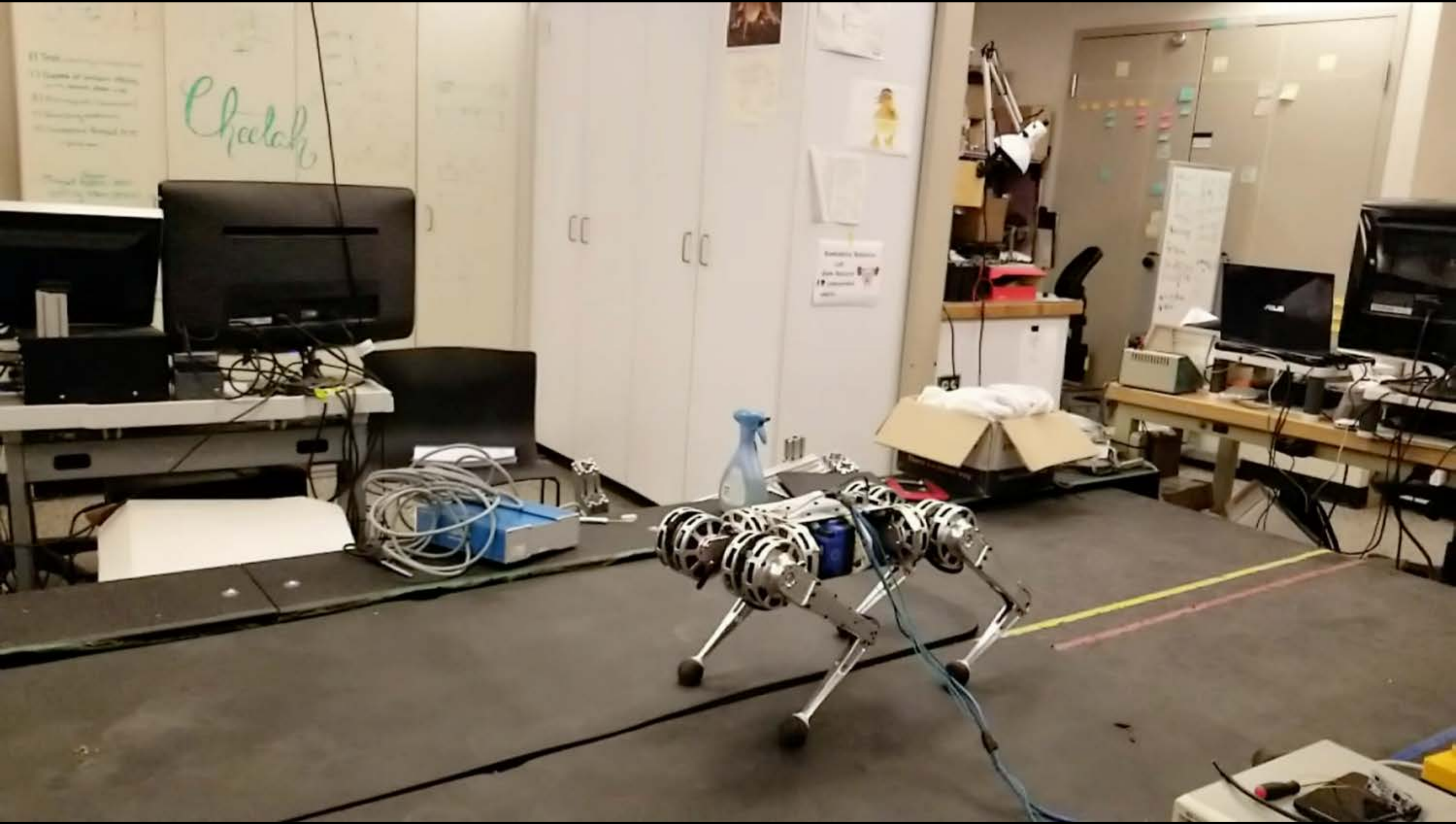




Outdoor


Cheetah 3 (40Kg)
Joint torque 230/212 Nm
Mini-Cheetah (10Kg)
60% of Cheetah 3
Joint torque 18/28 Nm

Mini Cheetah



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Humanoid Dynamic Synchronization through Whole-Body Bilateral Feedback Teleoperation

Joao Ramos, and Sangbae Kim

MITMECHE
BIOMIMETIC ROBOTICS LAB

MIT HERMES

Bi-lateral teleoperation (DEMO)

Questions?