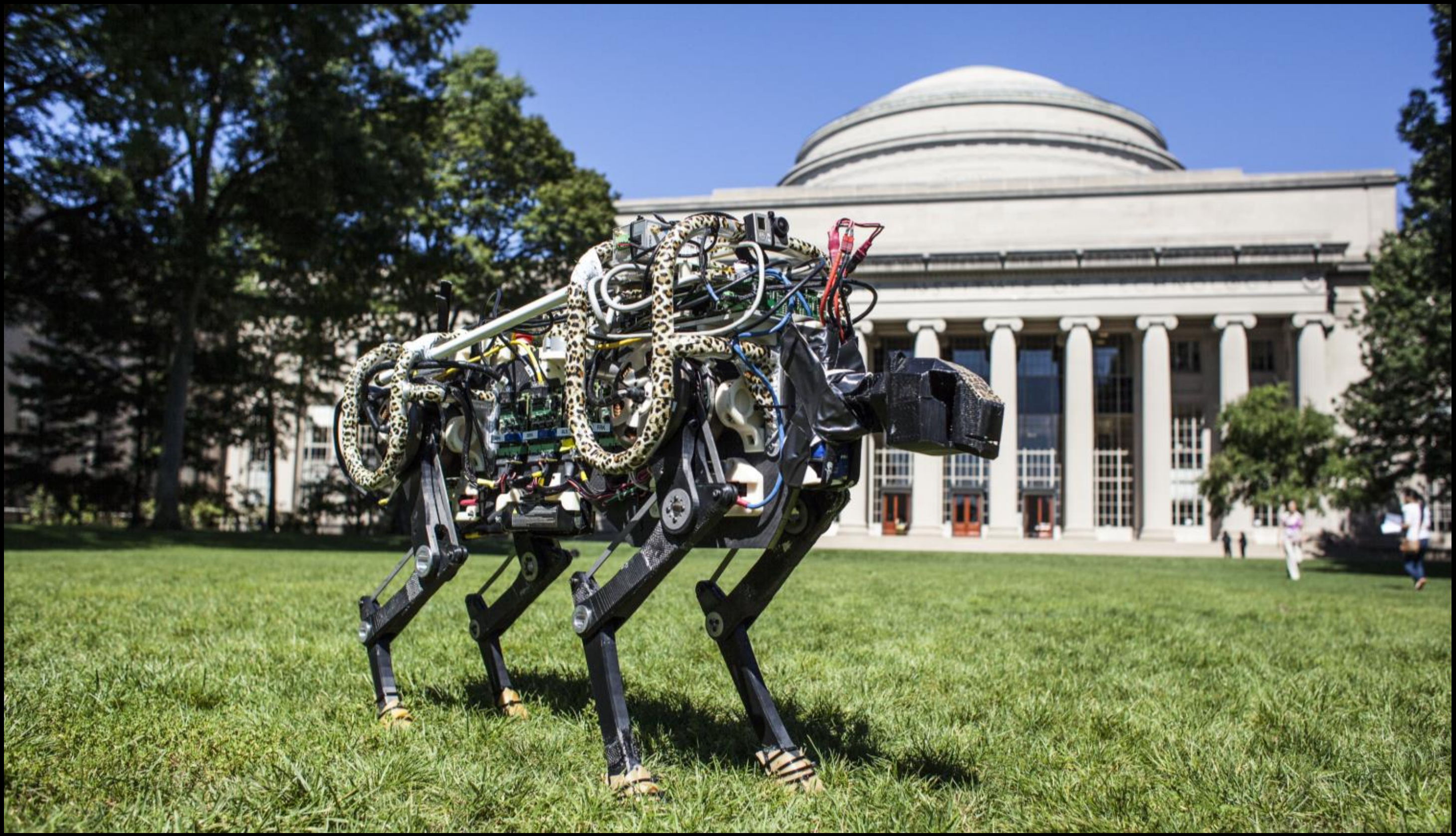


RSS 2015 workshop

Toward Robustness: Dynamic Locomotion using simplified models

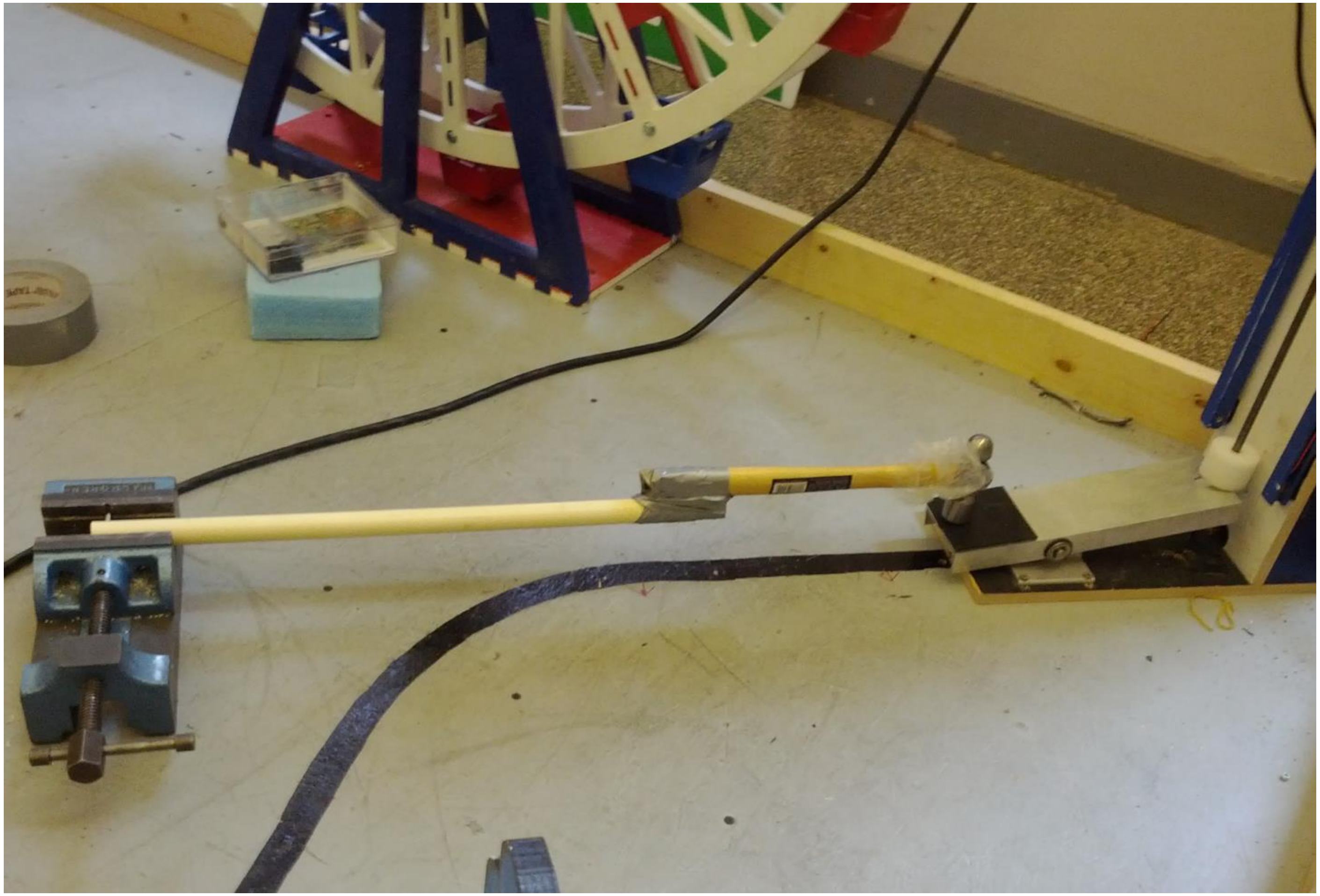
Sangbae Kim
Associate professor
Mechanical Engineering
Biomimetic robotics Lab, MIT

NHK World Documentary: Robot Revolution – from YouTube.
Nuclear disaster at the Fukushima Daichi Power Plant, Japan, March 2011.

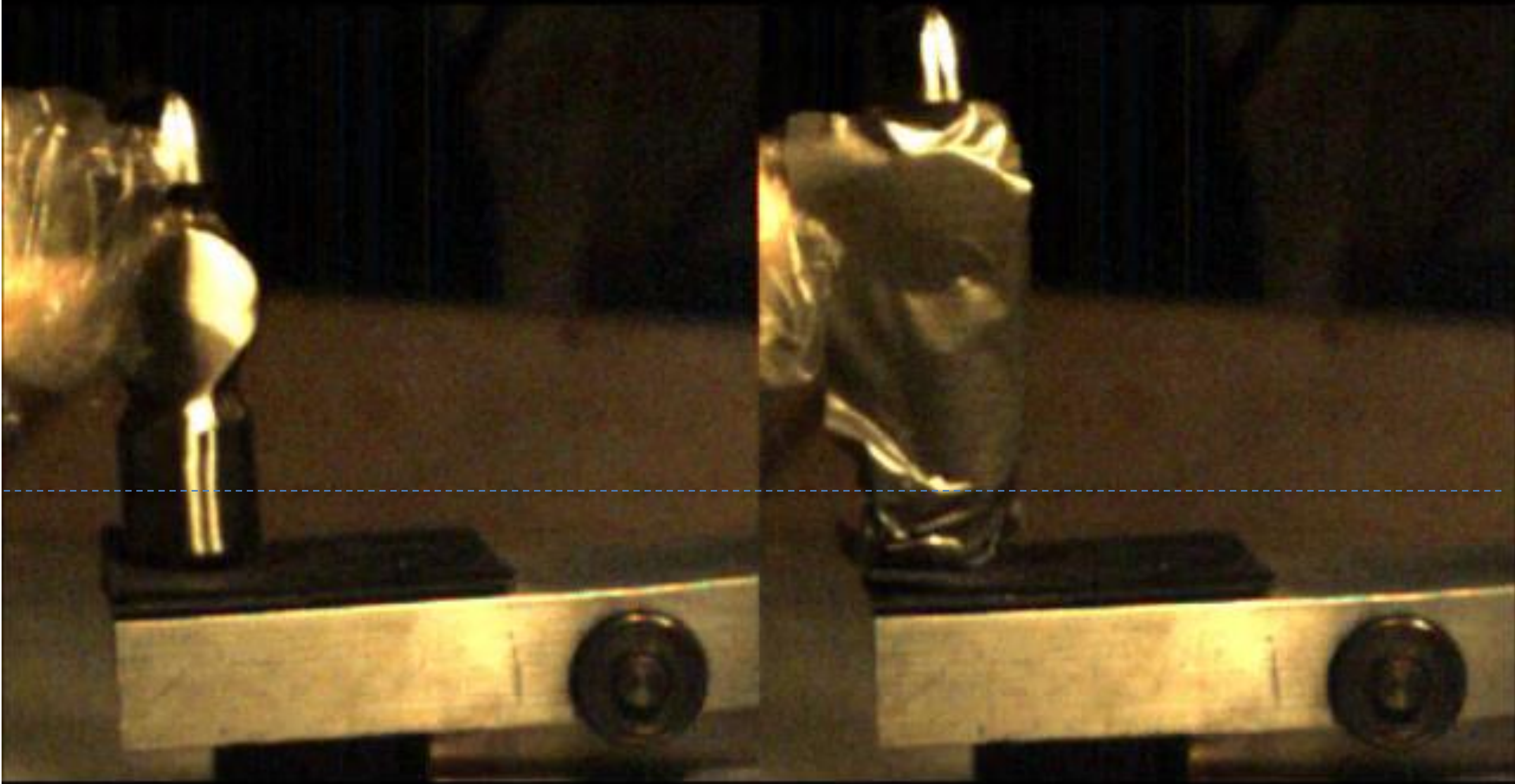
MAGIC HAMMER?

MIT class 2.007 Design and Manufacturing

Test setup



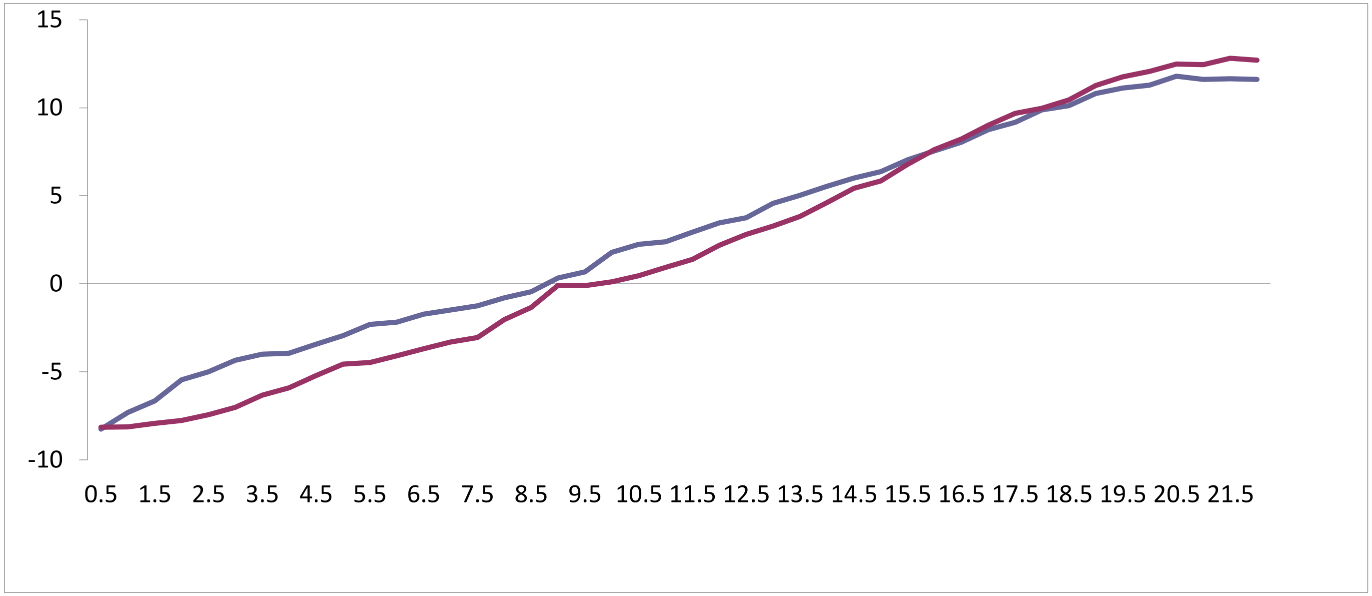
2000 frames/second



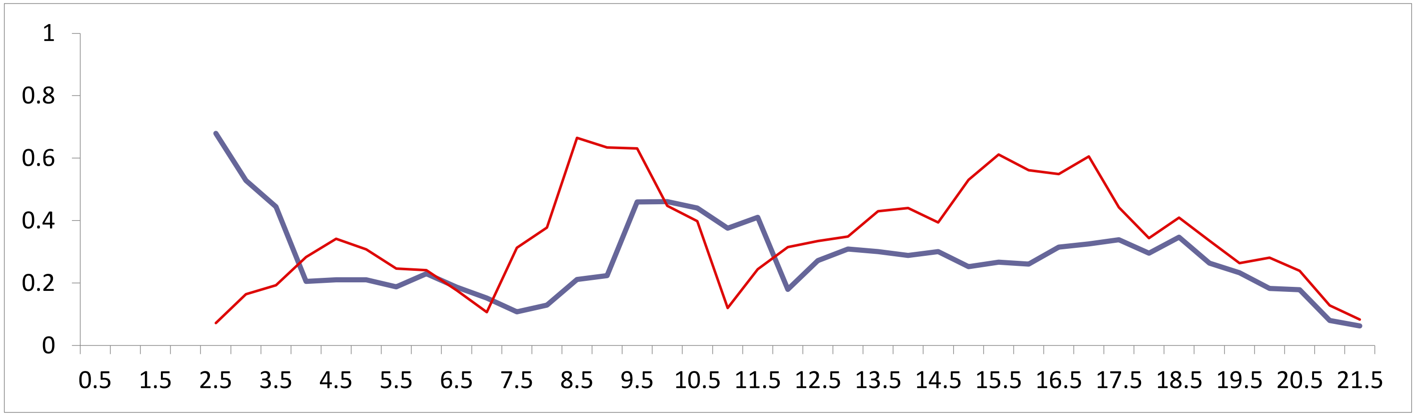
578 msec
– 55cm

876 msec
– 103cm

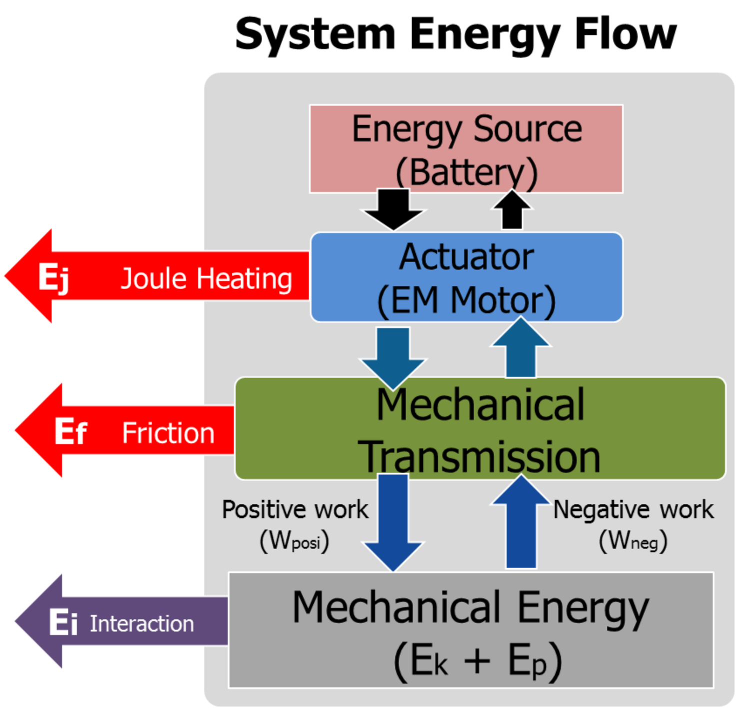
Angle

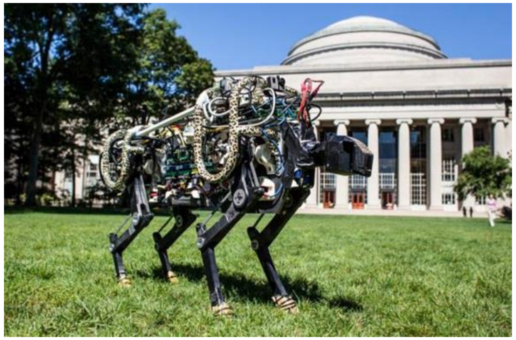


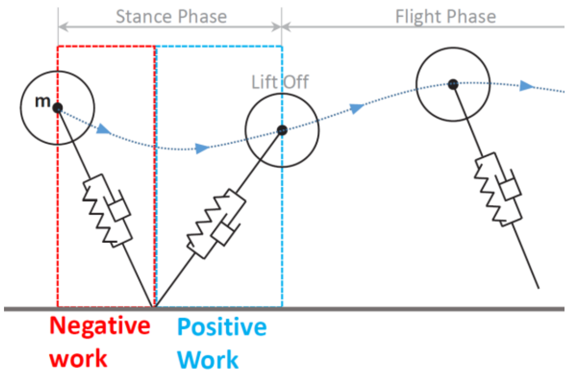
Angular Velocity²



Physical interaction requires two directions of work







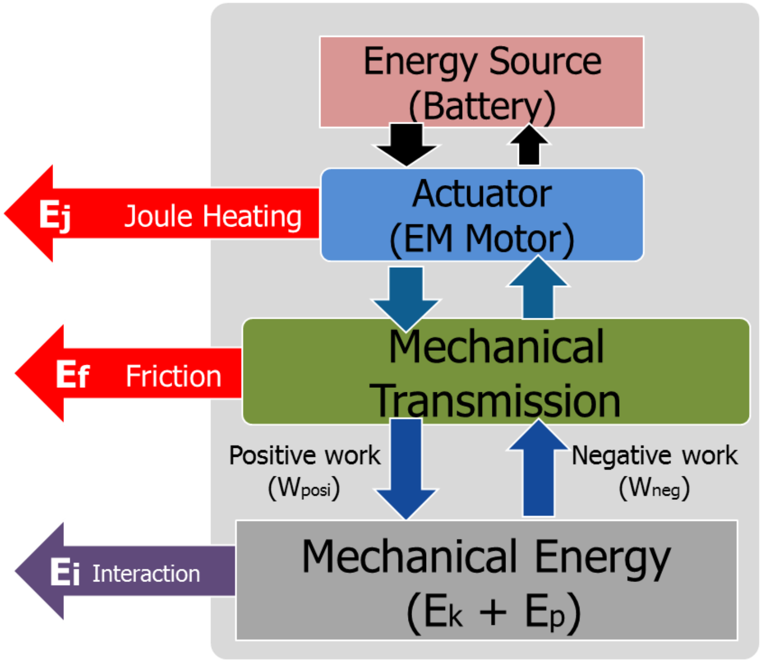
Seok et al., *Mechatronics, IEEE/ASME Transactions* , June 2015

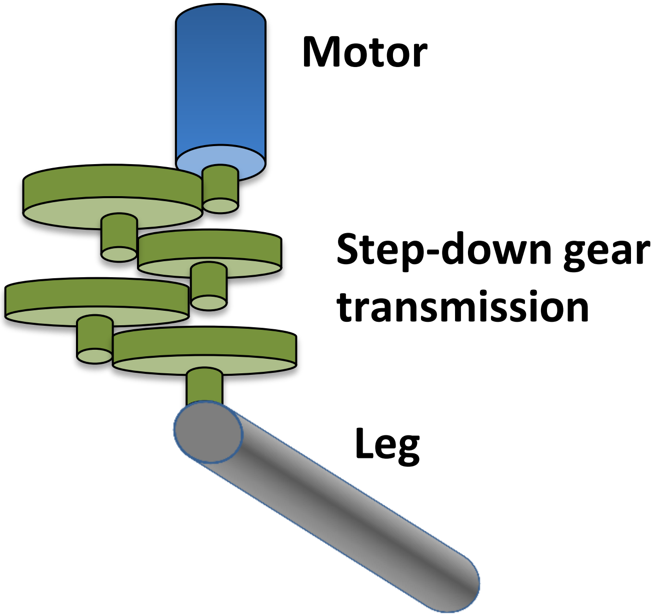
Introducing Directional Efficiency

-Load dependent efficiency or friction loss in the geared transmission is different for positive and negative work

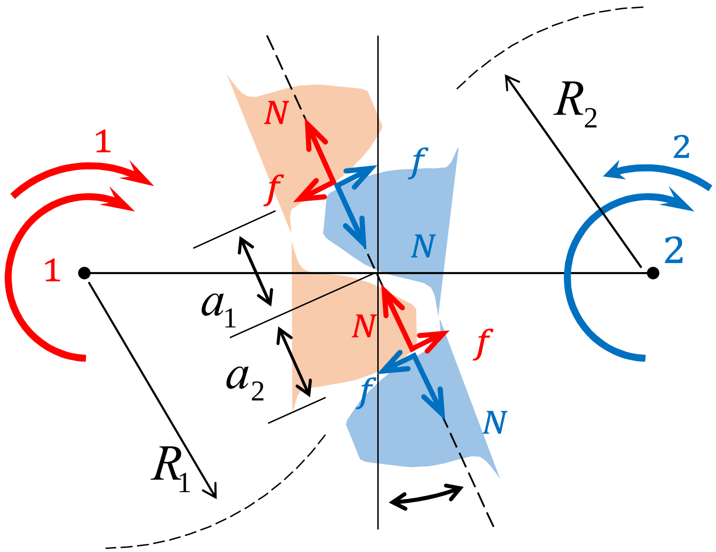
-Degrades force feedback at the motor

System Energy Flow



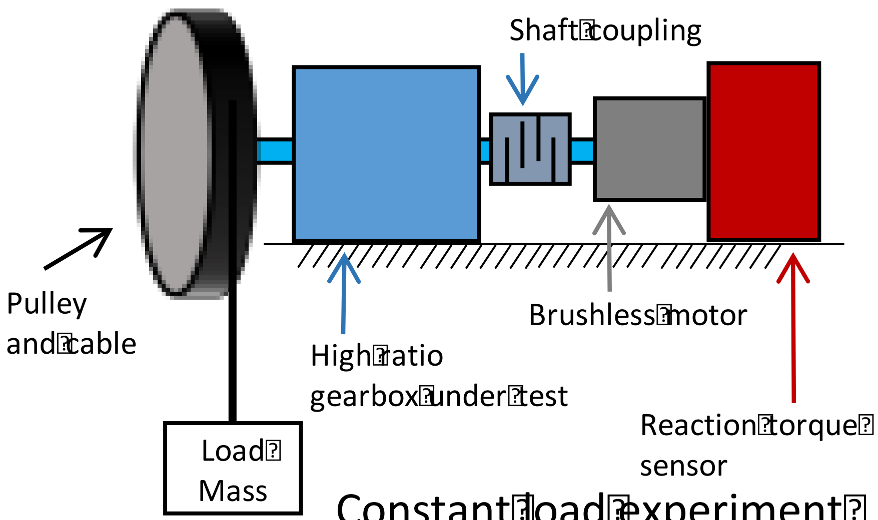


Friction model & experiments



Sliding contact model with Coulomb friction

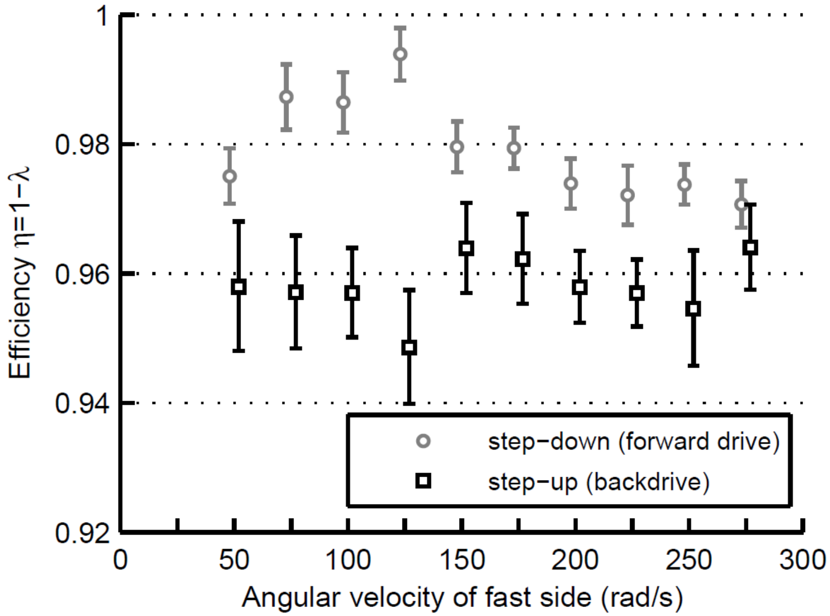
Dual motor experiment



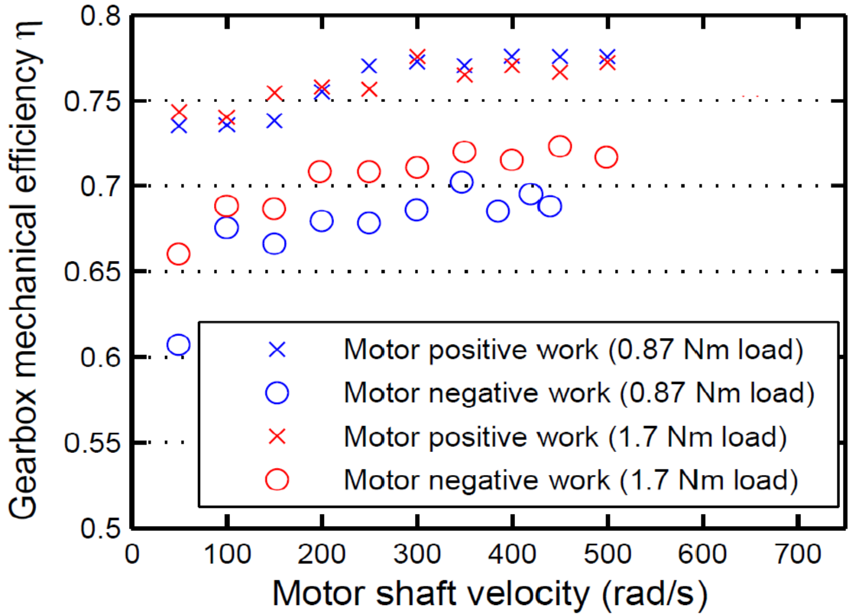
Constant load experiment

Step-up efficiencies (backdrive) are lower than step-down

PIC Designs 6:1 Industrial servo reducer



Modified Dynamixel MX-106 servo (247.5:1)



Step-up vs step down: 96% , 98%

Step-up vs step down: ~68% , ~75%

A. Wang, S. Kim, Directional Efficiency in Geared Transmissions: Characterization of Backdrivability Towards Improved Proprioceptive Control ICRA 2015

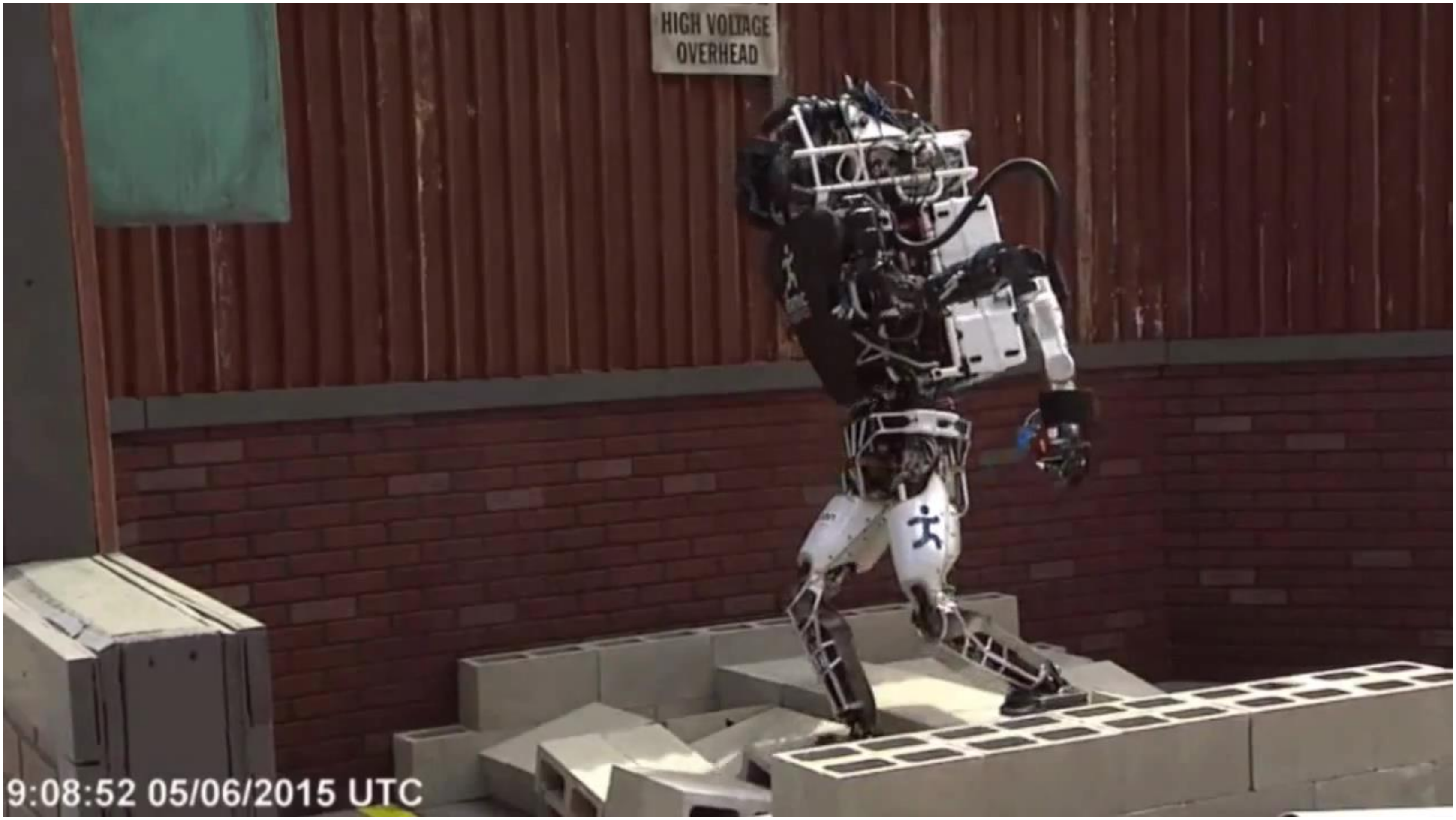
Kia Motors' Slovakian plant

Design paradigm shift

DARPA Robotics Challenge

DARPA Challenge

- Quasi-static locomotion and manipulation
- Collision is NO, NO, NO



Dynamic mobile robot?

Most robots are rigid, fragile, heavy complex, expensive, and SLOW

Manufacturing robot tech.

Asimo, etc

Lack of compliance control
Lack of efficiency (?)
Lack of power (?)

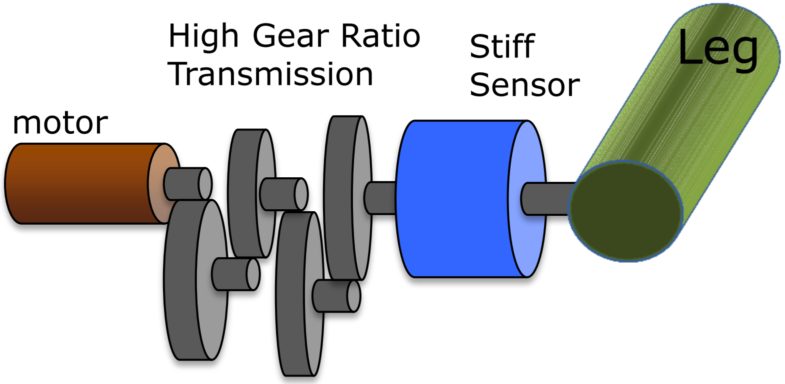
Construction robot tech.

Boston Dynamics

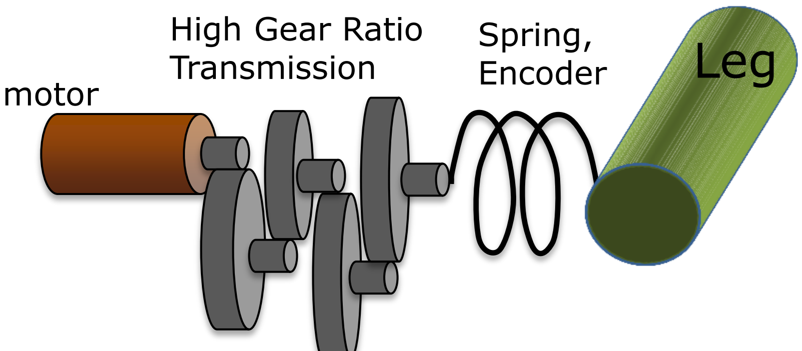
Lack of efficiency

High Force Proprioceptive Actuator

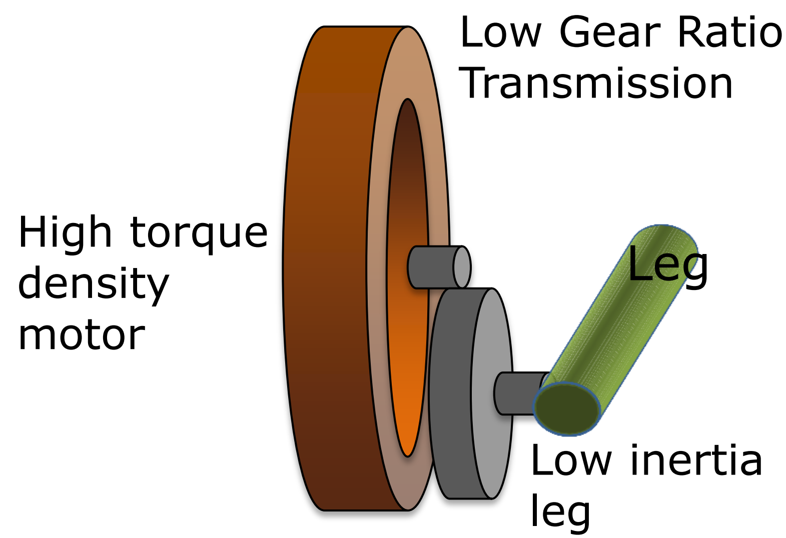
Maintain force transparency in transmission



Geared Motor with Torque(Force) Sensor



Series Elastic Actuator



No Force(Torque) Sensor
No Series Elastic

Proprioceptive force control

Phantom – Haptic display device 1994

Kenneth Salisbury

$$M_q\ddot{q} + V_q(q,\dot{q}) + G_q(q) + \tau_{fric} = \tau_{motor} + J^T F_{ext}$$

minimize (τ_{fric})

minimize ($M_q\ddot{q}$)

Mechanical compensation ($G_q(q)$)

Impedance + force

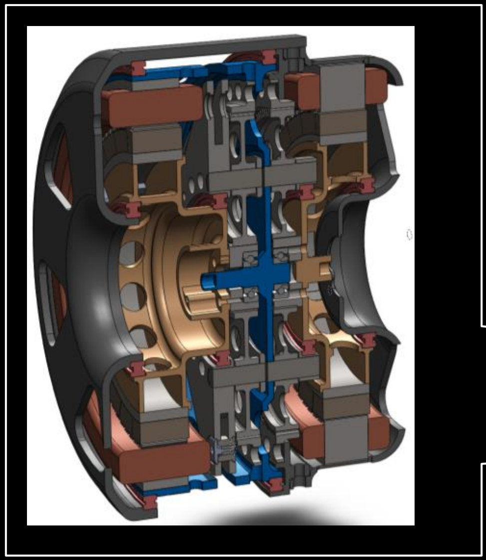
$$M_{des}\ddot{x} + B_{des}\cdot(\dot{x}_0 - \dot{x}) + K_{des}(x_0 - x) + F_{act} = F_{ext}$$

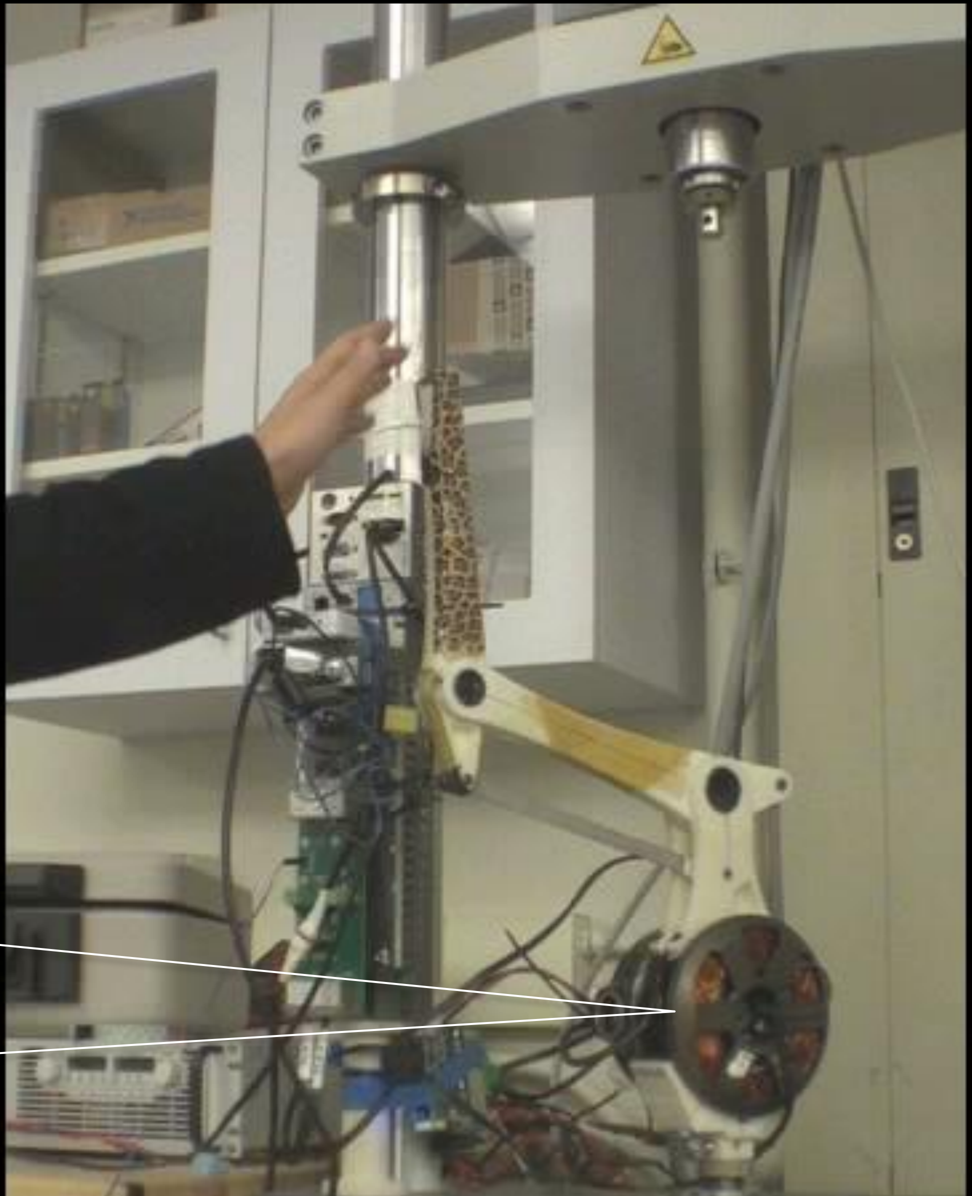
Impedance

Force command

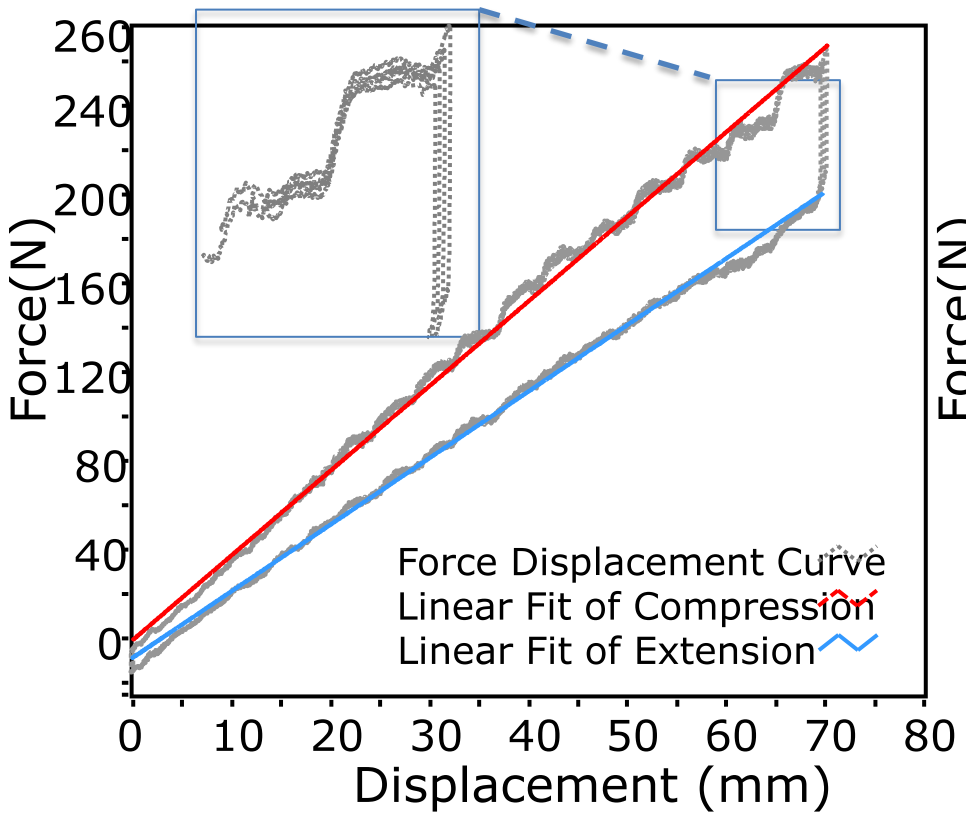
1. Unique actuation
Flexibility (impedance) control for physical-interaction

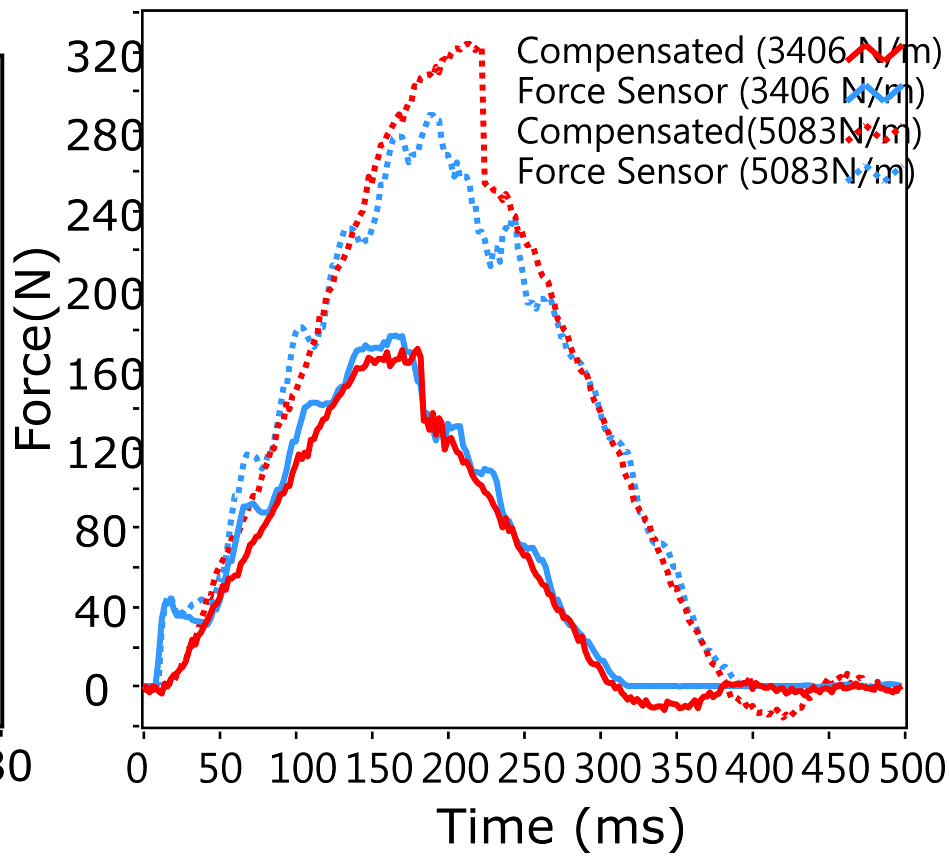
1. Minimum distal mass
2. Max. torque density – Min. mechanical impedance
3. Proprioceptive control (collocated sensing, no force sensors)



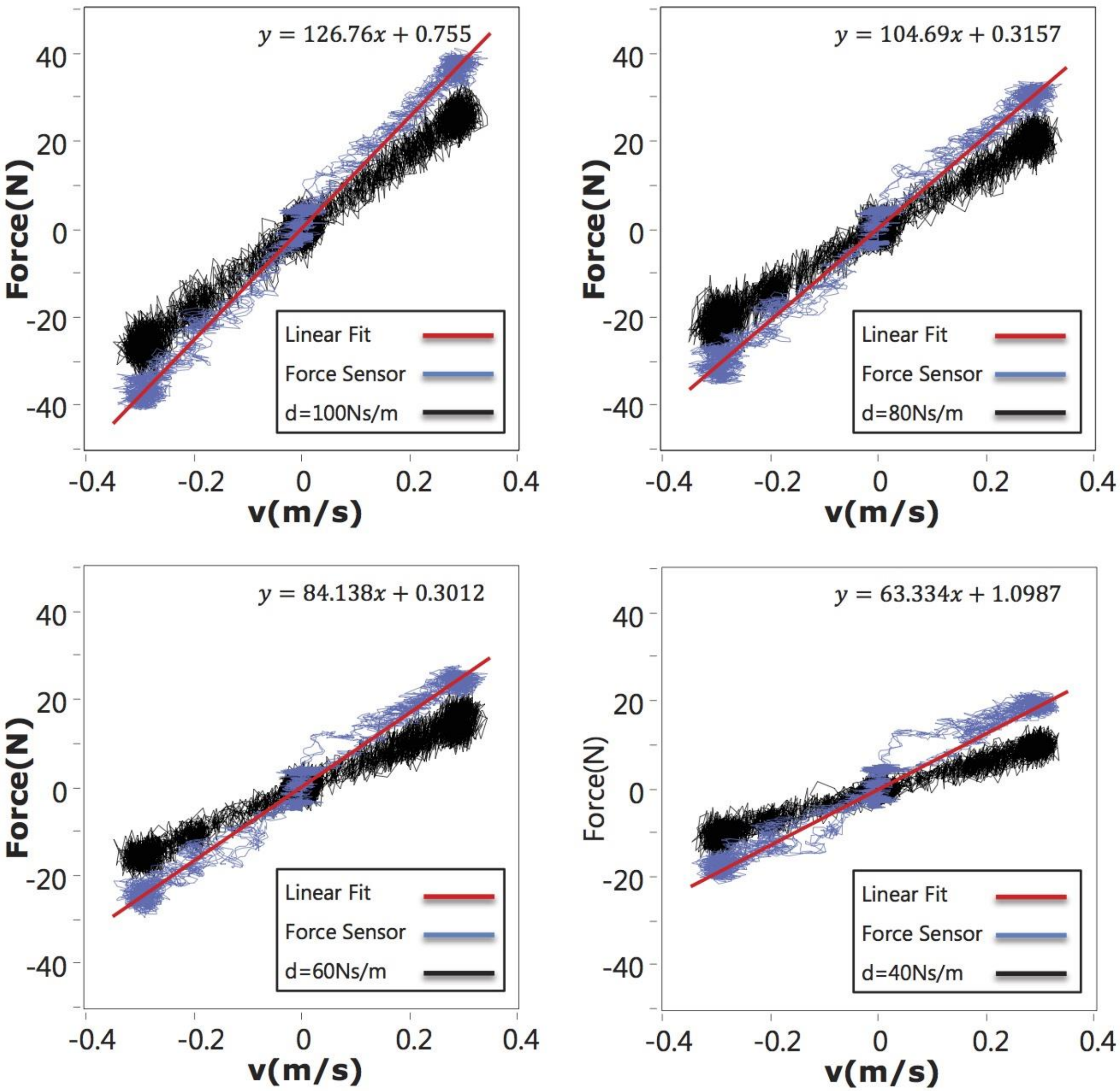


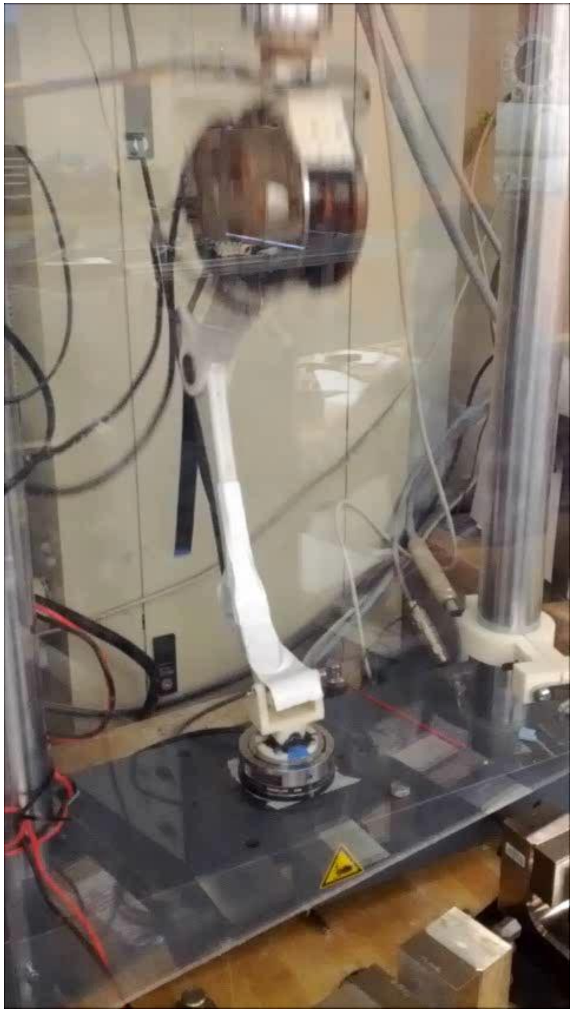
Stiffness control



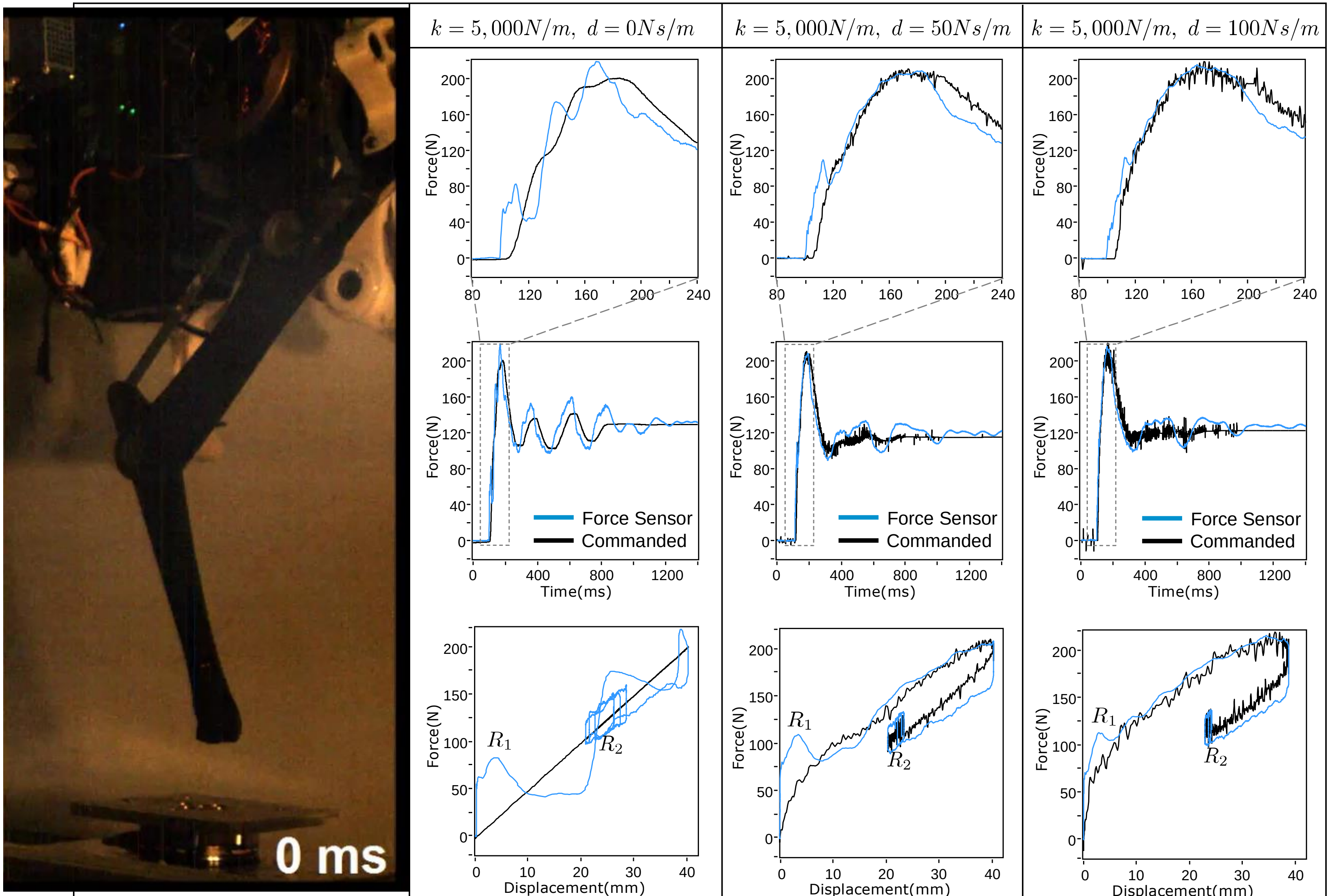


Damping control



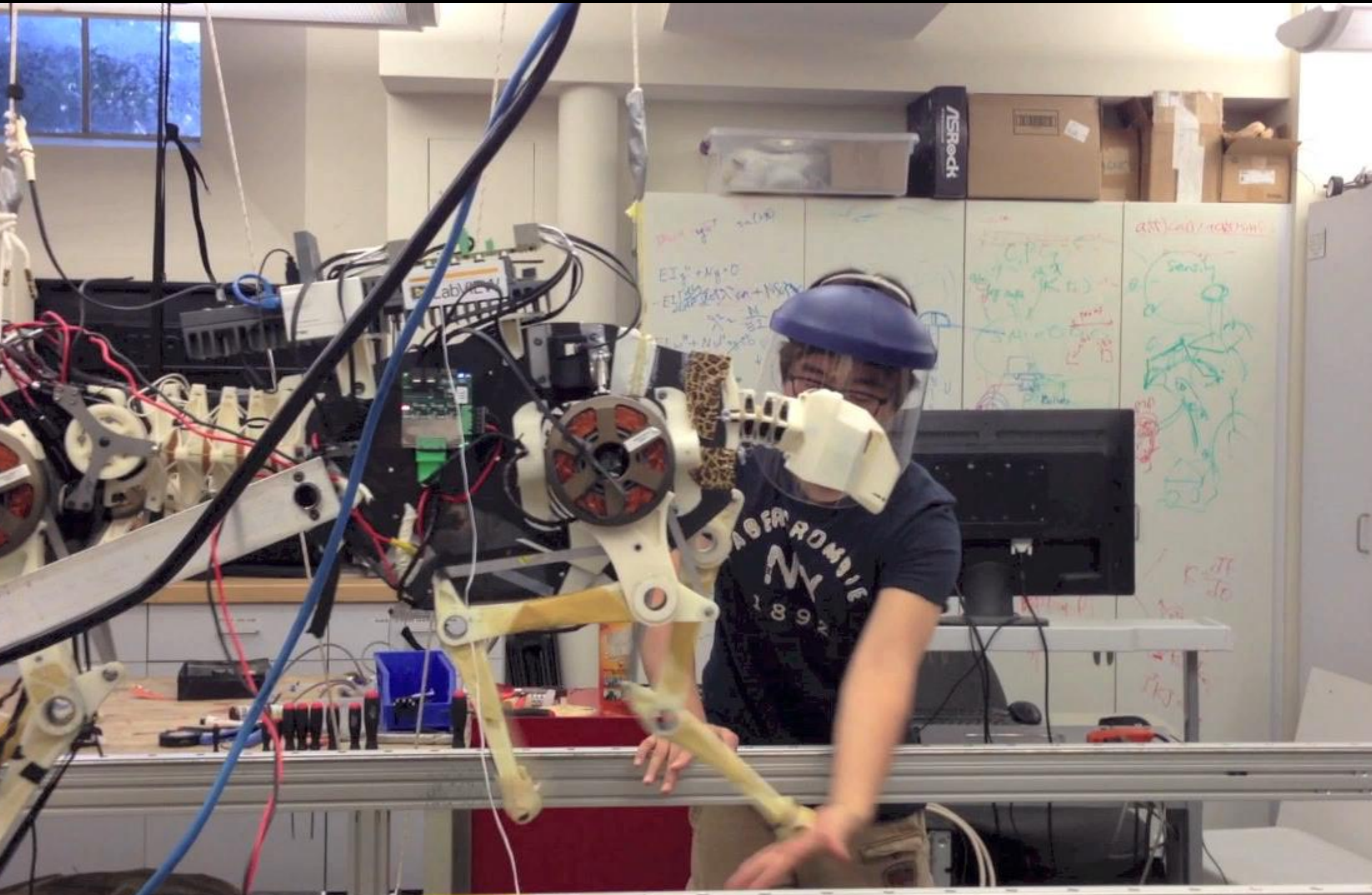


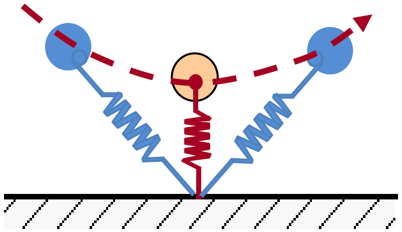
Impact test



a) Test setup

b) Test result


ASRock



Passive dynamics vs. control authority SLIP MODEL? Is the SLIP (template) supposed be a control target?

Sangbae, why not using Spring ?

Well.. I want high force bandwidth to maximize stability

Why do we need high bandwidth? Neuro-signals are slow.

Well.. Don't animals have amazing anticipatory brain/spinal cord…local feedback etc… And 200 muscles?

Daniel Wolpert "We have a brain for one reason and one reason only, and that's to produce adaptable and complex movements,"

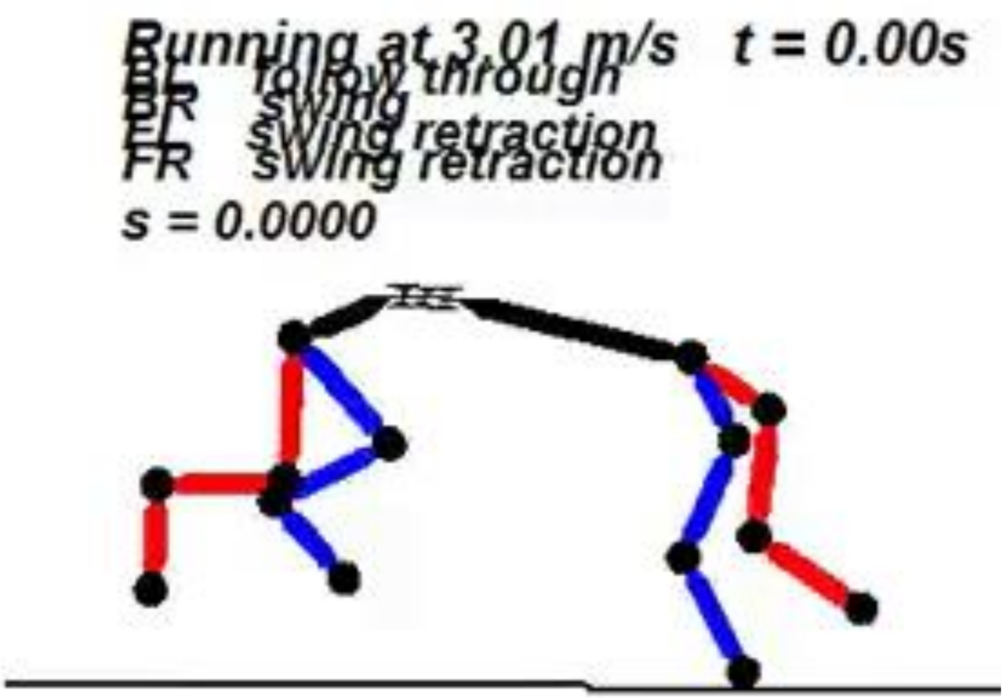
Grégoire Courtine "I believe computation is happening every part of neuro-channel"

SLIP is steady state model
GRF generation & stability coupled

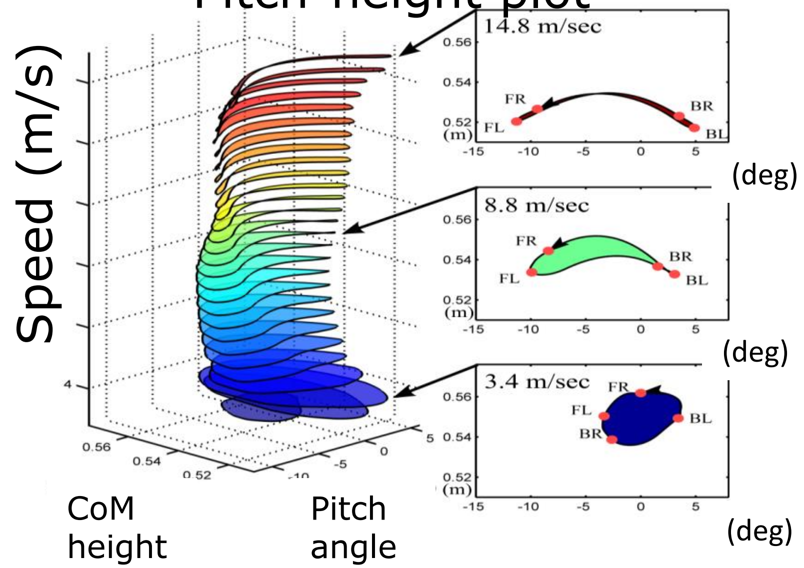
Force/impulse control Hypothesis

Speed Change from 3-14.8m/sec (33mph)

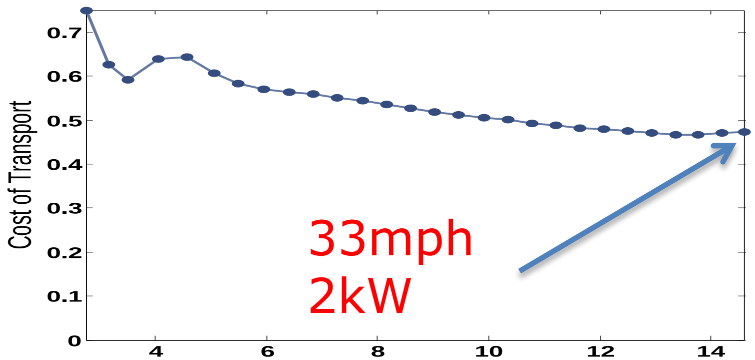
- Vertical impulse prescription + speed regulation



Pitch-height plot

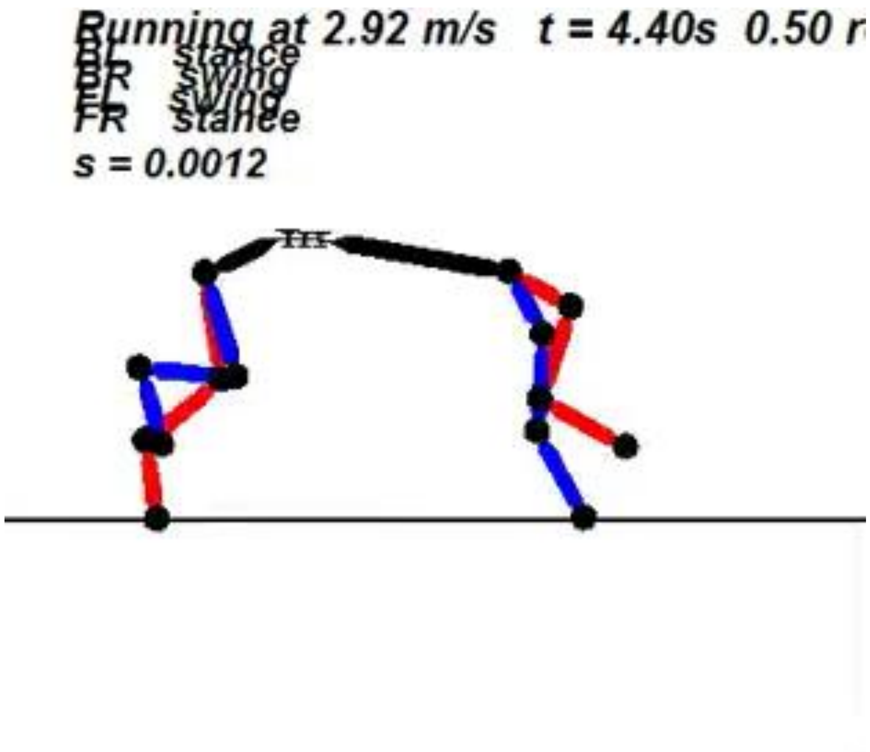


Total cost of transport
(including motor model, transmission losses)

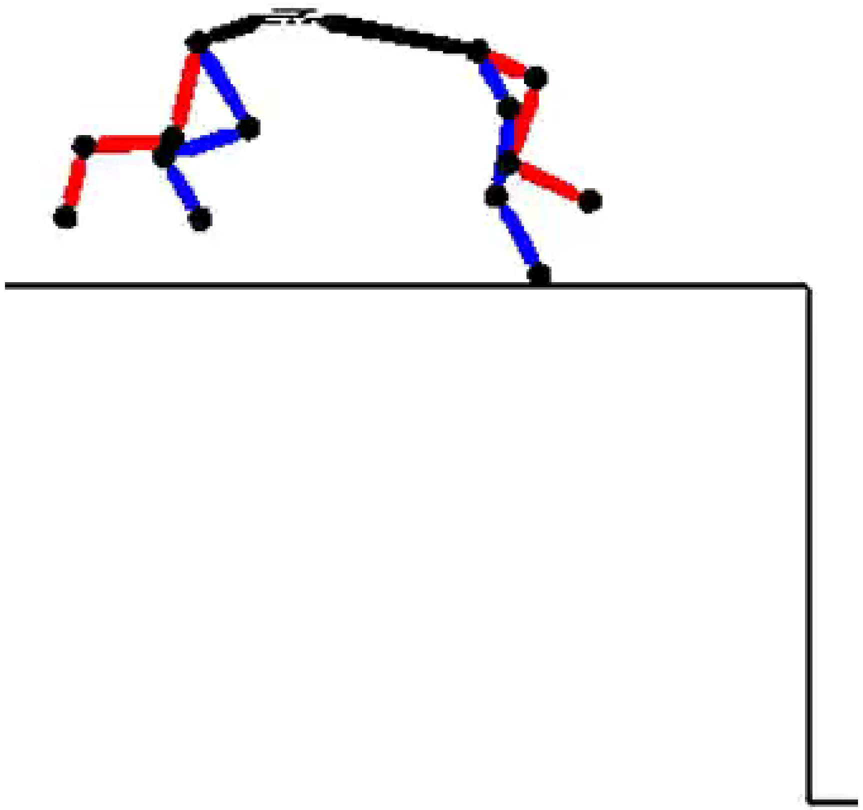


Step down

70cm drop

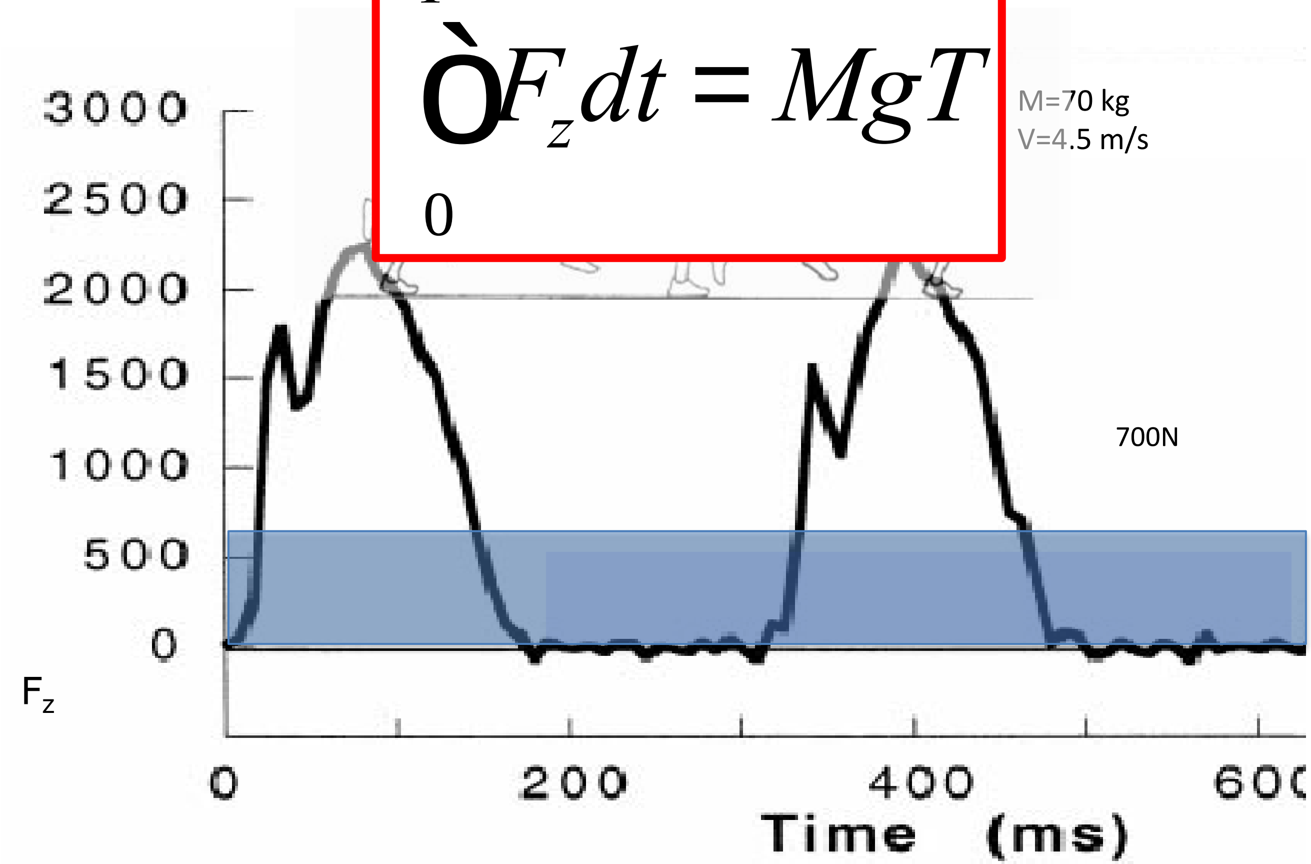


127 cm drop



Impulse planning

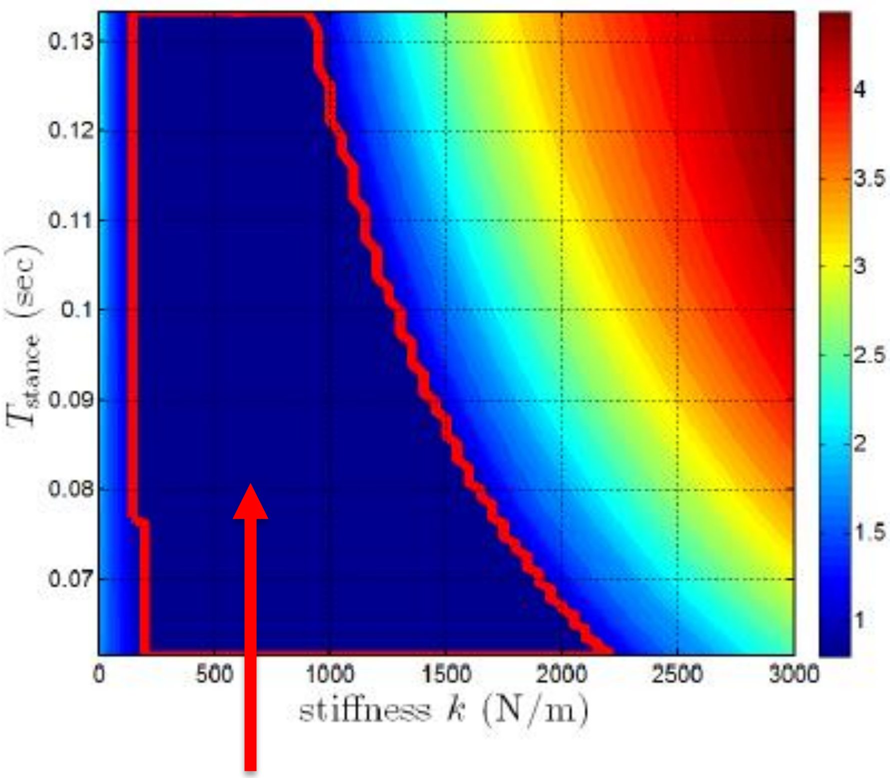
$$\int_0^T F_z\,dt = MgT$$



P. Weyand et al., *J. Appl. Physiol.* 89: 1991–1999, 2000

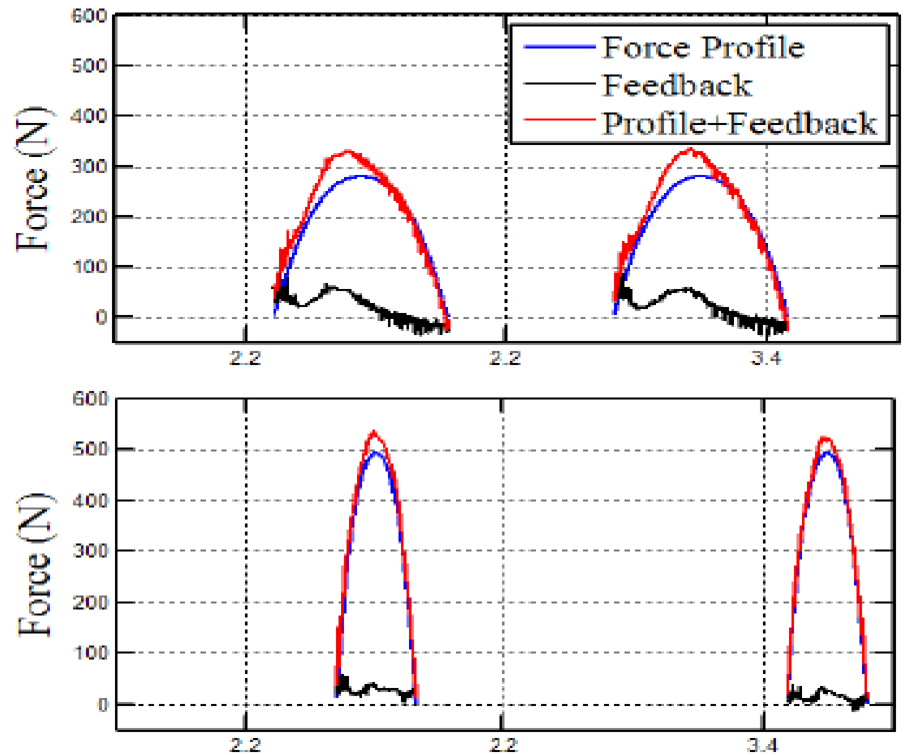
Decoupling GRF generation and stability

Eigen value analysis



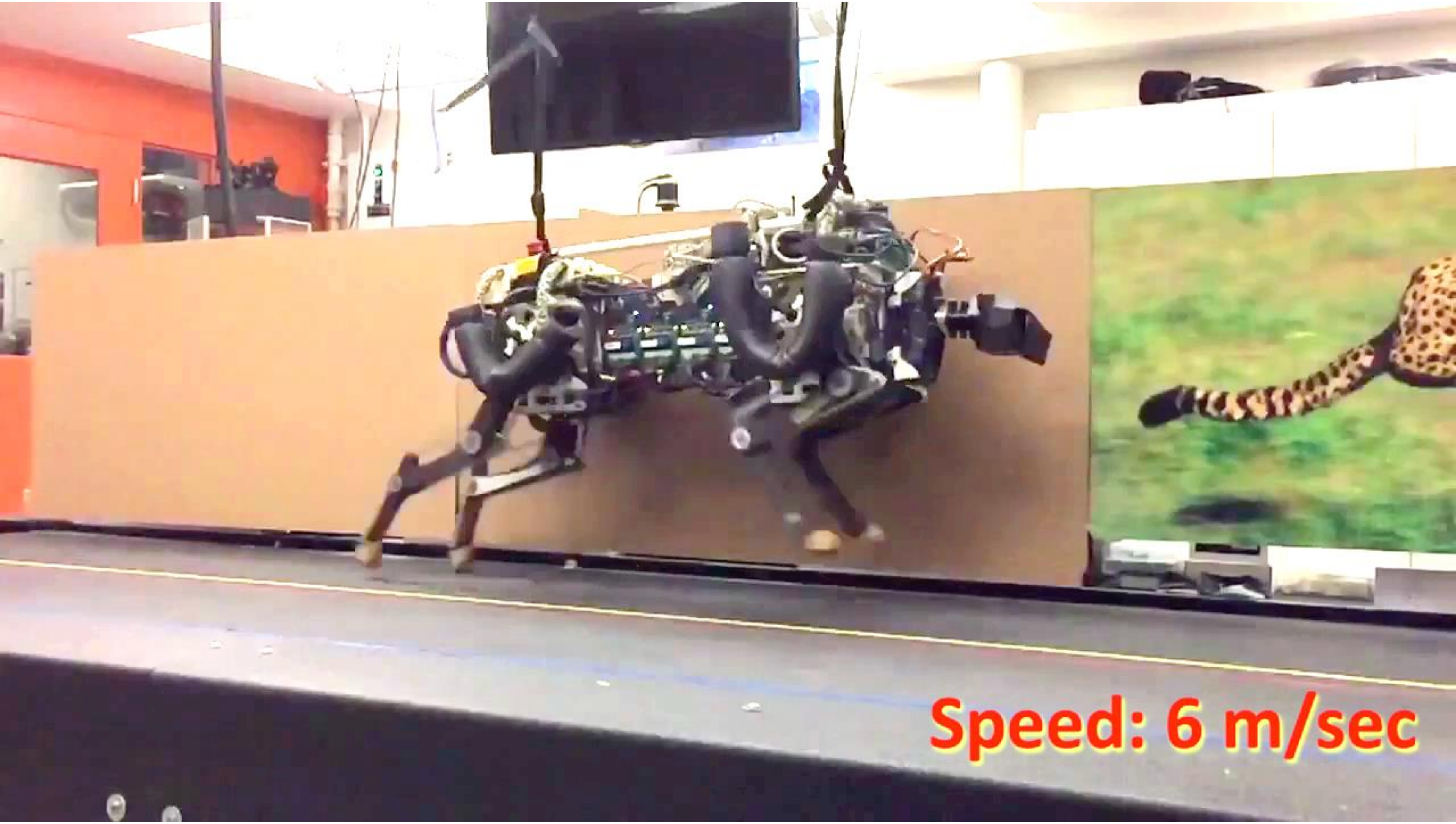
700 N/m

Commanded vertical force



Previous trot :7000 N/m

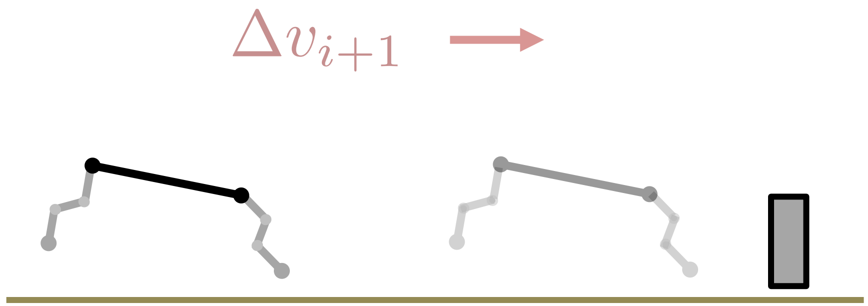
1/10 of stiffness is used to stabilize the limit cycle

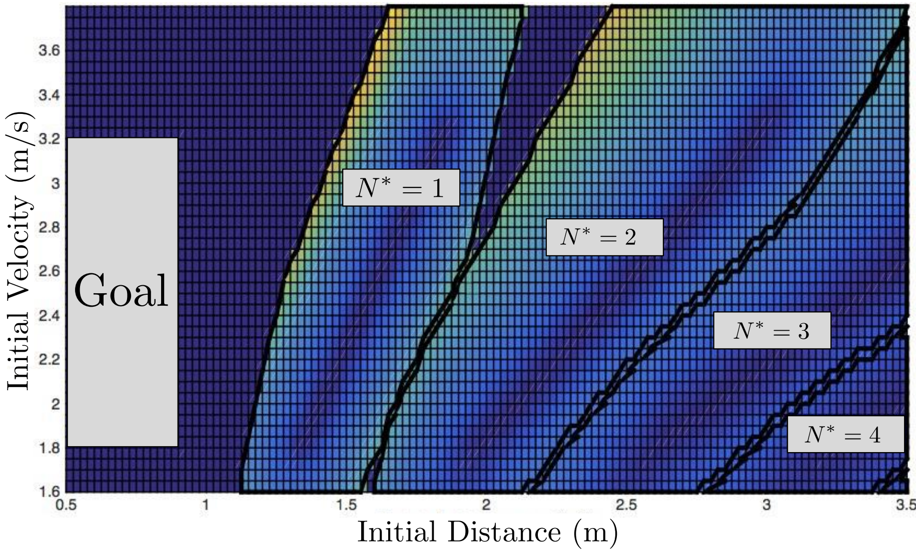

Speed: 6 m/sec

Dr.
Park

Dr.
Wensing

Gait Adjustment: QP





$$\min \; (\mathbf{x}_N - \mathbf{x}_N^d)^T \, \mathbf{Q}_F \, (\mathbf{x}_N - \mathbf{x}_N^d) + \frac{1}{N} \sum_{i=0}^{N-1} r_i \Delta v_i^2$$

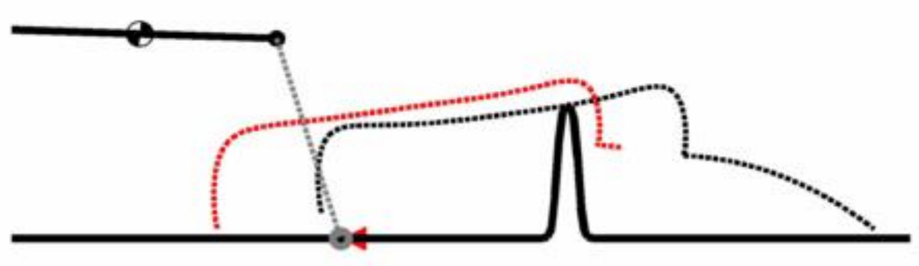
$$\begin{aligned} \text{s.t. } & \mathbf{x}_{i+1} = \mathbf{A}\, \mathbf{x}_i + \mathbf{B}\, \Delta v_i \\ & \underline{\mathbf{x}}_N \le \mathbf{x}_N \le \overline{\mathbf{x}}_N \\ & \underline{v} \le v_i \le \overline{v} \\ & |\Delta v_i| \le \beta v_i \end{aligned}$$

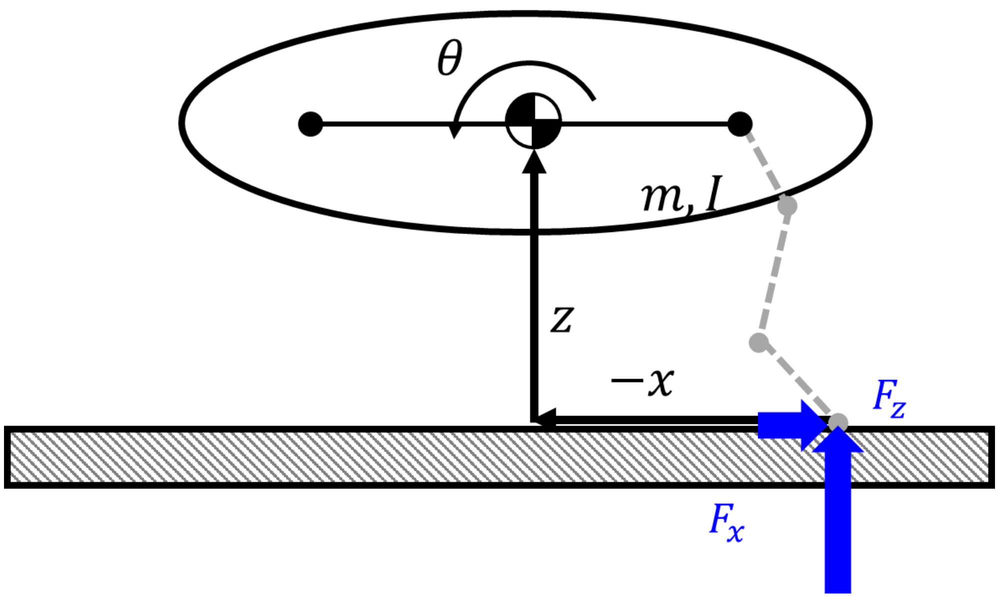
Cheetah's Model – Analytical Solution

$$m\ddot{x} = F_x$$

$$m\ddot{z} = F_z - mg$$

$$I\ddot{\theta} = -xF_z + zF_x$$

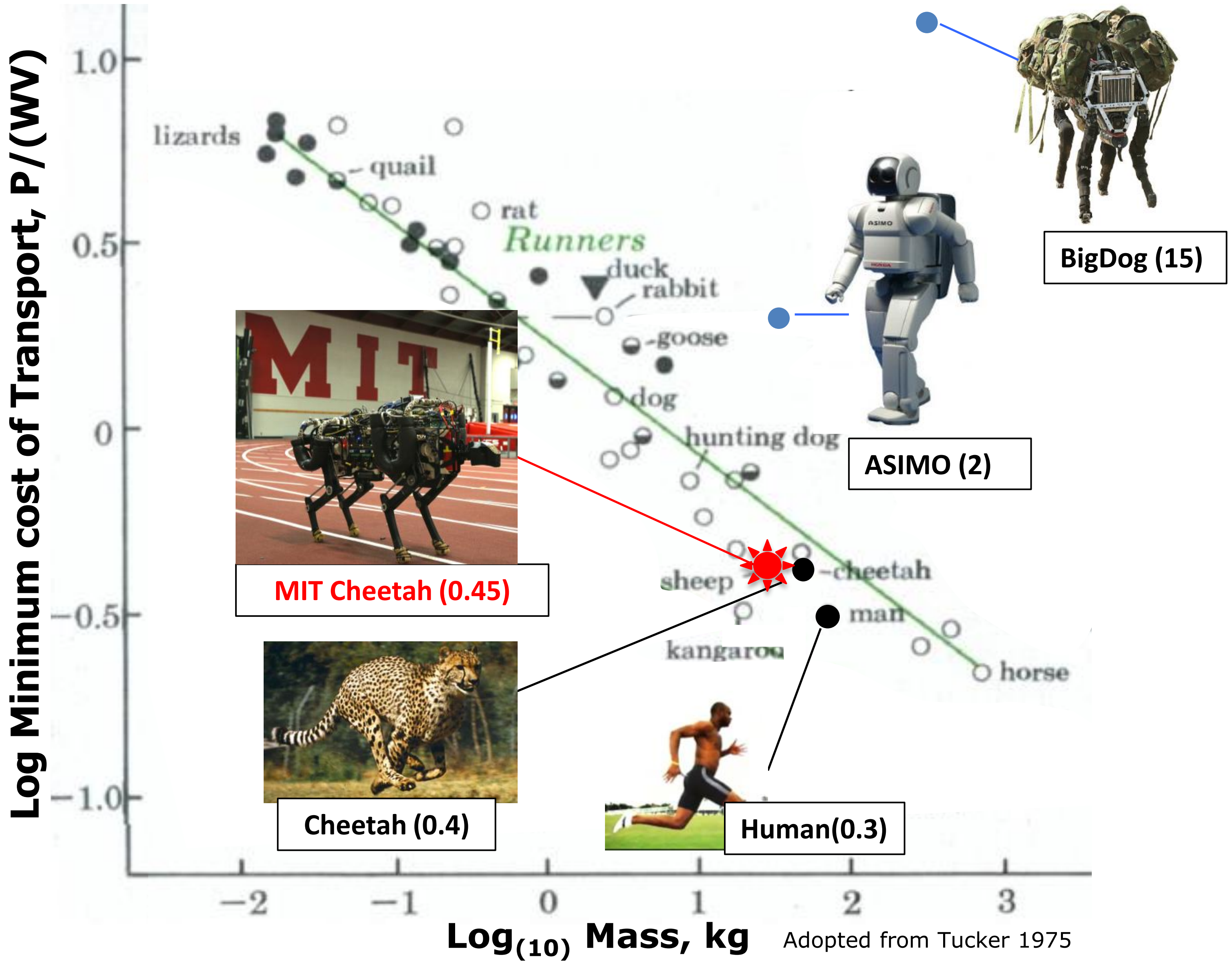




NO COST FUNCTION

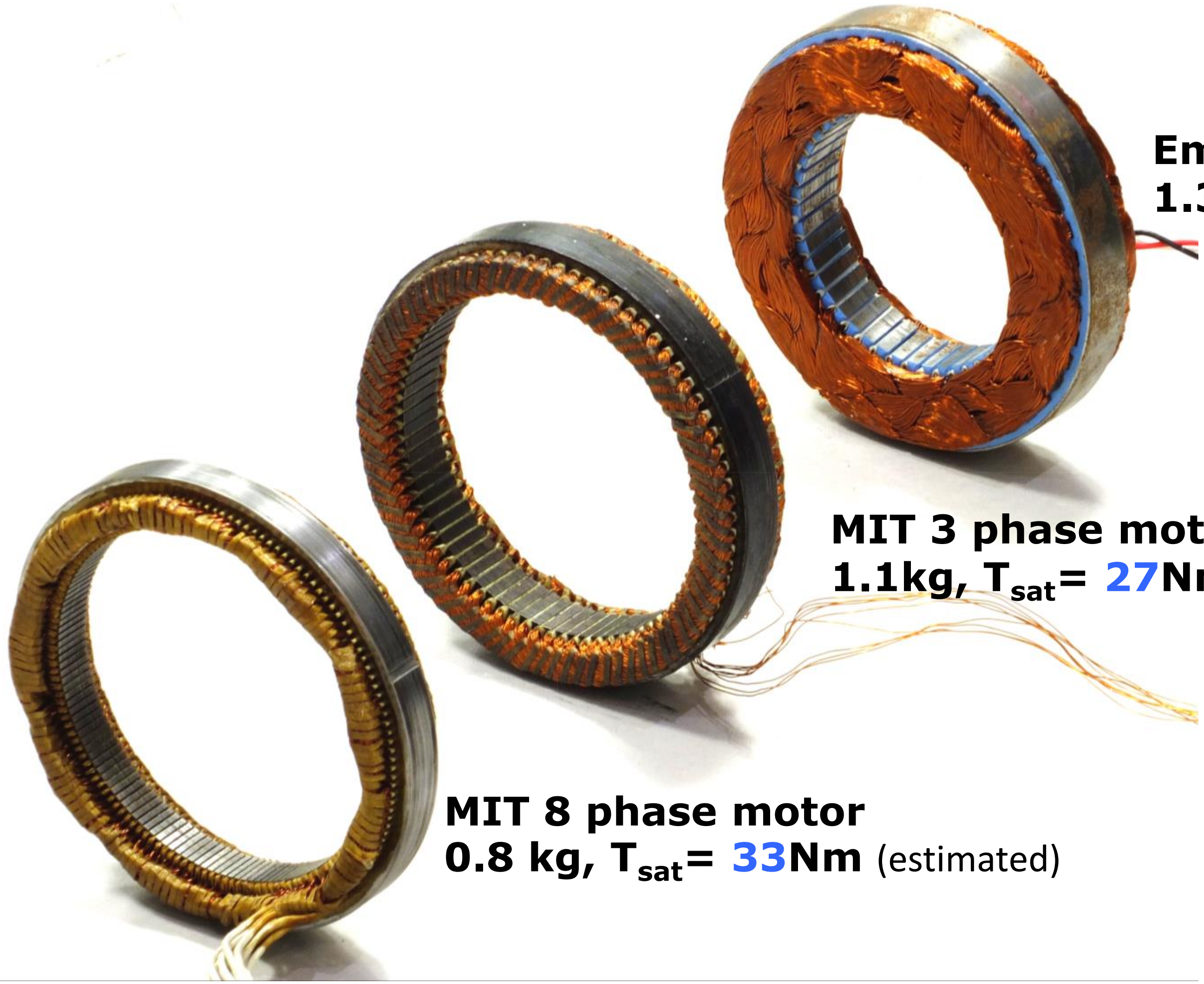
& Many non-linear constraints

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



Adopted from Tucker 1975

Custom Electric Motor in collaboration with Jeff Lang

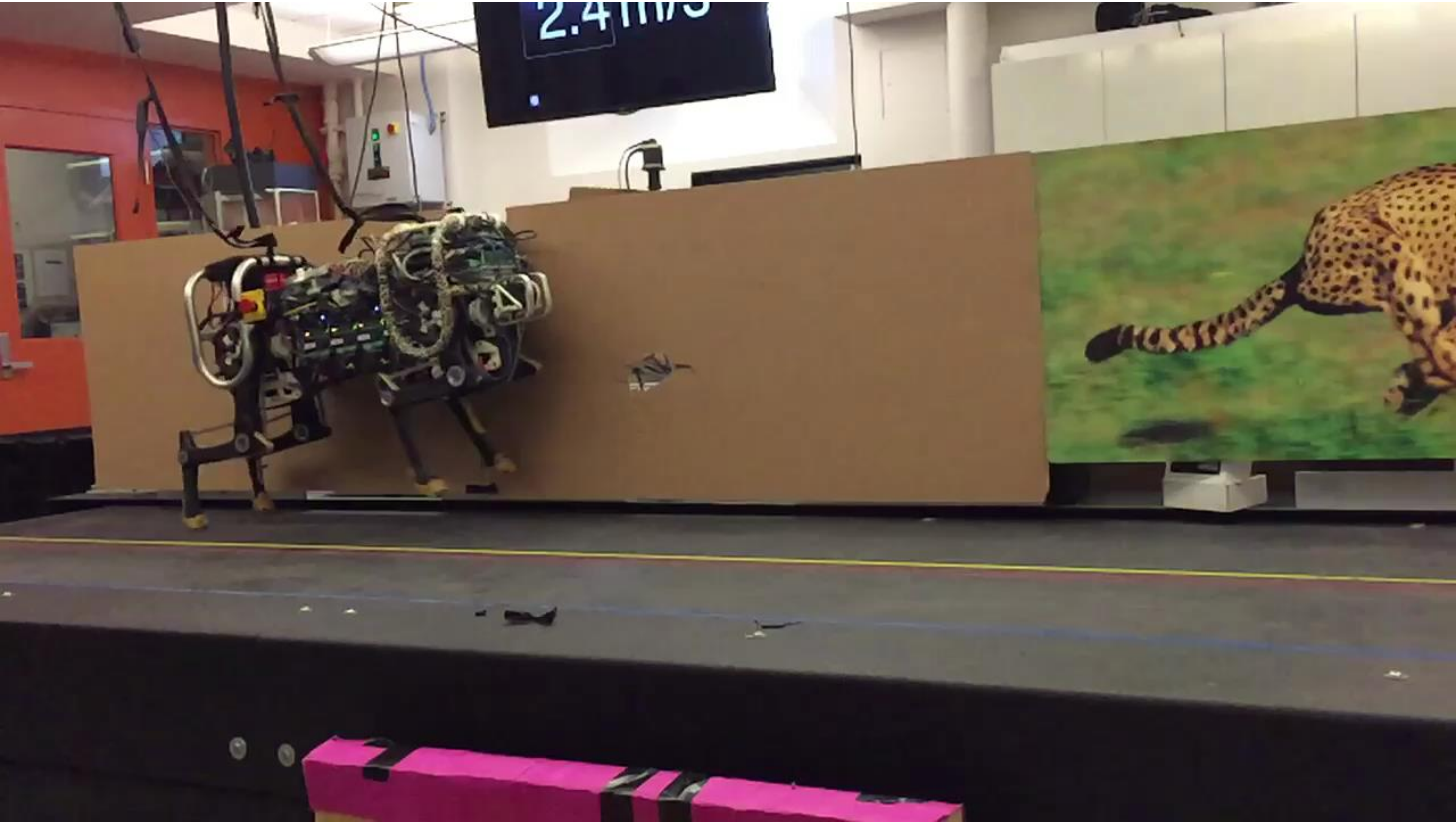


Emoteq
1.3kg, T_{sat}= 10Nm

MIT 3 phase motor
1.1kg, T_{sat}= 27Nm

MIT 8 phase motor
0.8 kg, T_{sat}= 33Nm (estimated)

Acrobatic robotics?


2.4 m/s

Autonomous locomotion +Tele-operated manipulation

Manipulation mode

Quadruped mode

Albert Wang, Joao Luiz Almeida Souza Ramos, Wyatt Ubellacker, John Mayo

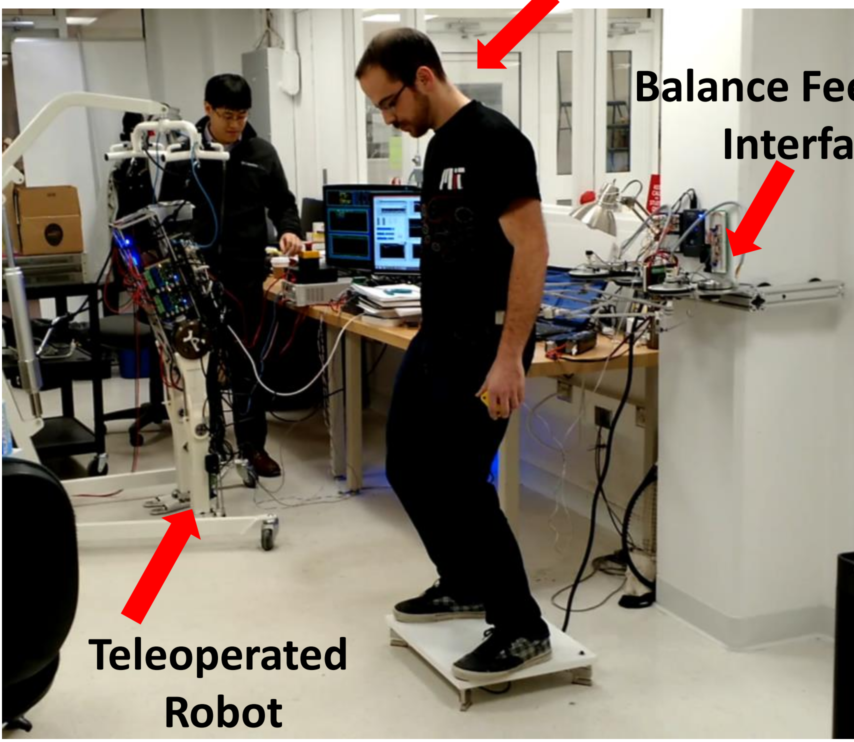
- Quadrupedal humanoid
- Tele-operation with balance feedback
- Power manipulation

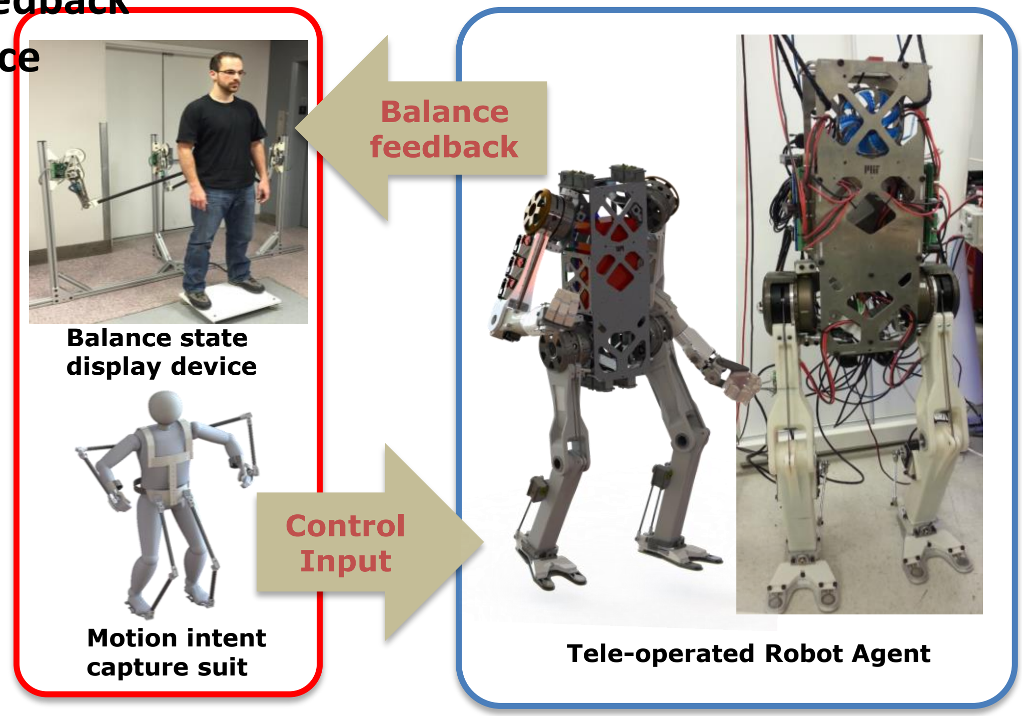
Build & Dump

Batting

HERMES : Disaster response robot that combines quadrupedal locomotion and tele-manipulation of humanoid

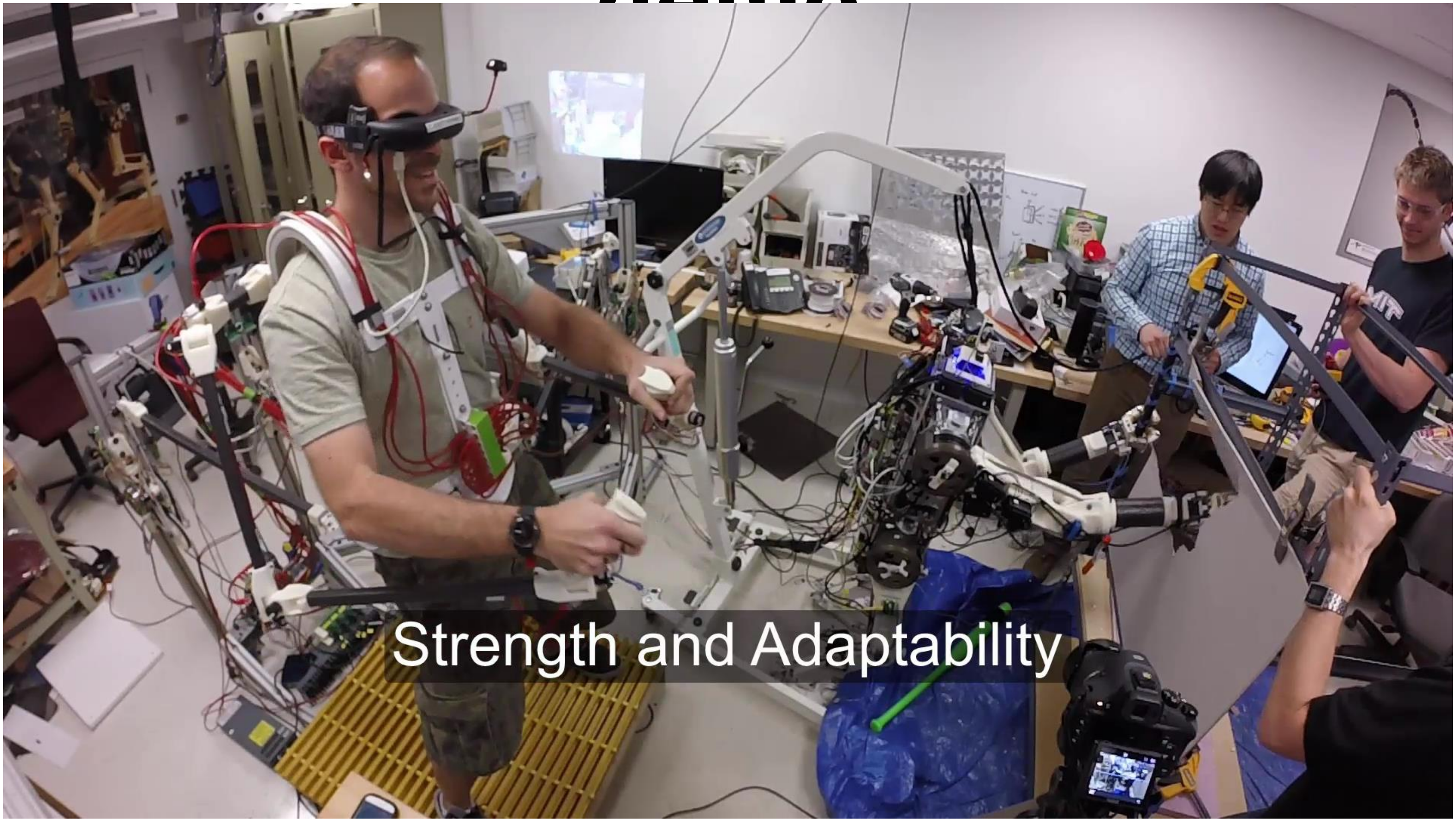
– DARPA Young Faculty Award -





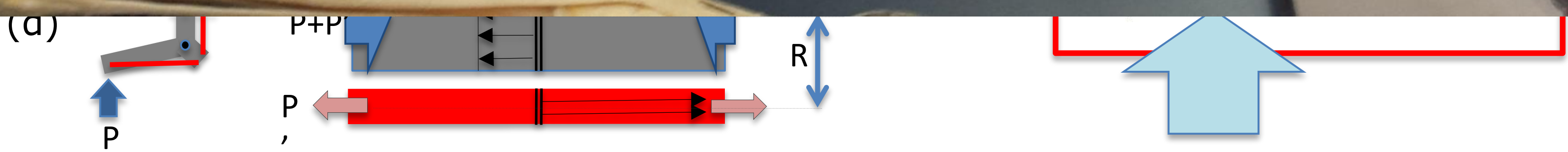
Dynamic manipulation with significant physical interactions in disaster environments

HERMES demo videos – DRC demo



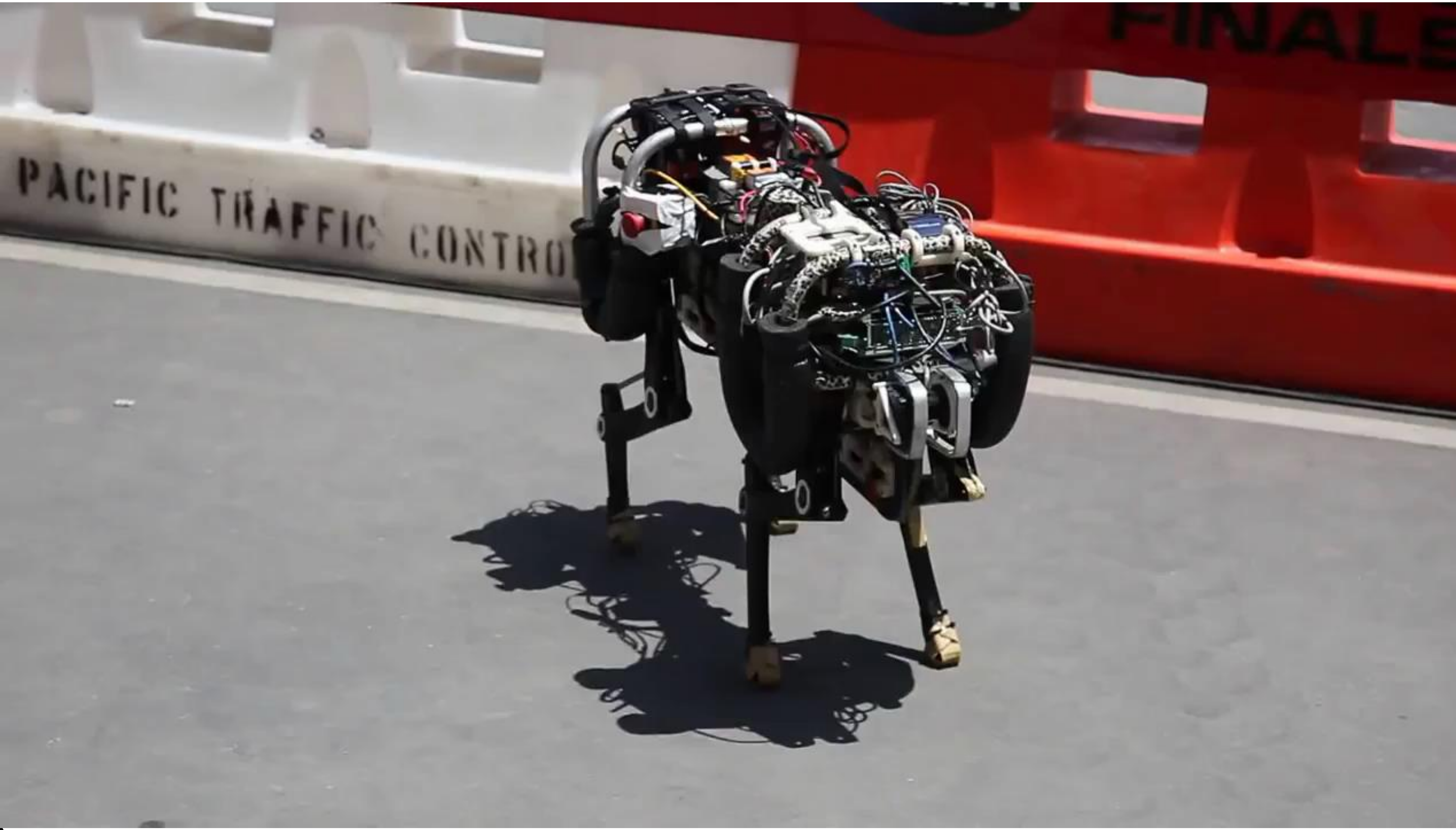
Robustness on impact

Bio-tensegrity coined by Steve Levin MD



Let's bring robots into our lives!!

DRC demo



Conclusion

- Real world is MUCH dirtier than you think!! (LOTs of nonlinear constraints) Be ready to get your hands dirty.
- Simple model is sometimes more useful esp. for on-line planning. Real situation is always uncertain
- Optimal control is not always required, feasibility is more URGENT
- Robustness (mechanical and controller) is MUST not optional


This project is funded by
DARPA M3 program
DARPA