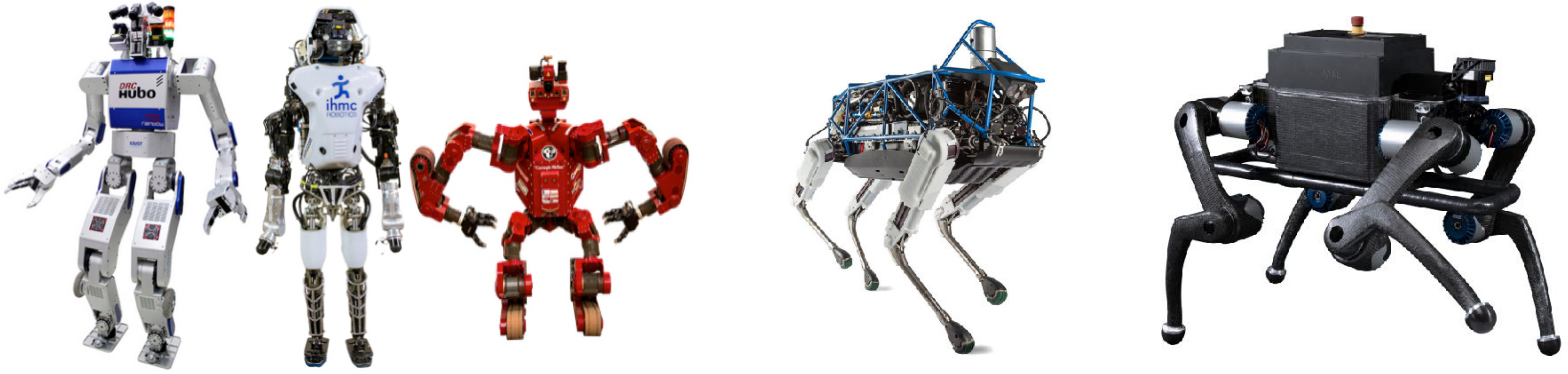


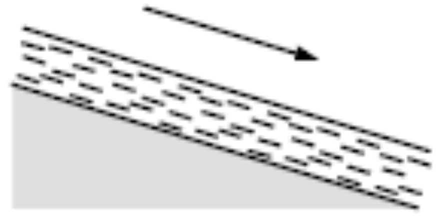
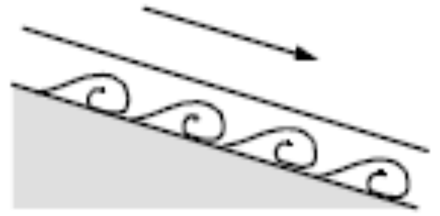
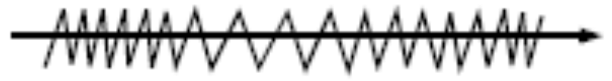
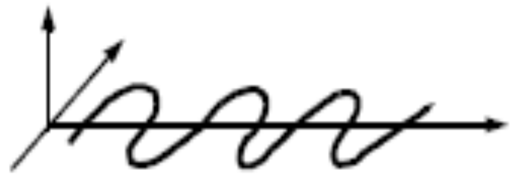
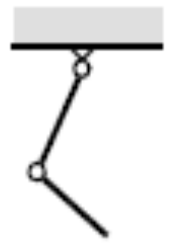
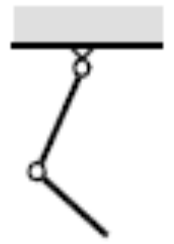
Locomotion Concepts

Spring 2017

Péter Fankhauser, Marco Hutter
Roland Siegwart, Margarita Chli, Martin Rufli

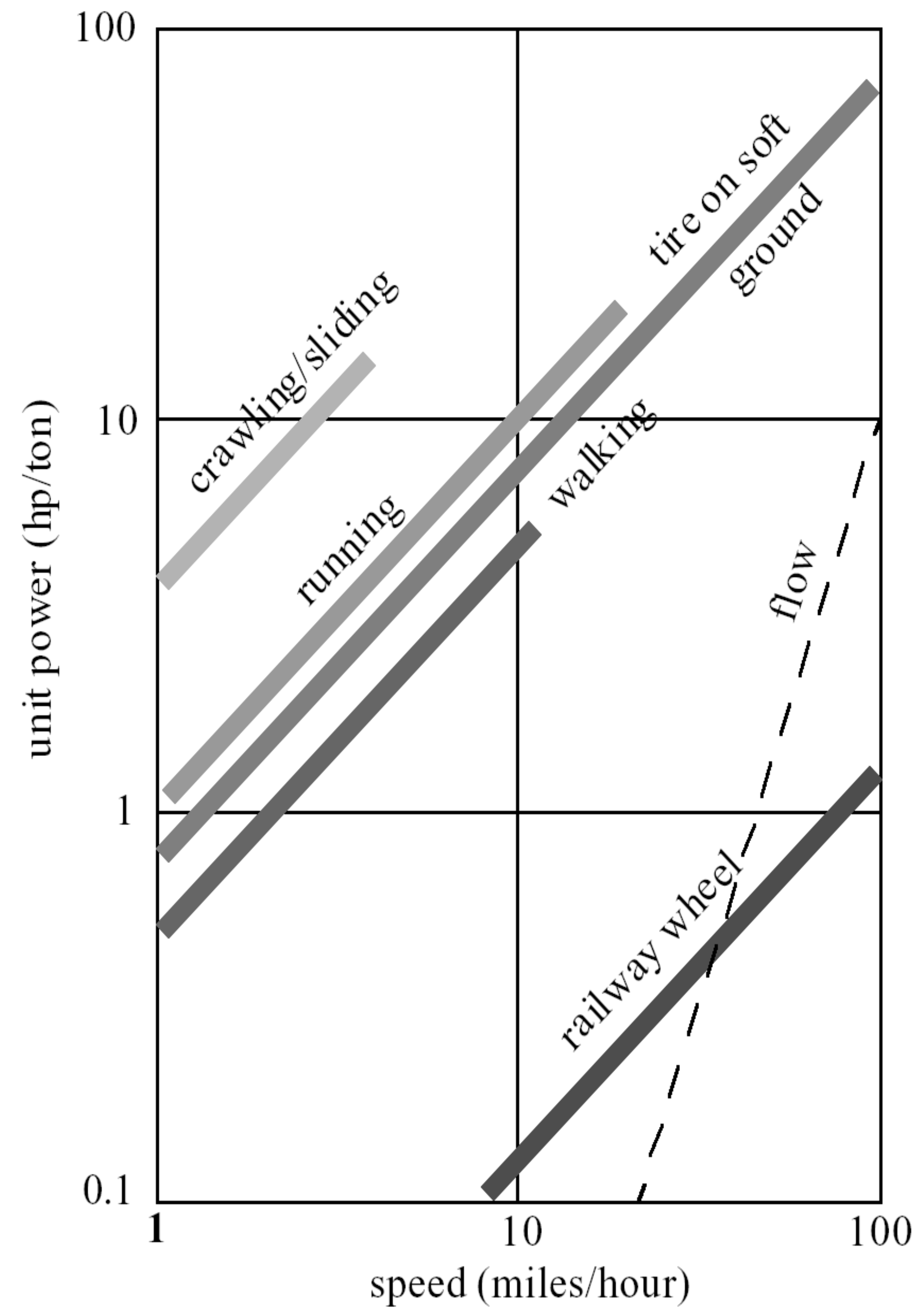
Autonomous Systems Lab
RSL Robotic Systems Lab

Locomotion Concepts
Principles Found in Nature

Type of motion	Resistance to motion	Basic kinematics of motion
Flow in a Channel 	Hydrodynamic forces	Eddies 
Crawl 	Friction forces	 Longitudinal vibration
Sliding 	Friction forces	 Transverse vibration
Running 	Loss of kinetic energy	Oscillatory movement of a multi-link pendulum 
Jumping 	Loss of kinetic energy	Oscillatory movement of a multi-link pendulum 
Walking 	Gravitational forces	Rolling of a polygon (see figure 2.2) 

- Nature came up with a multitude of locomotion concepts
- Concepts found in nature
  - Difficult to imitate technically
  - Do not employ wheels
  - Sometimes imitate wheels (bipedal walking)

Locomotion Concepts
Principles Found in Nature

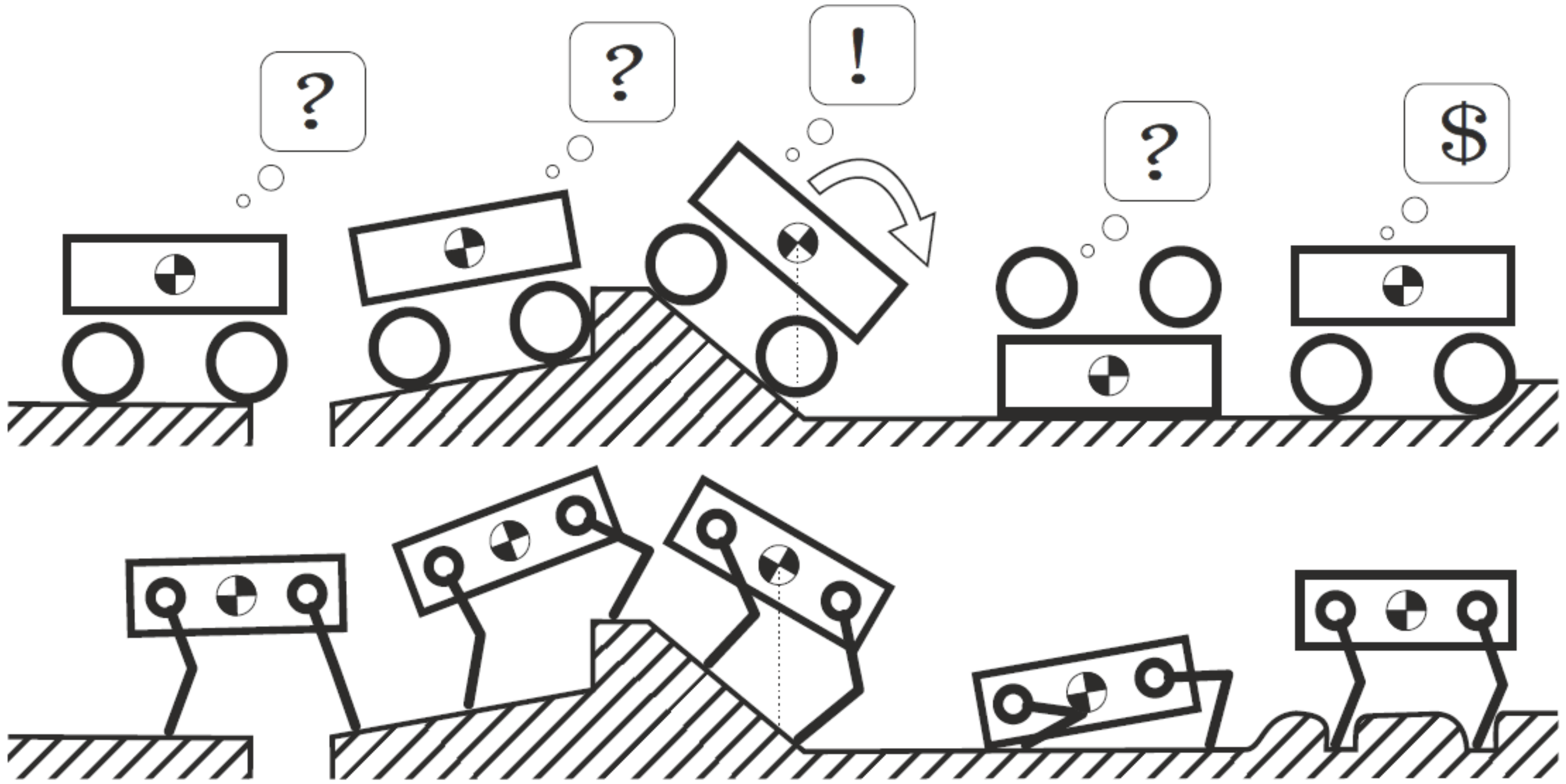


- Nature came up with a multitude of locomotion concepts
- Concepts found in nature
  - Difficult to imitate technically
  - Do not employ wheels
  - Sometimes imitate wheels (bipedal walking)
- Most technical systems today use wheels or caterpillars

Locomotion Concepts
Walking vs. Rolling

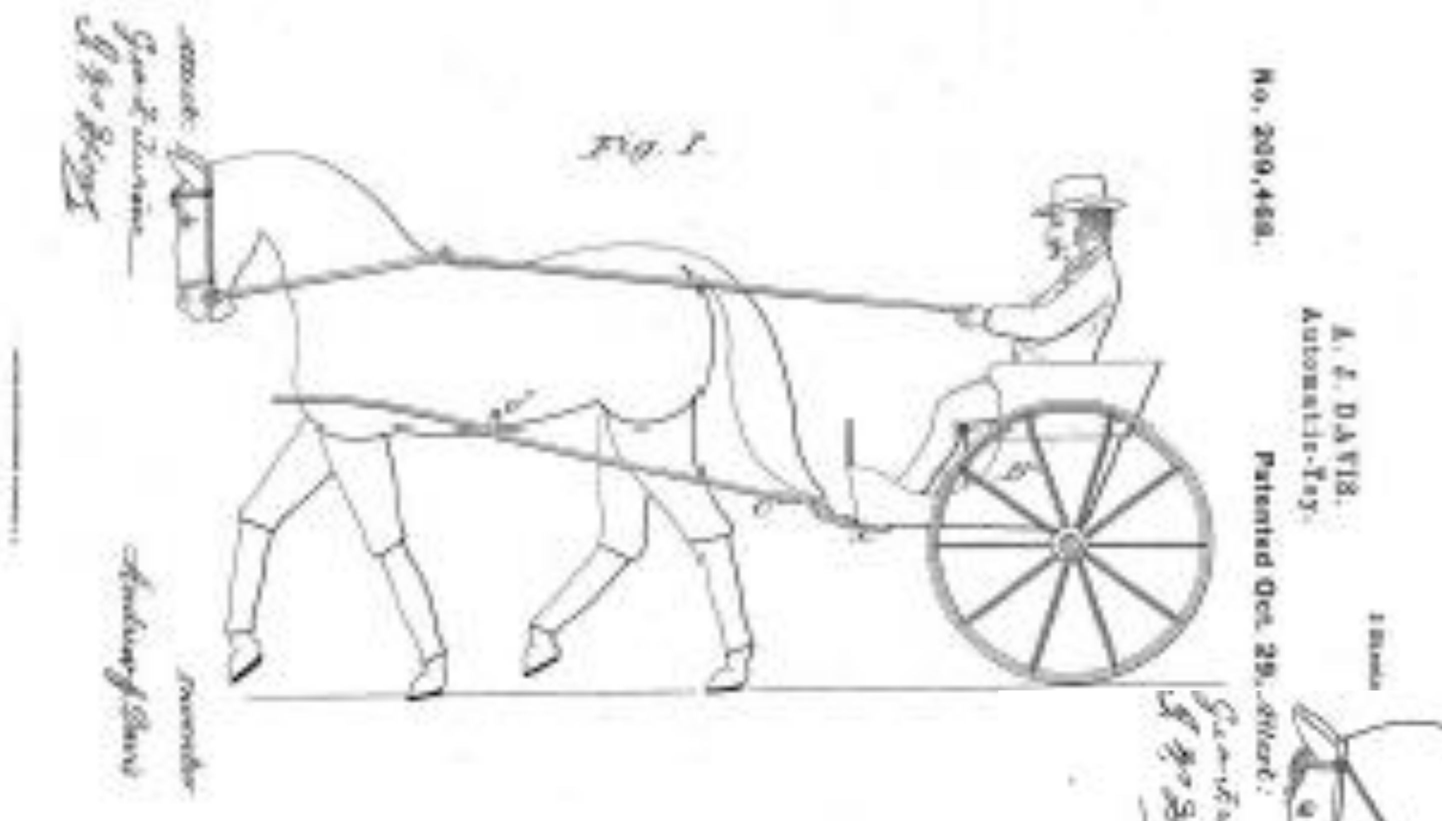
- Legged systems can overcome many obstacles

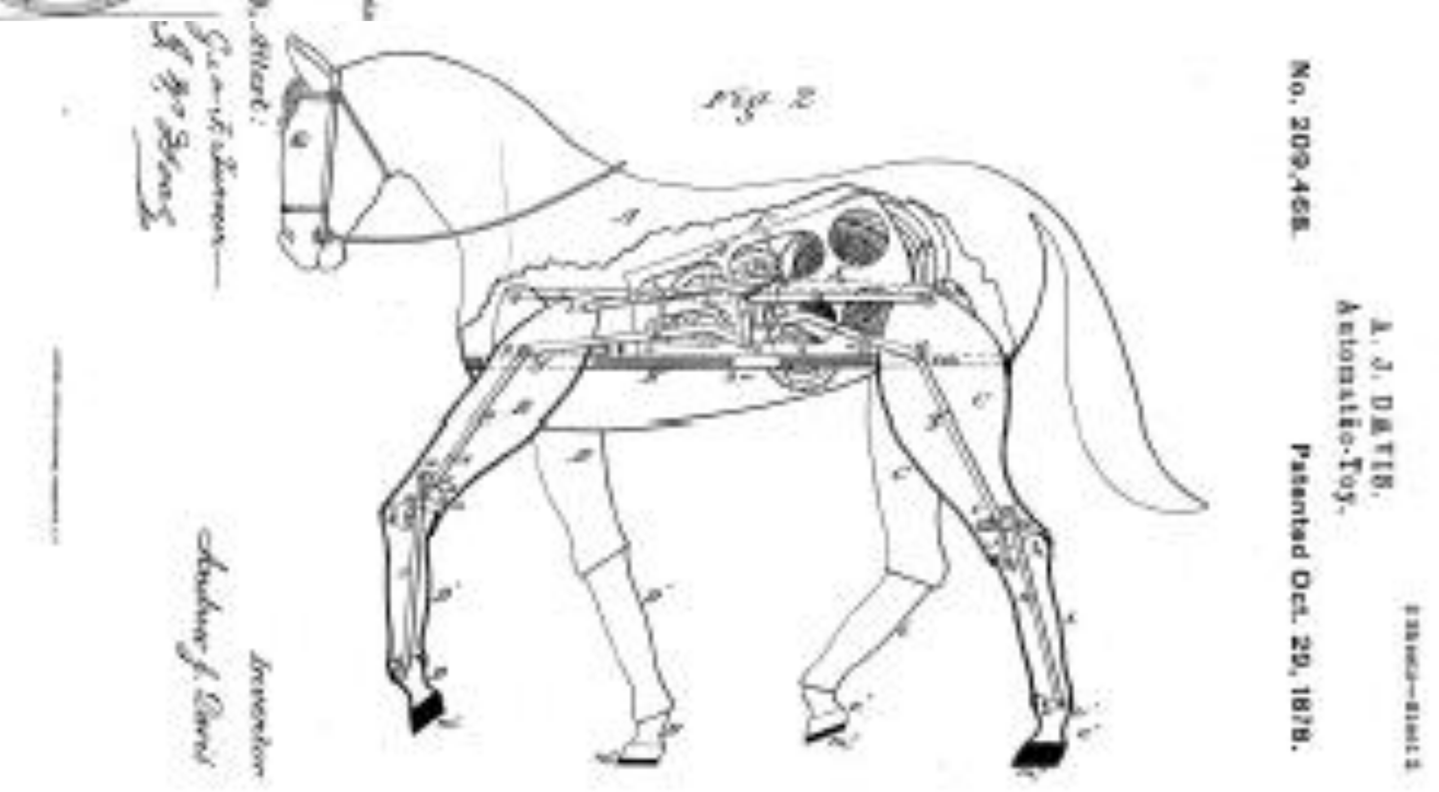
Locomotion Concepts
Walking vs. Rolling



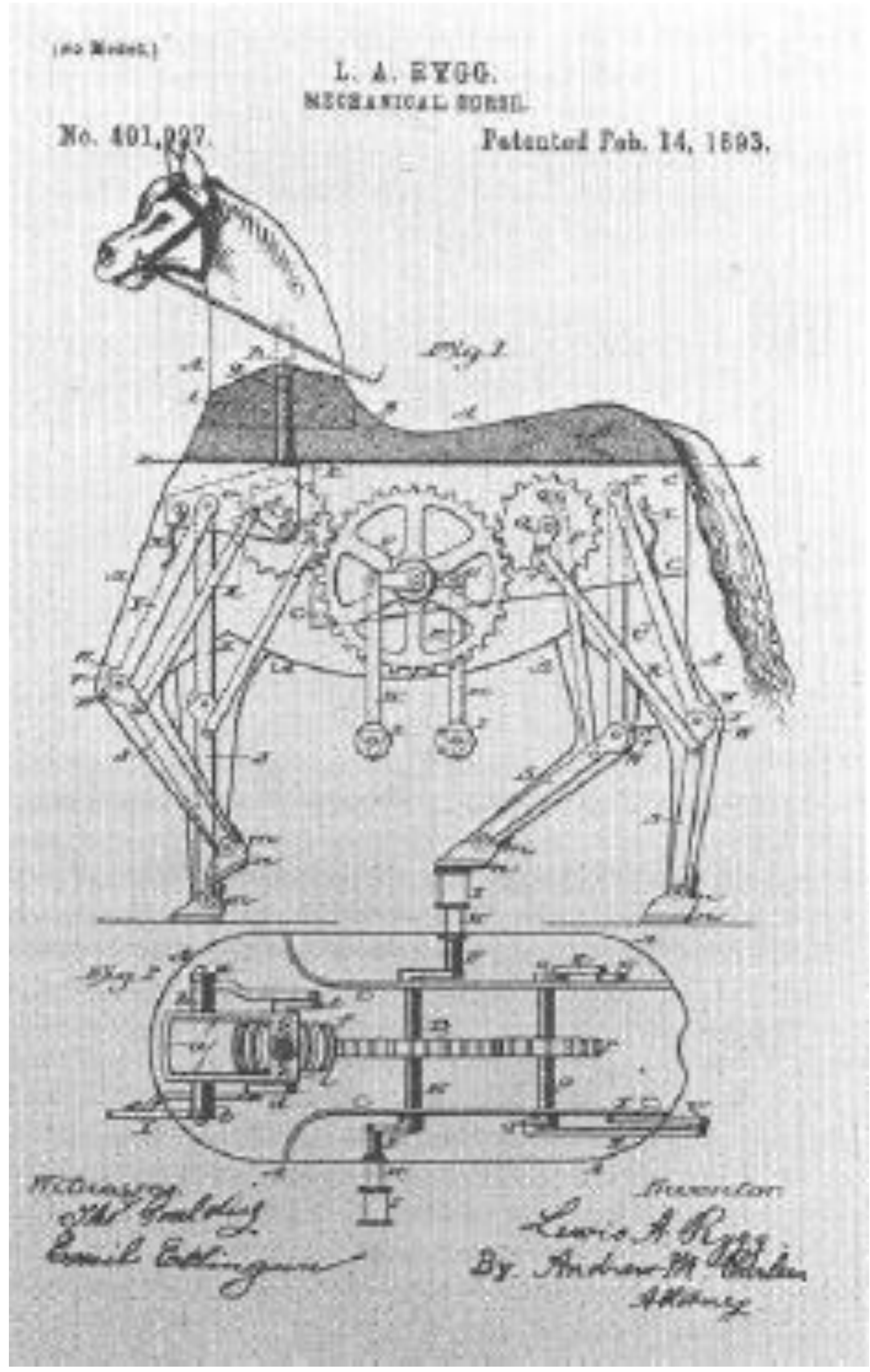
- Legged systems can overcome many obstacles
- But it is hard to achieve this:
  - Floating base (vs. fixed-base)
  - Many DOFs must be controlled in a coordinated way
  - The robot must interact with (uncertain) terrain

History of Legged Robotics
Walking Mechanism – First Patents



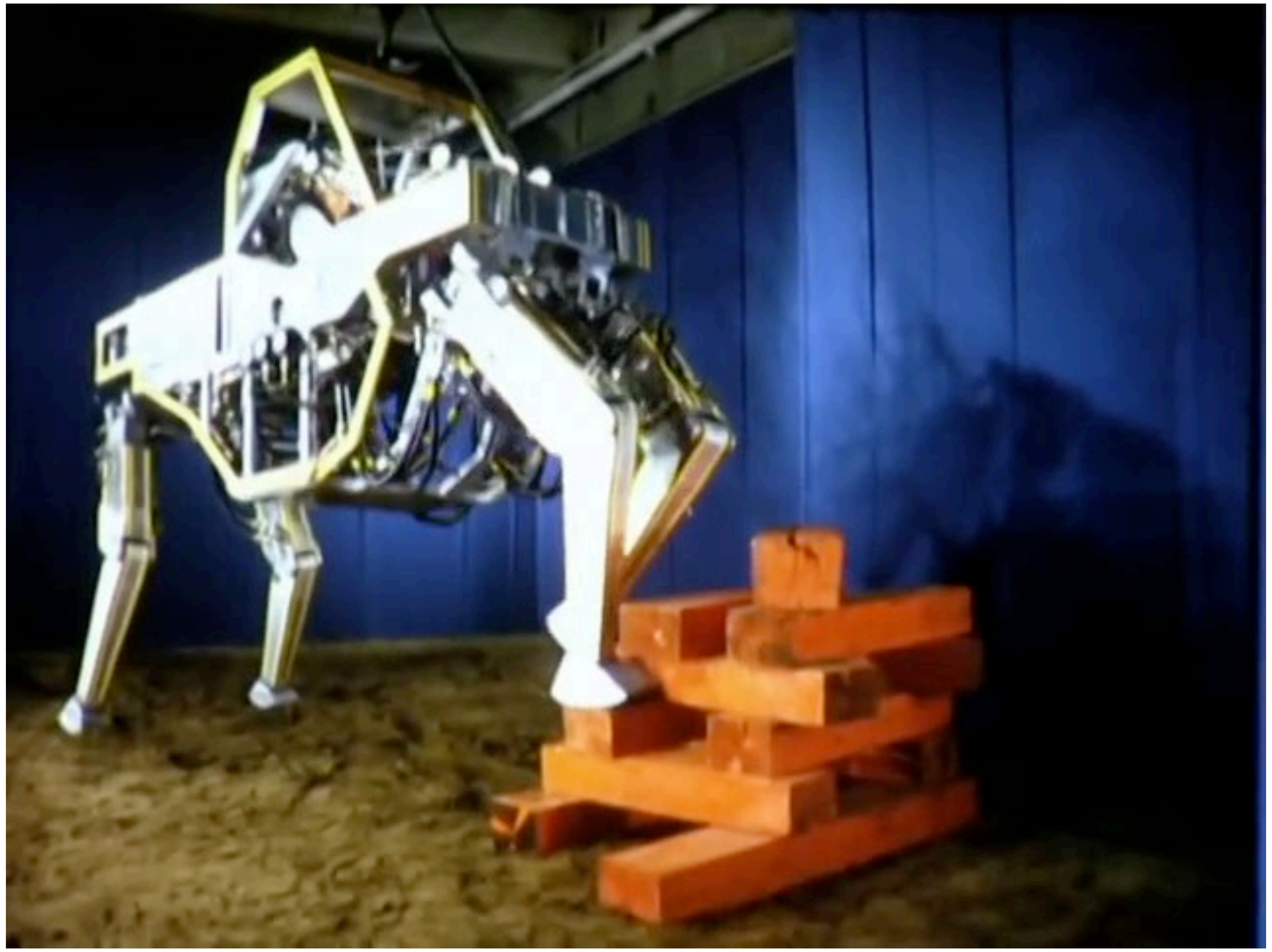


Davis, 1878

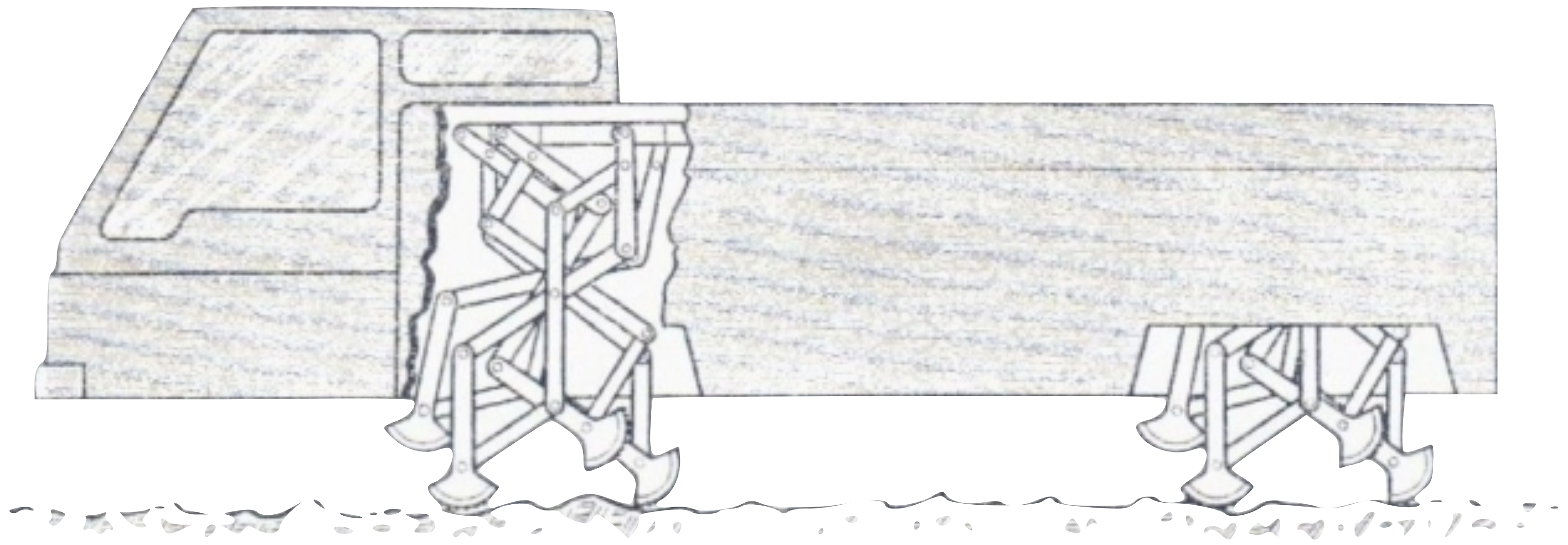


Rygg, 1893

History of Legged Robotics
Walking Mechanisms



General Electric’s Walking Truck, ca. 1965



Shigley's Walking Machines, 1957–60

History of Legged Robotics
Walking Mechanisms

OSU ASV (Adaptive Suspension Vehicle), 1984

History of Legged Robotics
Large Scale Legged Locomotion and Manipulation



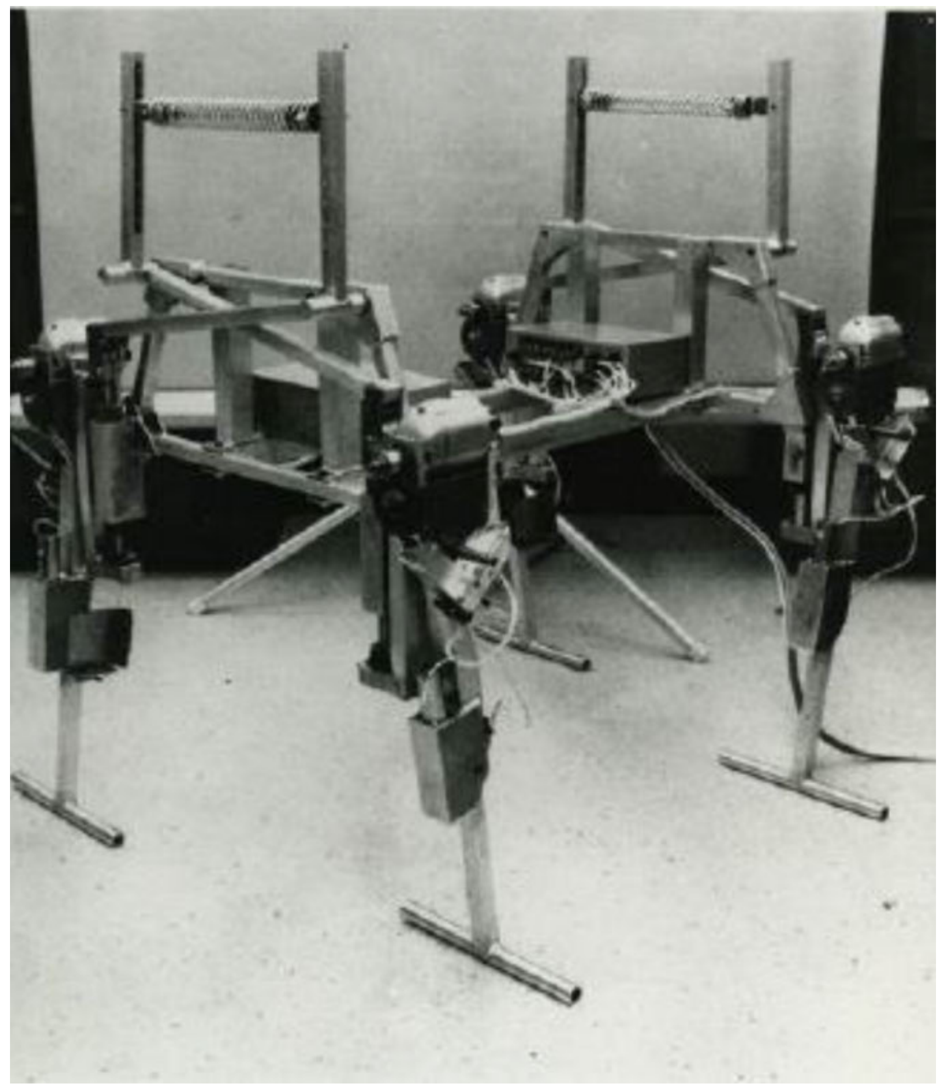


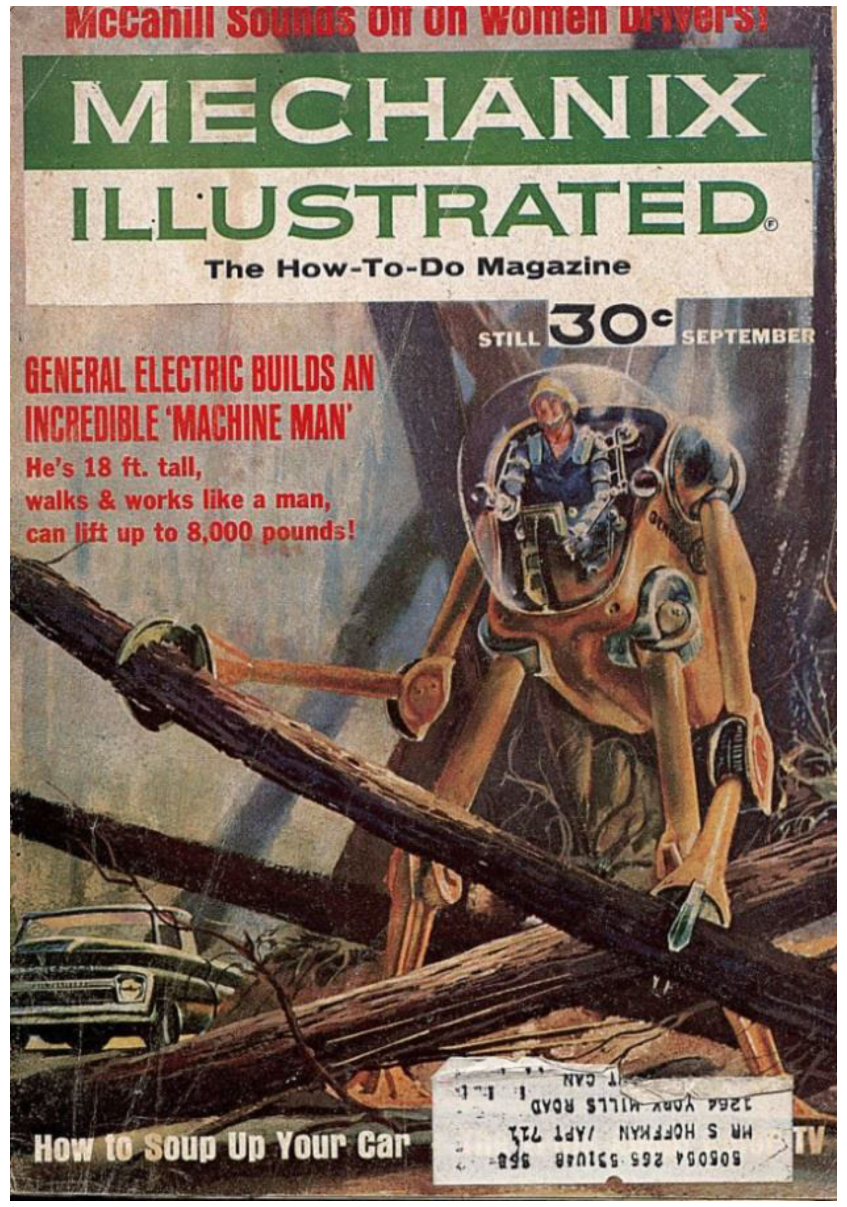


Menzi Muck

History of Legged Robotics

Phony Pony, GE Hardiman and many more…

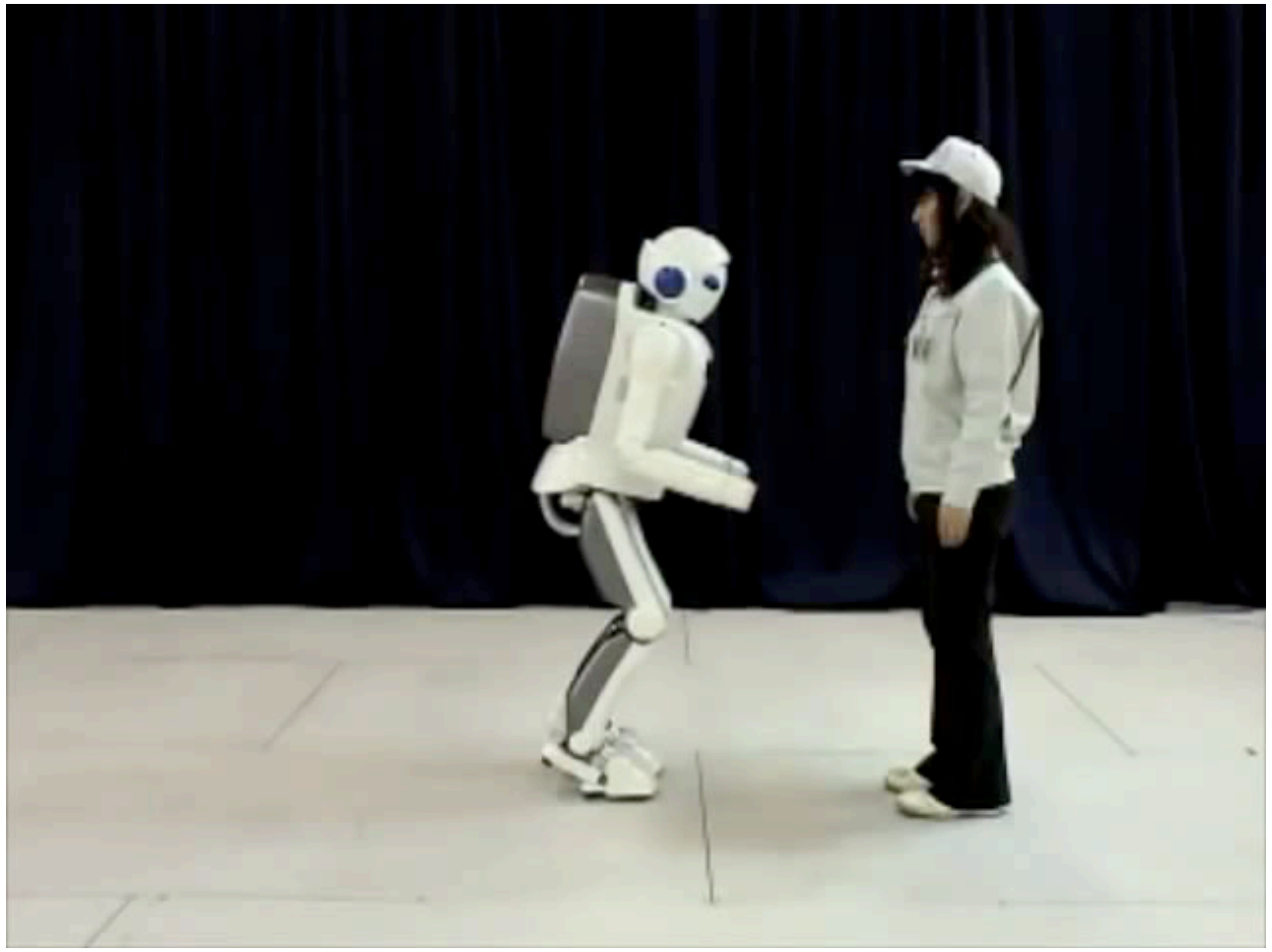




- More on http://cyberneticzoo.com
- steam-actuated humans
- mechanical elephants
- …

History of Legged Robotics
Humanoid Robots After 2000

Honda Asimo

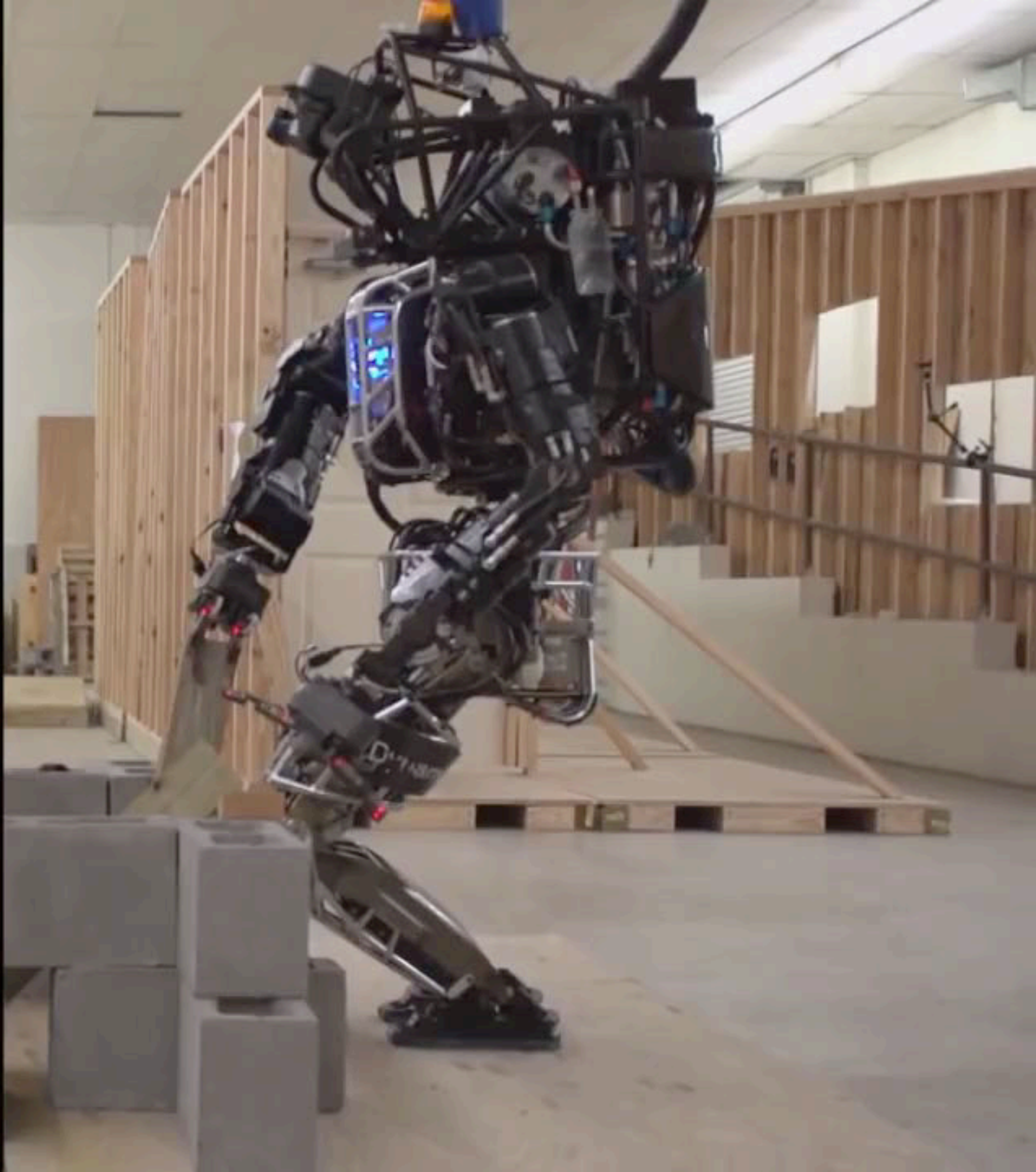


Toyota Humanoid

History of Legged Robotics
Humanoid Robots After 2000

Fukushima, 2011

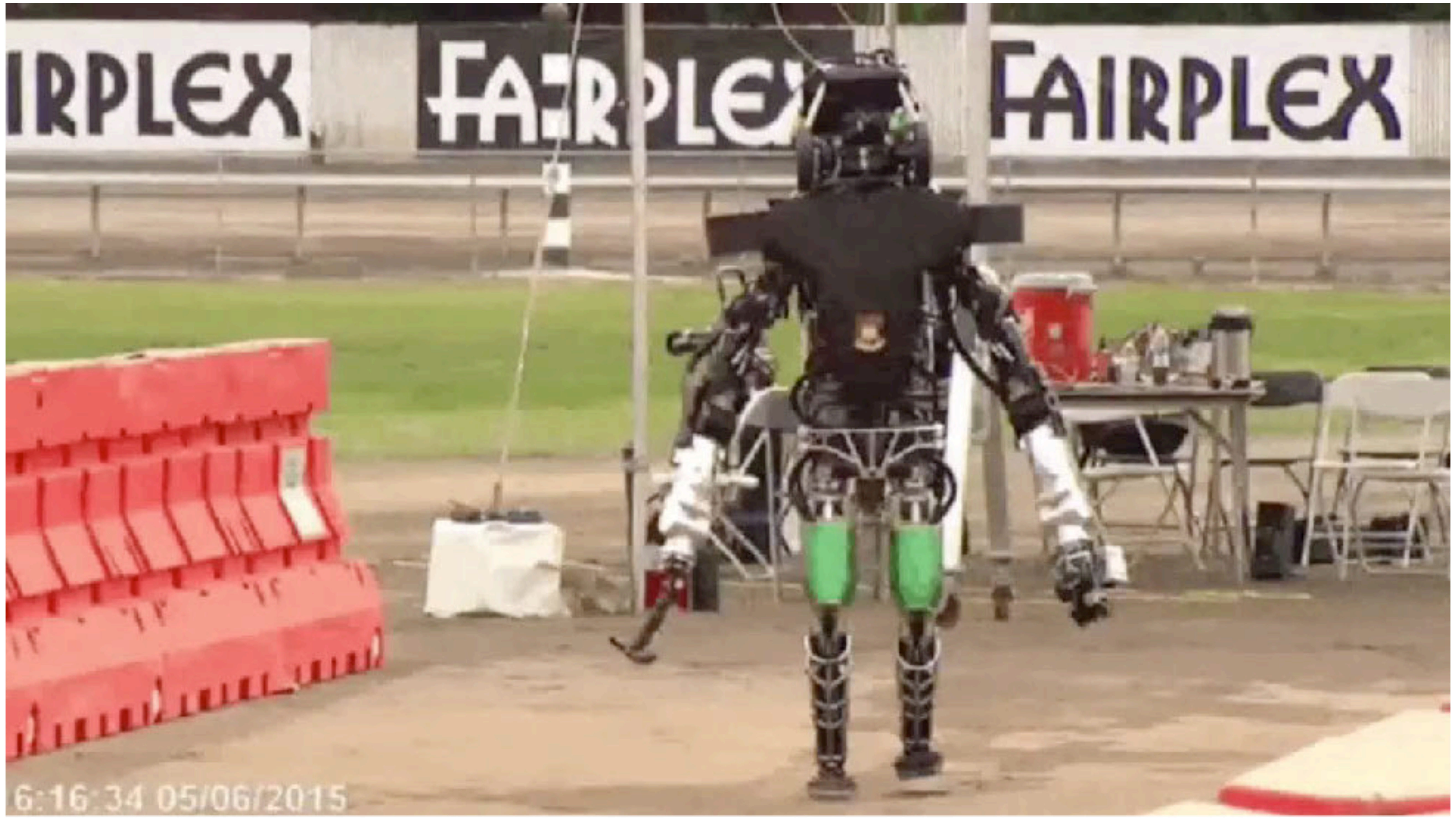
DARPA Robotics Challenge, 2012

DARPA Robotics Challenge

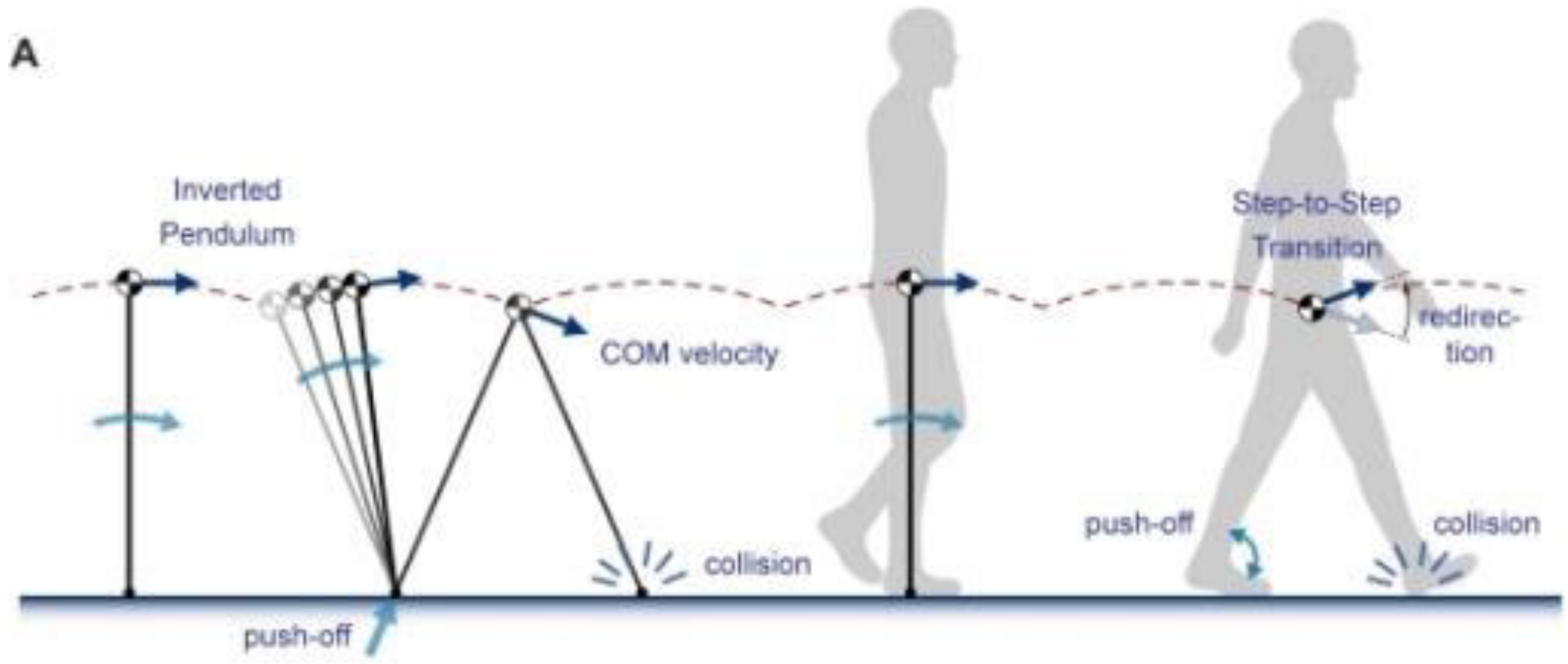
… and a thing we learned after the DRC Finals

Walking is still difficult

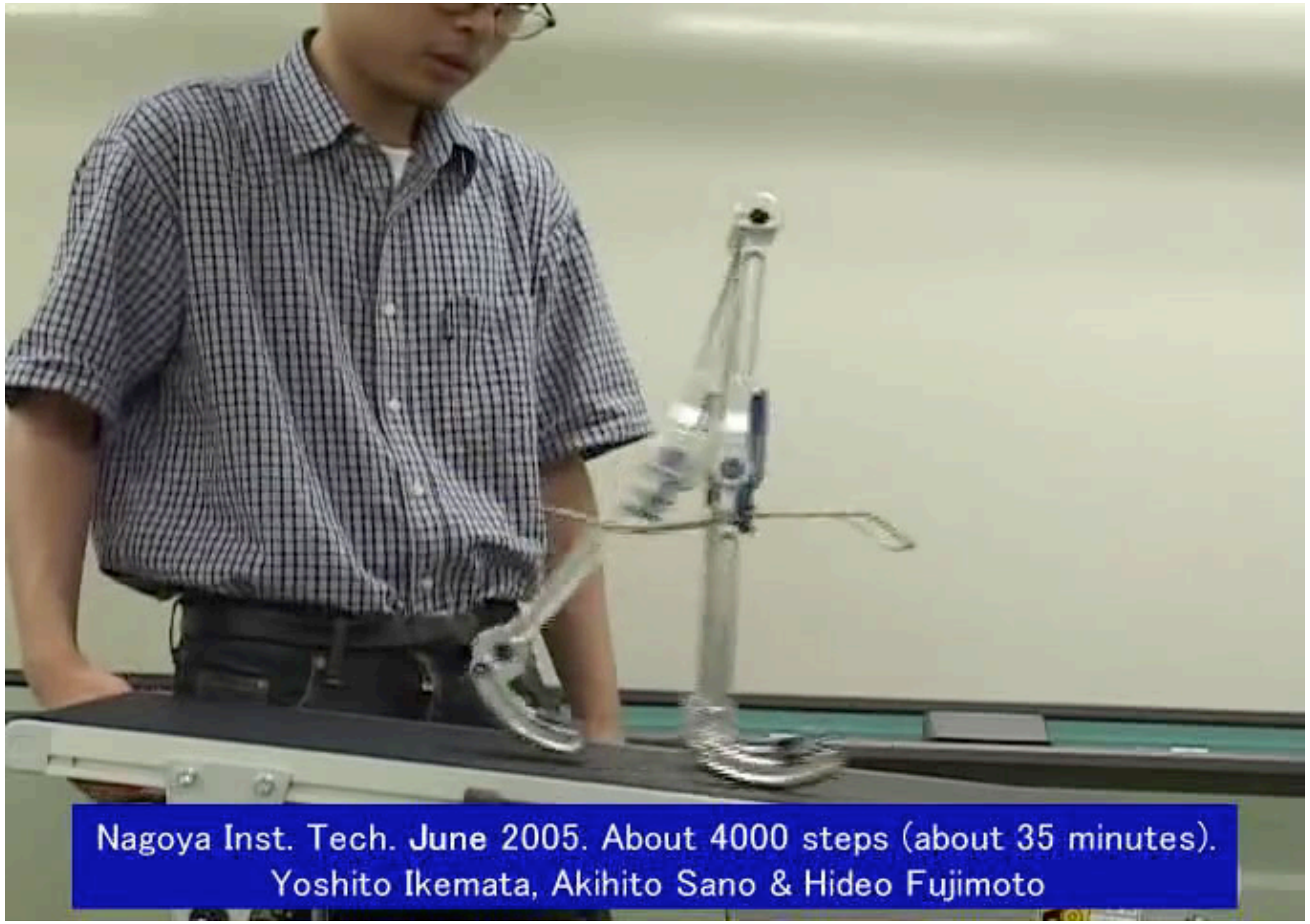


Modeling Legged Locomotion
Inverted Pendulum

Walking can be represented by an inverted pendulum



Modeling Legged Locomotion
Passive Dynamic Walker



- Exploit the inverted pendulum character in *passive dynamic walkers*
- Forward falling combined with passive leg swing
- Energetically very efficient

Modeling Legged Locomotion
Passive Dynamic Walker

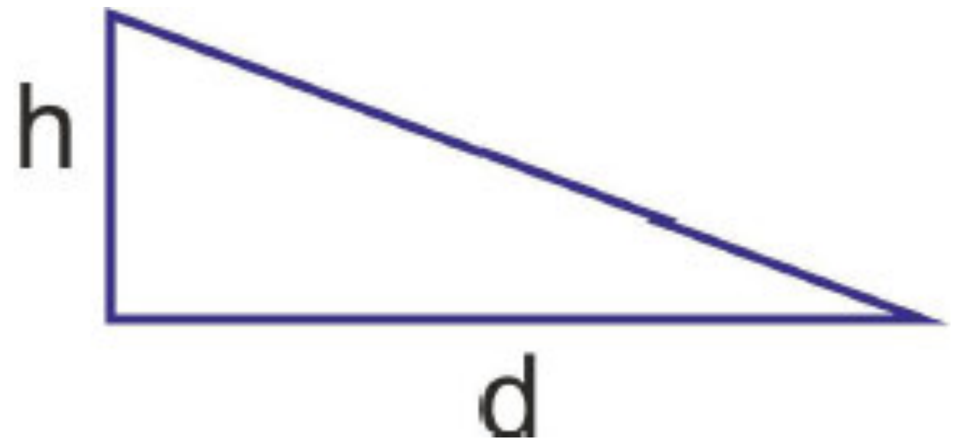
- Add little actuation to walk on flat ground

Cornell Ranger, 2011

Total distance	65.24 km
Total time	30:49:02
Power	16.0 W
COT	0.28

Modeling Legged Locomotion
Cost of Transport (COT)

$$COT = \frac{E_{used}}{m \cdot g \cdot d} = \frac{m \cdot g \cdot h}{m \cdot g \cdot d} = \frac{h}{d}$$



$c_{mt}^{est.} \approx 1.6$

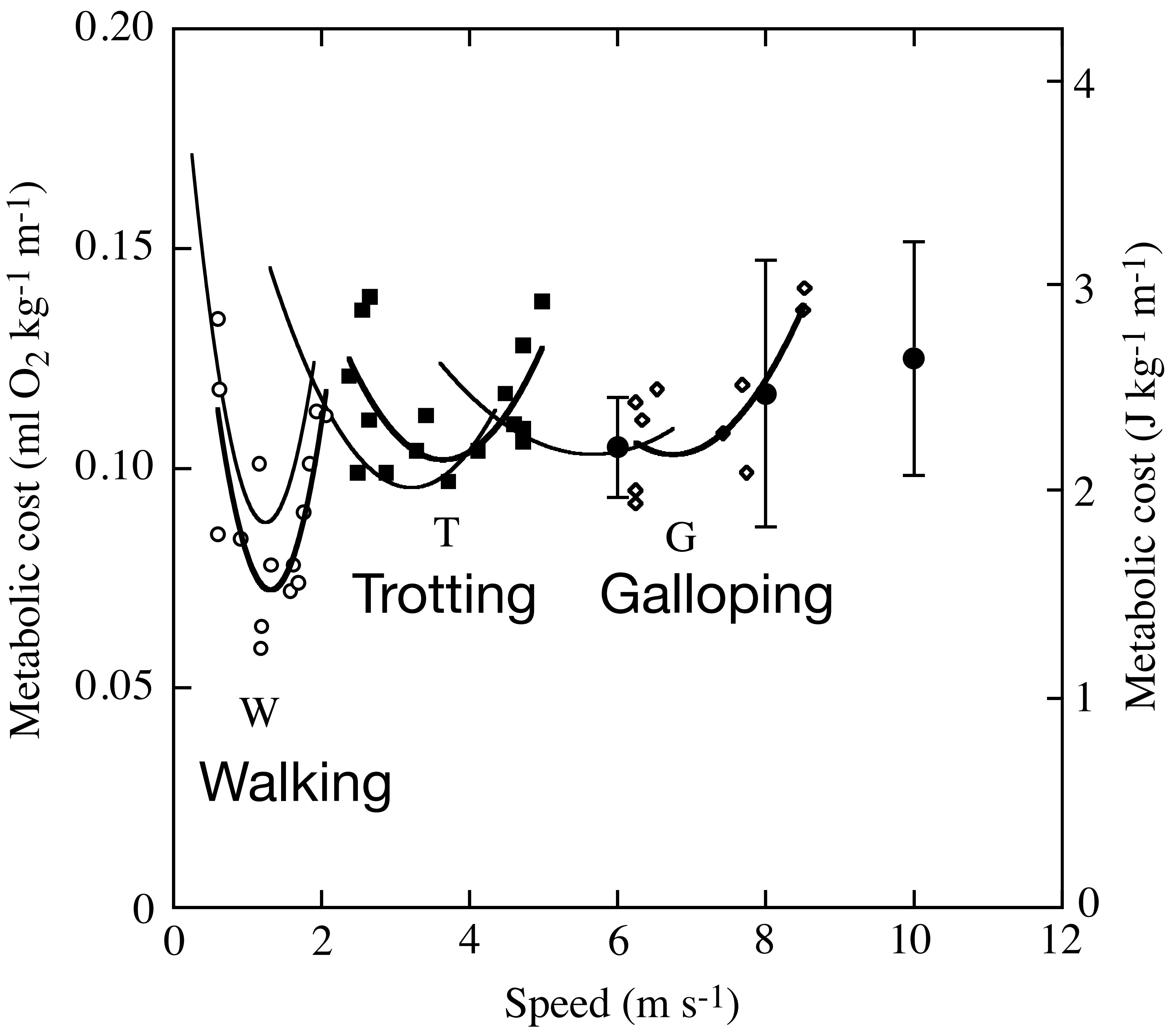
Collins *et al.* 2005

$c_{mt} \approx 0.31$

$c_{mt} \approx 0.055$

Collins *et al.* 2005

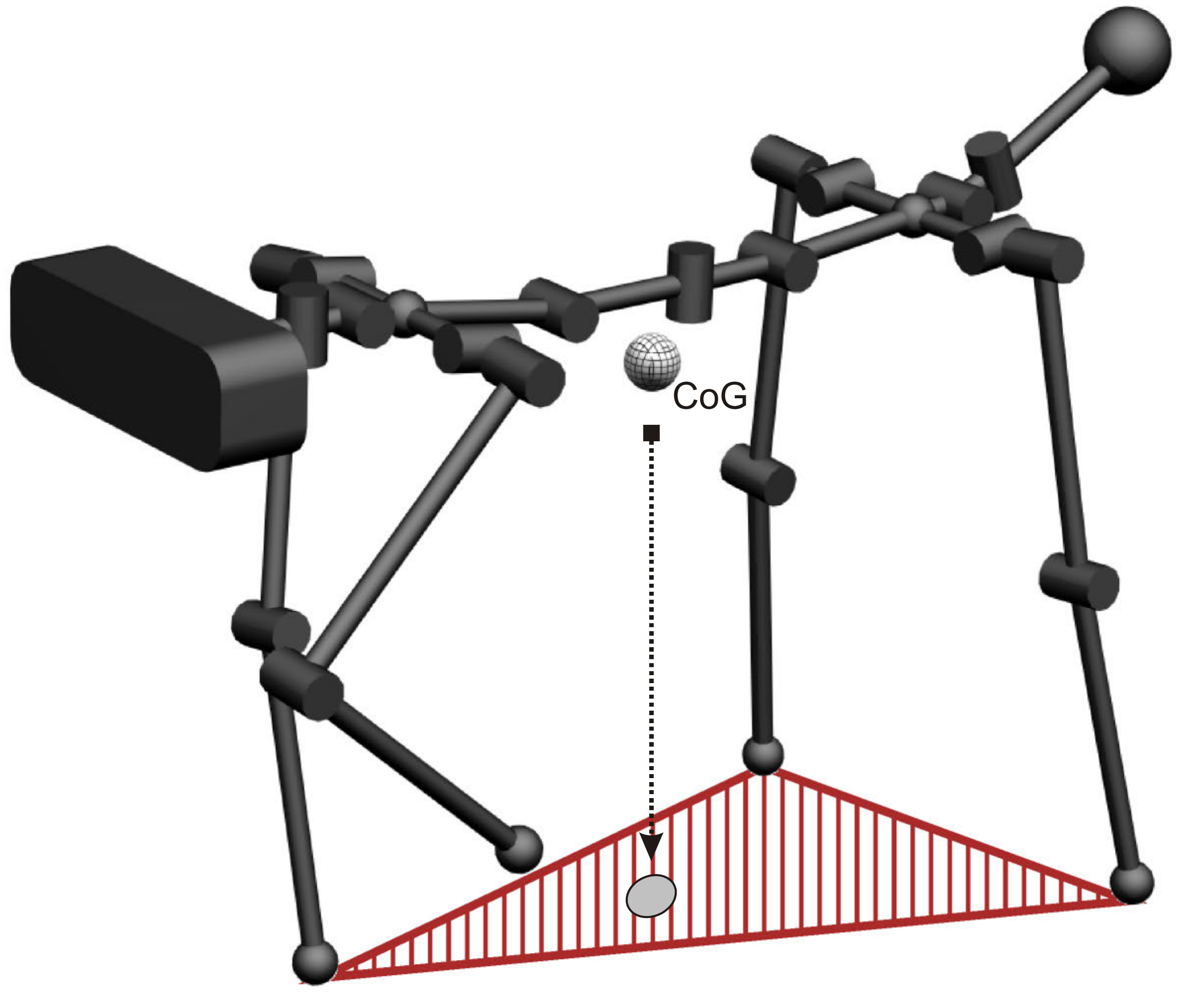
Modeling Legged Locomotion
Energy Expenditure for Different Gaits

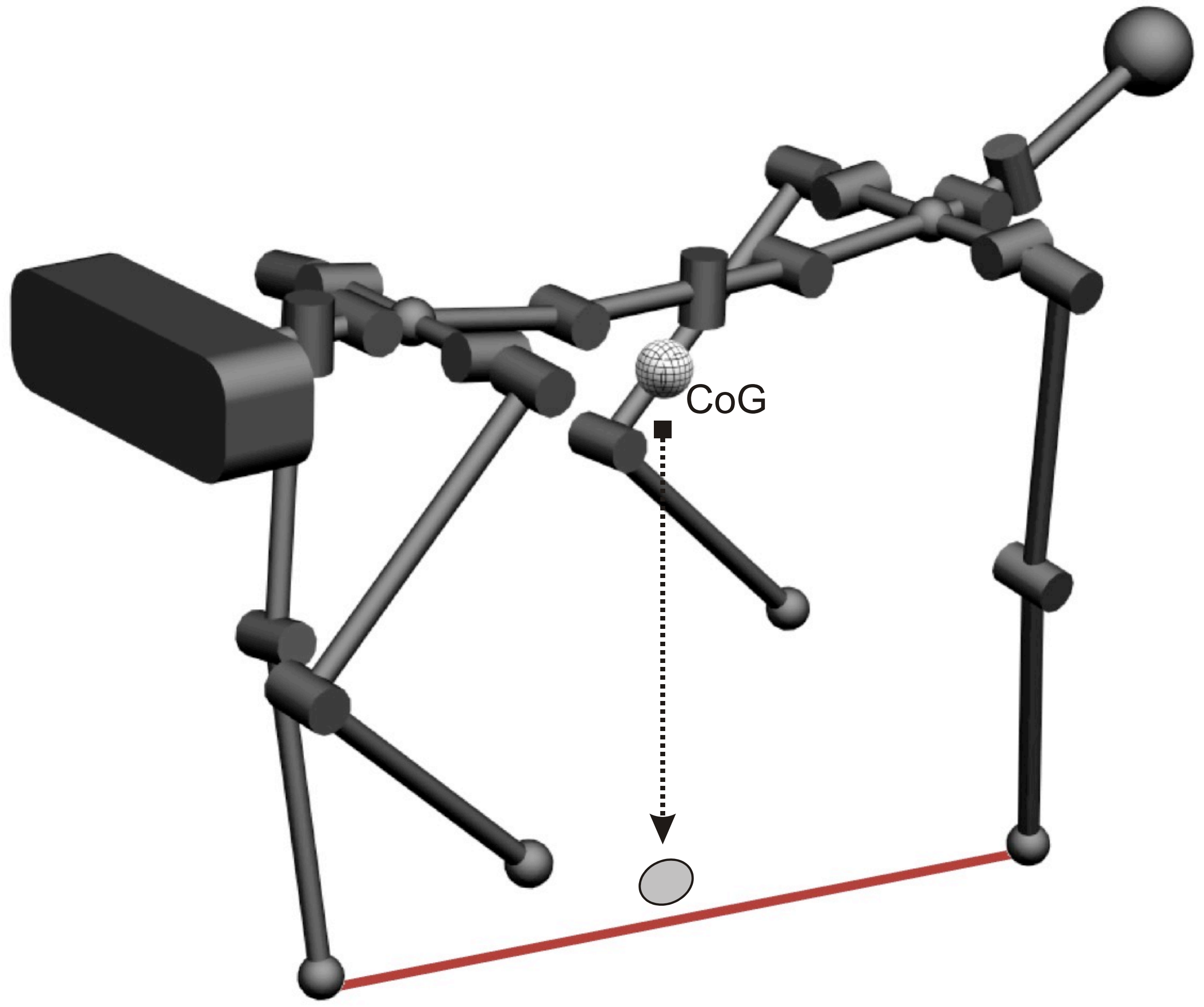


- Each gait has a specific velocity that minimizes energy expenditure
- Explains why animals and humans change gait for different speeds

Metabolic cost of transportation (normalized for body mass) for different gaits of horses
Minetti, 1999

Modeling Legged Locomotion
Dynamic vs. Static Locomotion



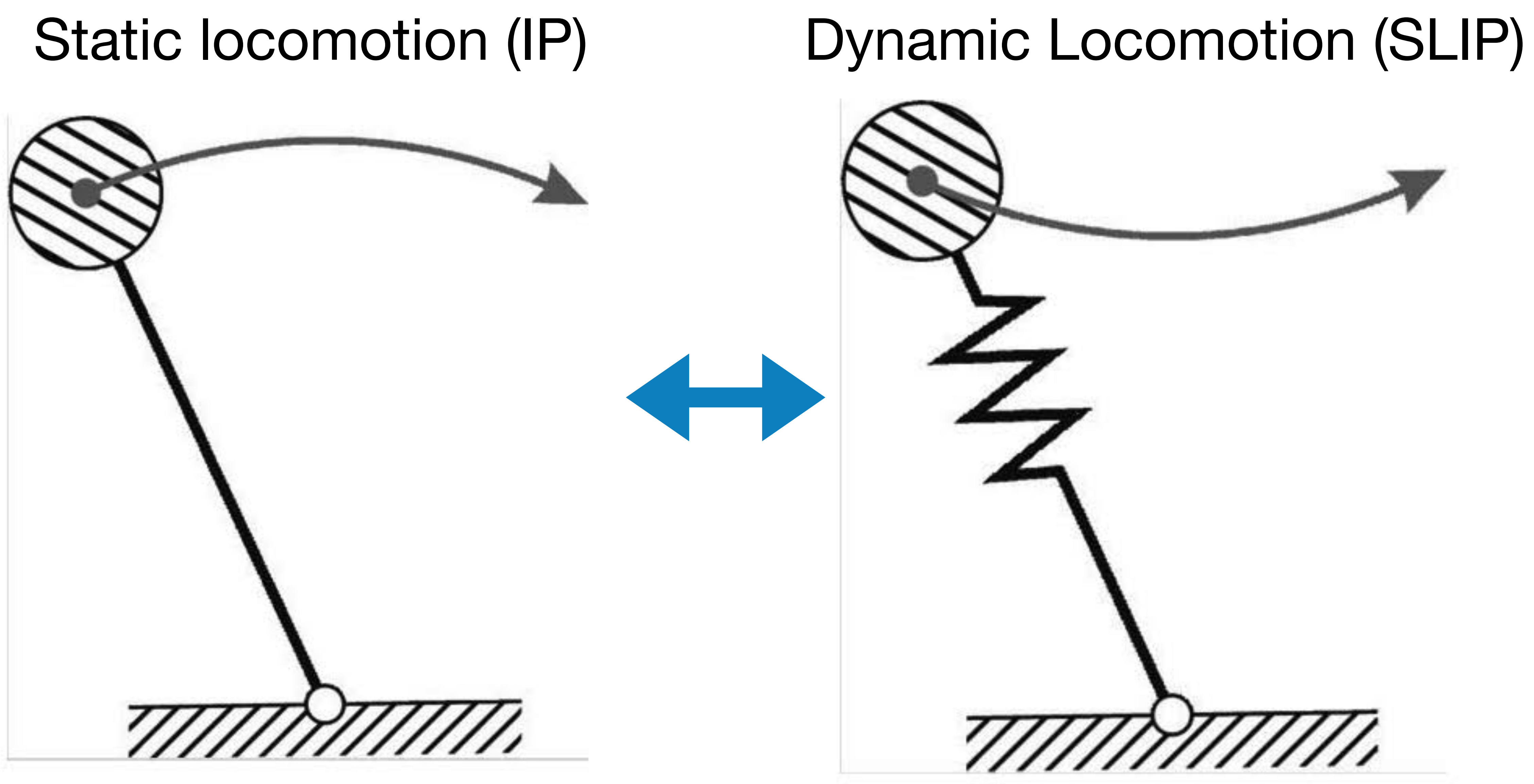


Statically stable
- Bodyweight supported by at least three legs
- Even if all joints 'freeze' instantaneously, the robot will not fall
- Safe and slow

Dynamically stable
- The robot will fall if not continuously moving
- Less than three legs can be in ground contact
- Fast and demanding for actuation and control

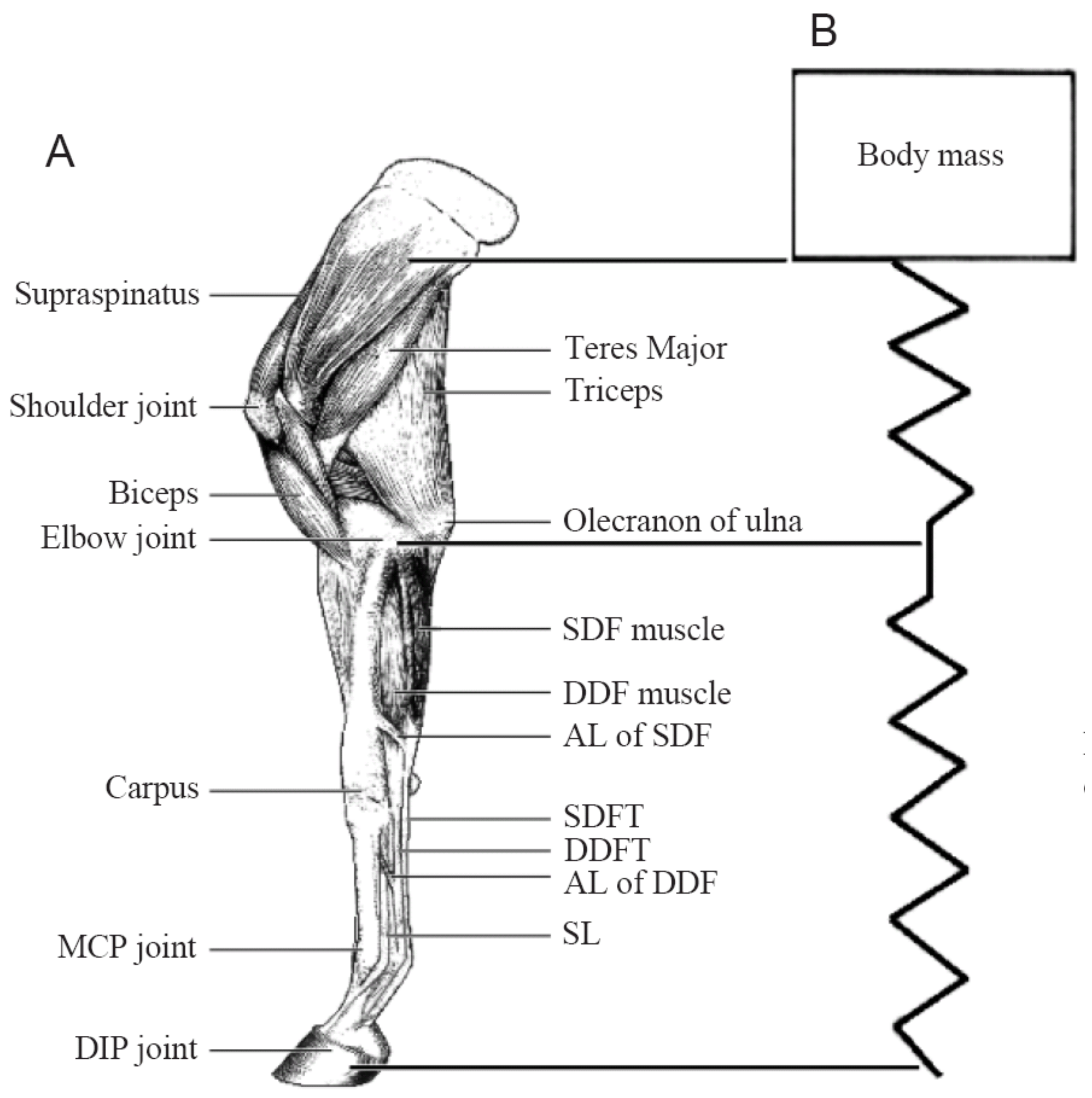
Modeling Legged Locomotion
Dynamic Locomotion

Modeling Legged Locomotion
Dynamic Locomotion: Leg Structure



- Leg during running is not an inverted pendulum
- Spring loaded inverted pendulum (SLIP)

Modeling Legged Locomotion
Dynamic Locomotion: Leg Structure



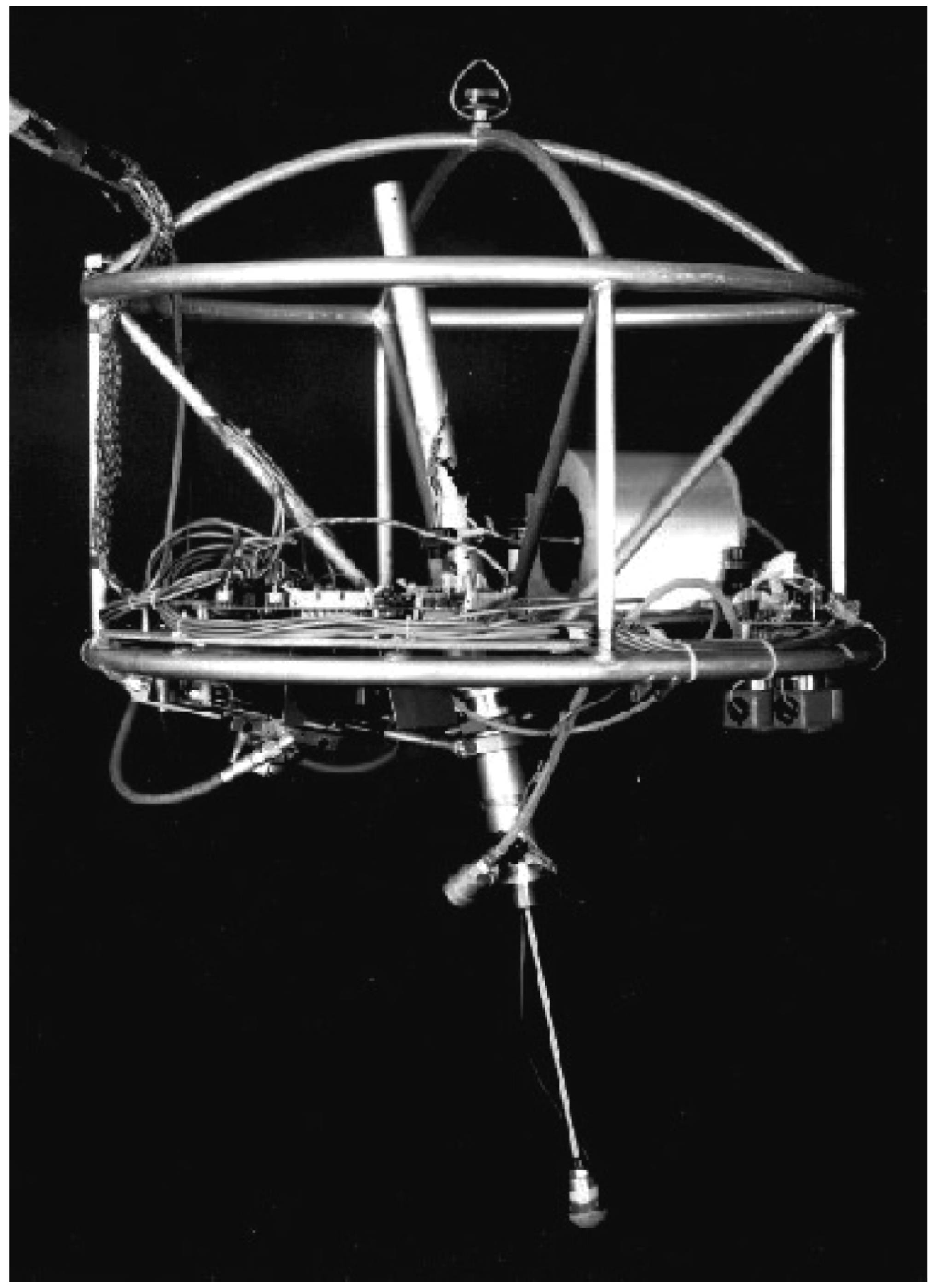
McGuigan & Wilson, 2003 – *J. Exp. Bio.*

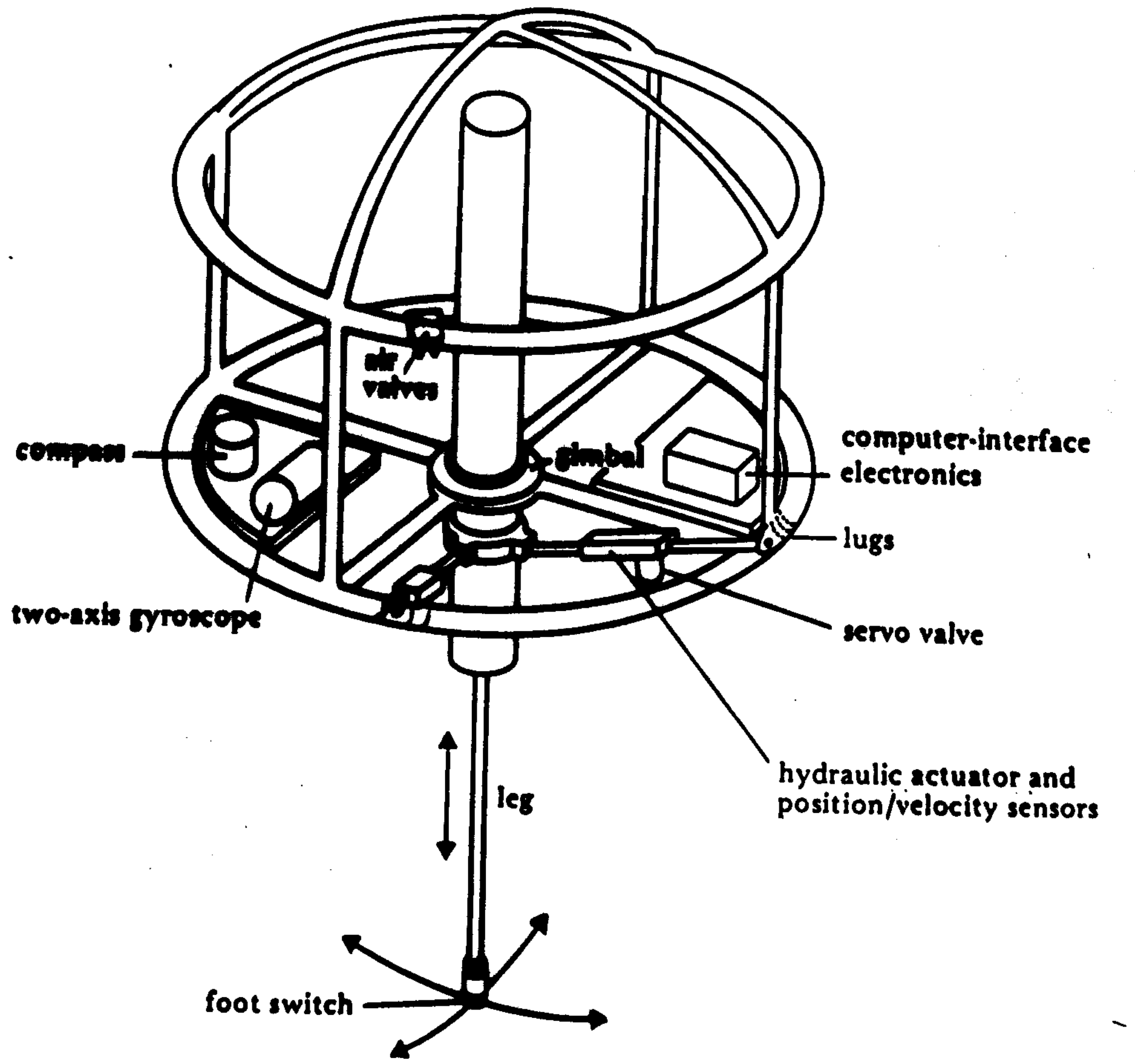
- Leg during running is not an inverted pendulum
- Spring loaded inverted pendulum (SLIP)
  - are robust against collisions
  - can better handle uncertainties
  - can temporarily store energy
  - reduce peak power

  [Alexander 1988, 1990, 2002, 2003]

Dynamic Locomotion
SLIP Principles in Robotics

- Pneumatic piston
- Hydraulic leg “angle” orientation

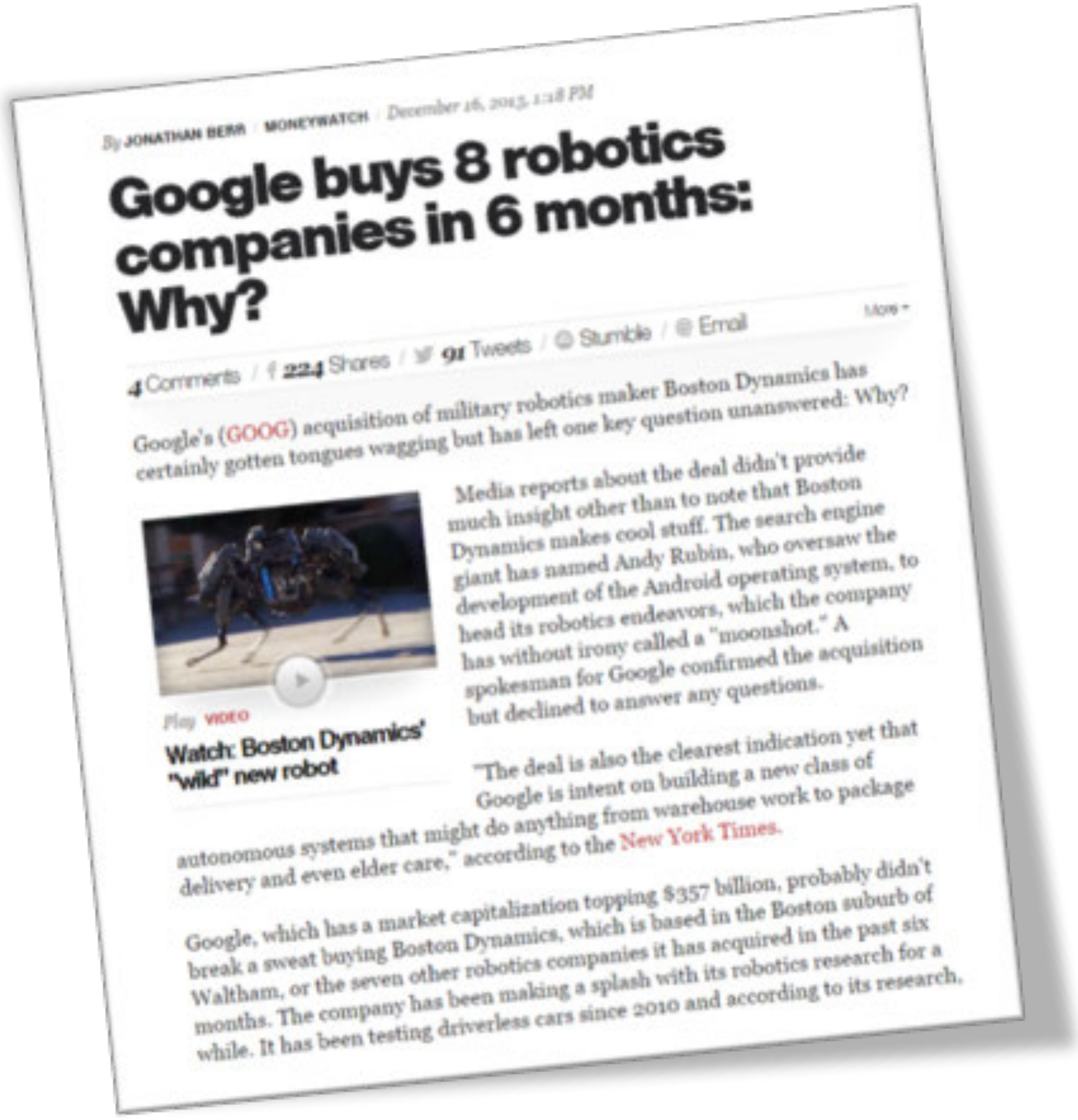




Early Raibert hoppers (MIT Leg Lab), 1983

Dynamic Locomotion
From Raibert Hopper to Humanoids and Quadrupeds

- Boston Dynamics
  - Founded 1992
  - Big Dog V1 (2005)
  - Big Dog V2 (2008)



By JONATHAN BERR / MONEYWATCH / December 16, 2013, 1:18 PM

Google buys 8 robotics companies in 6 months: Why?

4 Comments / 224 Shares / 91 Tweets / Stumble / Email / More

Google's (GOOG) acquisition of military robotics maker Boston Dynamics has certainly gotten tongues wagging but has left one key question unanswered: Why?

Media reports about the deal didn't provide much insight other than to note that Boston Dynamics makes cool stuff. The search engine giant has named Andy Rubin, who oversaw the development of the Android operating system, to head its robotics endeavors, which the company has without irony called a "moonshot." A spokesman for Google confirmed the acquisition but declined to answer any questions.

Play VIDEO
Watch: Boston Dynamics' "wild" new robot

"The deal is also the clearest indication yet that Google is intent on building a new class of autonomous systems that might do anything from warehouse work to package delivery and even elder care," according to the New York Times.

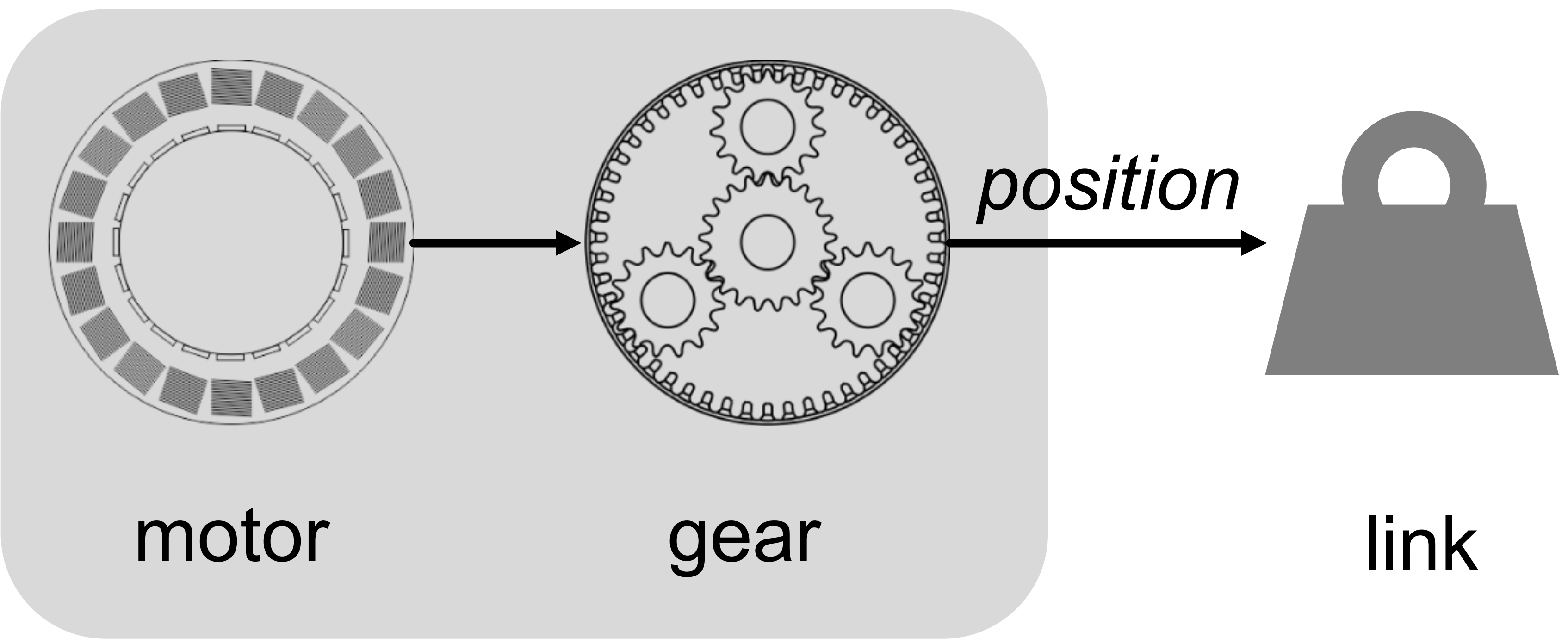
Google, which has a market capitalization topping $357 billion, probably didn't break a sweat buying Boston Dynamics, which is based in the Boston suburb of Waltham, or the seven other robotics companies it has acquired in the past six months. The company has been making a splash with its robotics research for a while. It has been testing driverless cars since 2010 and according to its research.

Dynamic Locomotion
From Raibert Hopper to Humanoids and Quadrupeds

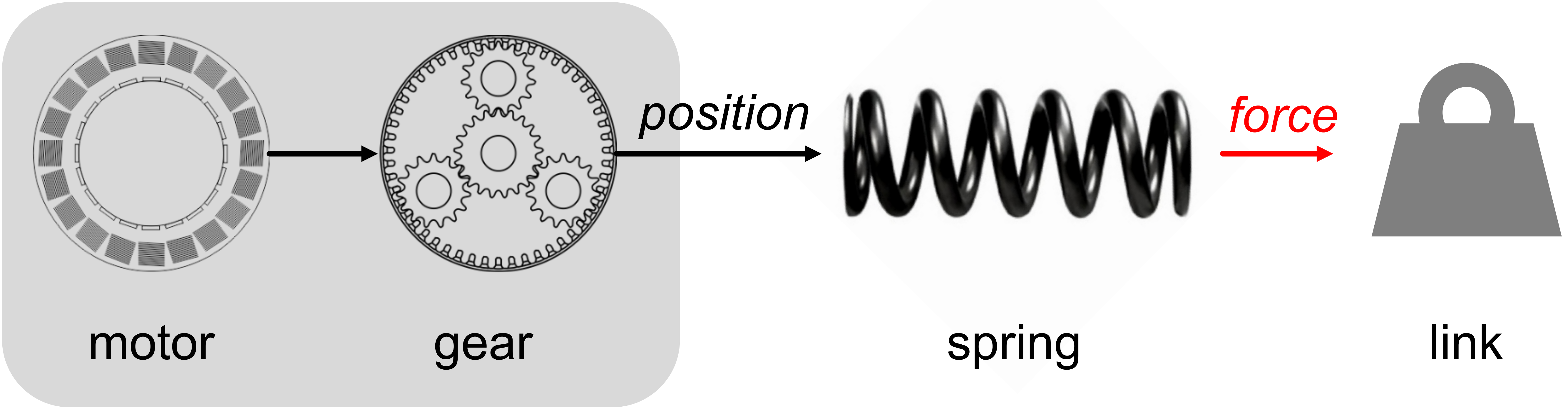
Dynamic Locomotion
From Raibert Hopper to Humanoids and Quadrupeds

Series Elastic Actuators
From Position to Force Controlled Systems

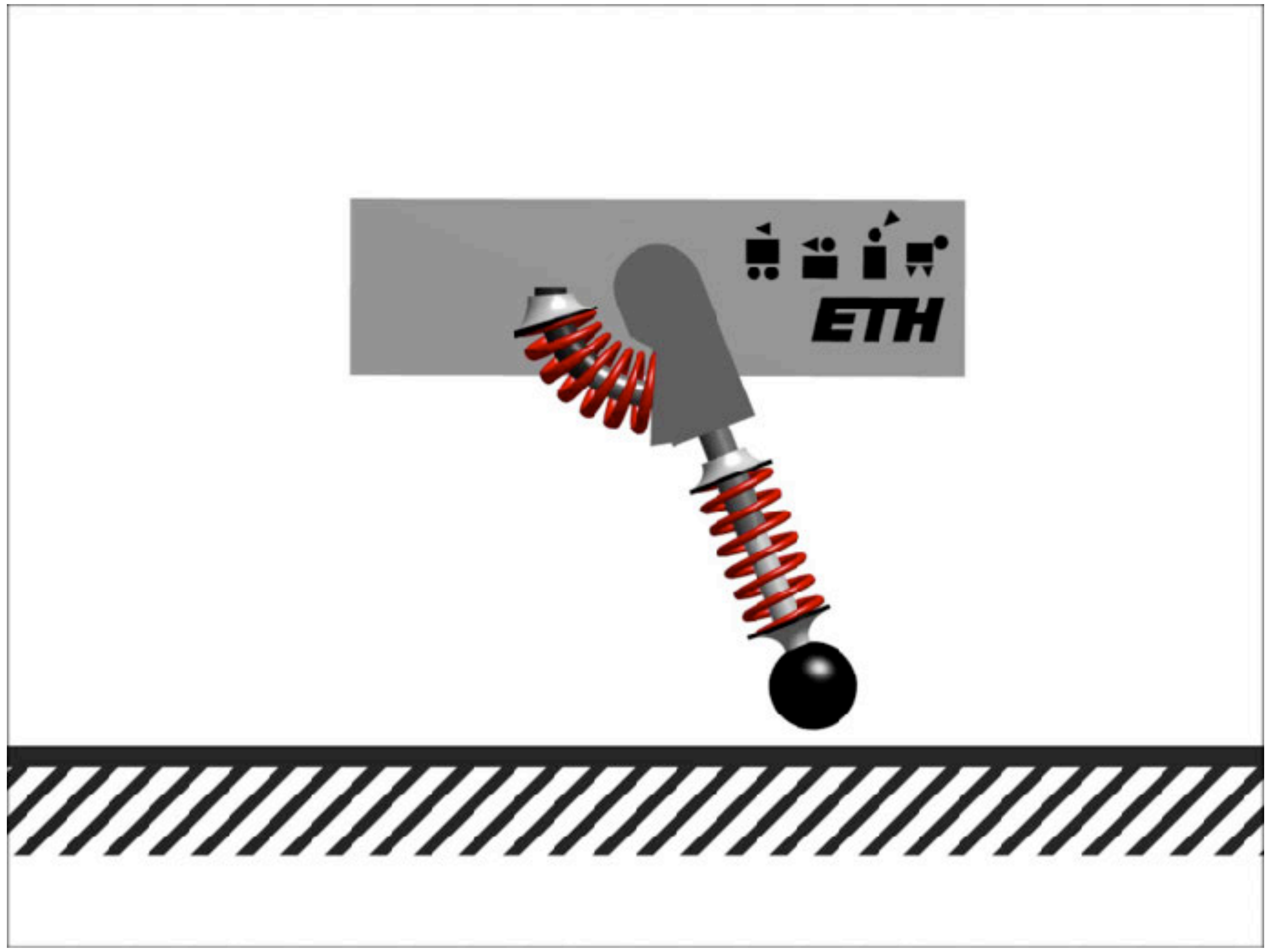
- Kinematic, position control

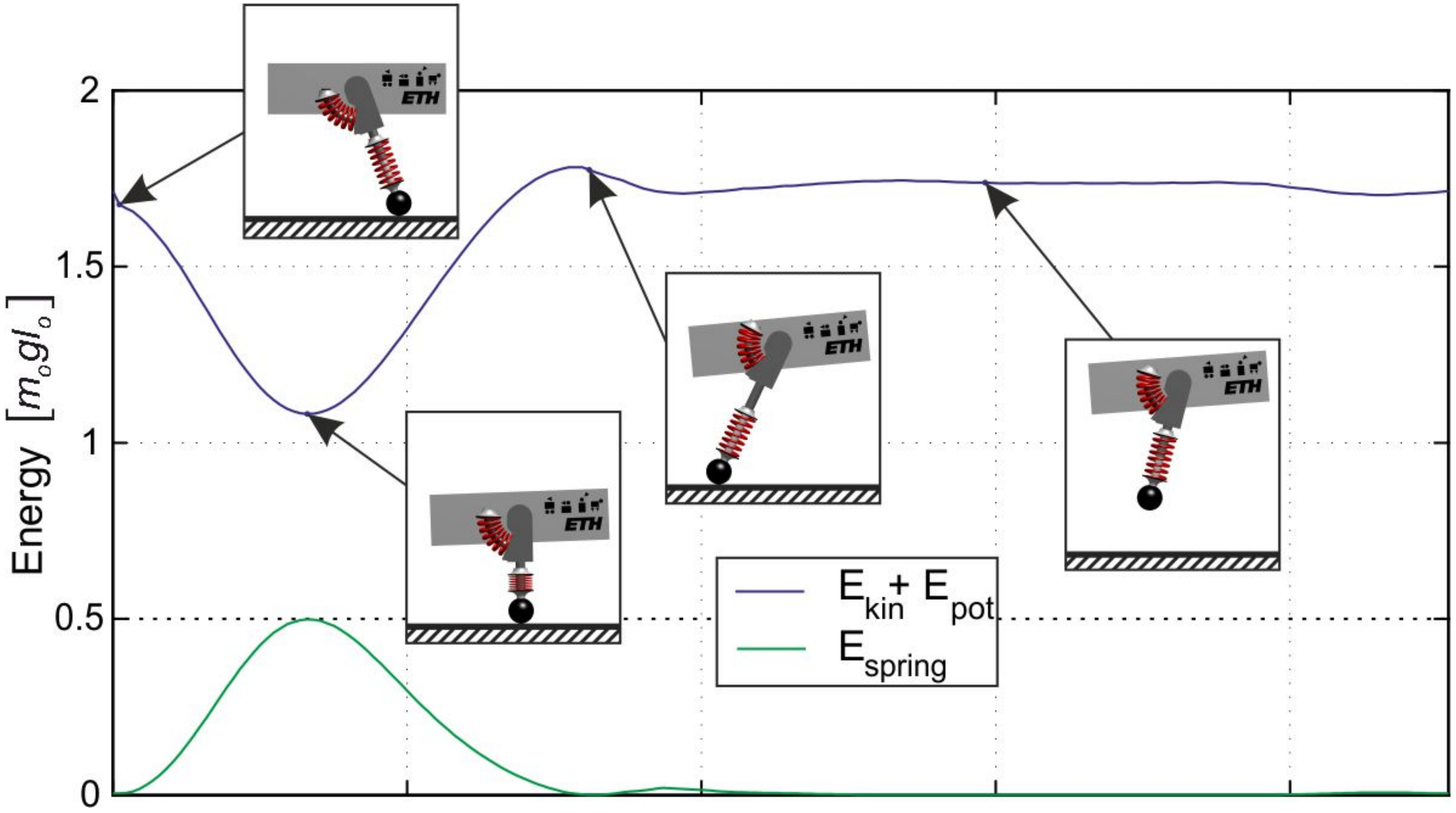


- Dynamic, force control

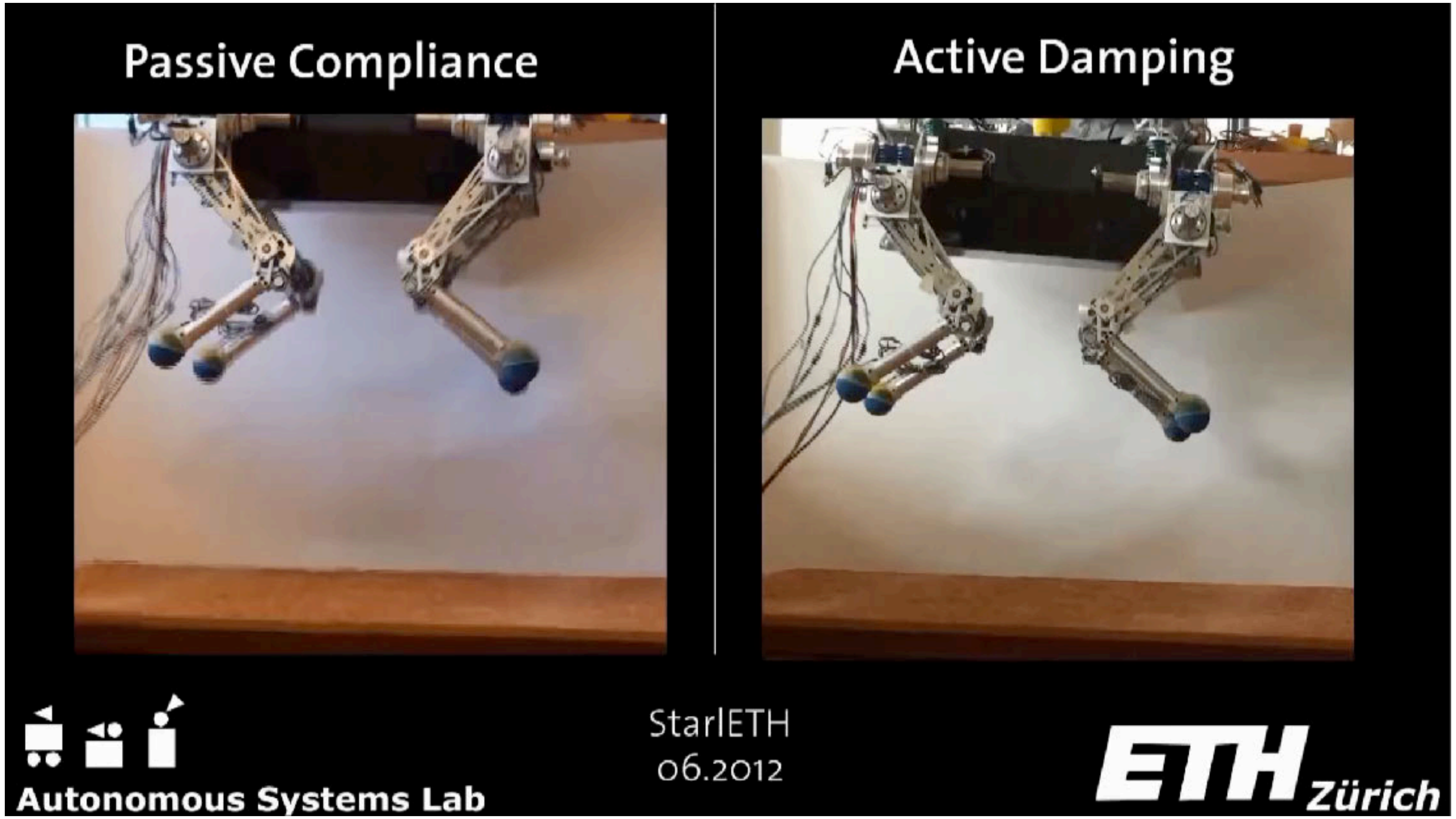


Series Elastic Actuators
Efficient Walking and Running





Series Elastic Actuators
StarlETH – A Complaint Quadrupedal Robot



Hutter, 2012 & Gehring, 2013

Series Elastic Actuators

ANYdrive – A Robust and Force Controllable Robot Joint

Fully integrated

Absolute position sensing

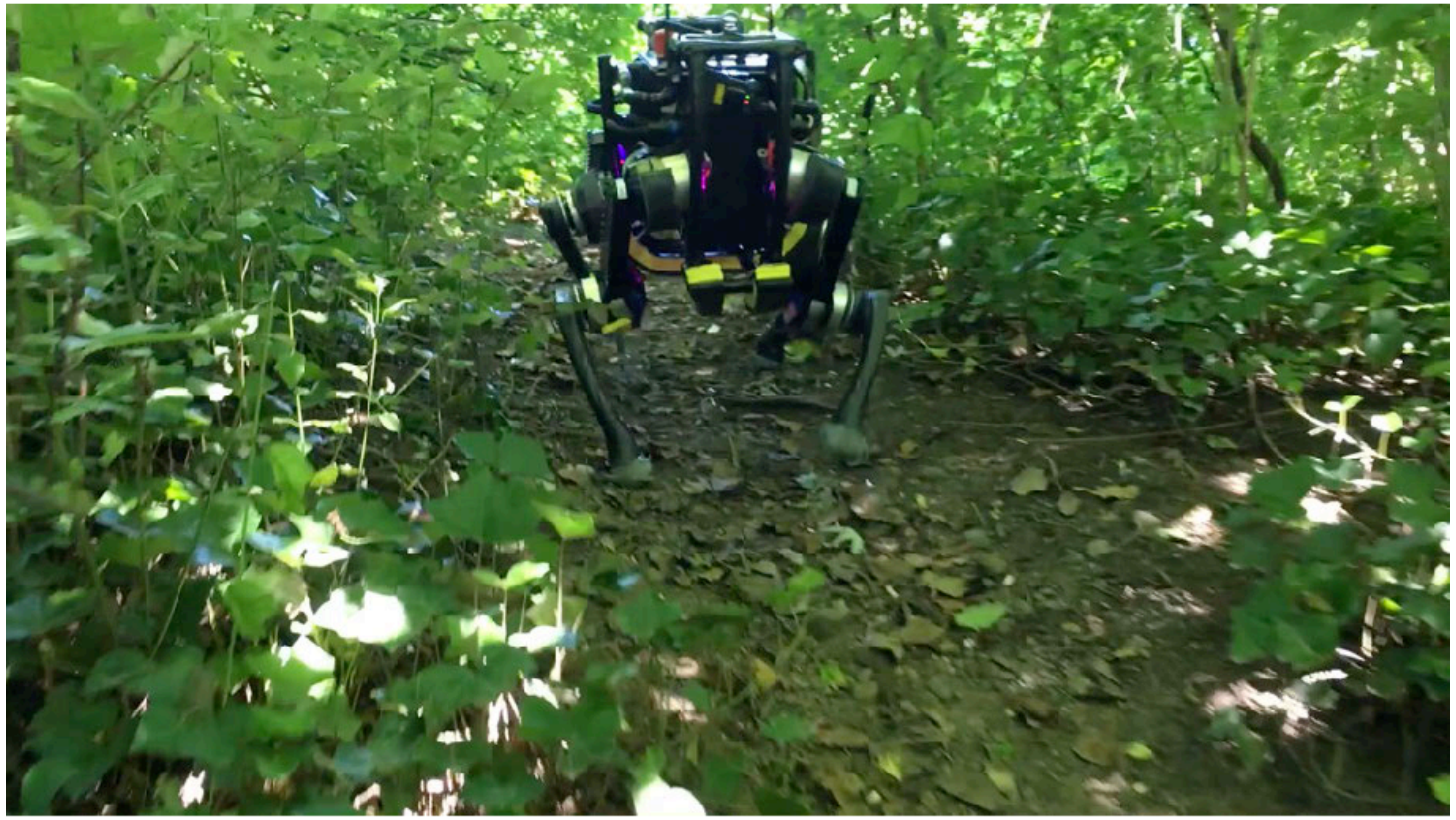
Programmable controller

Accurate position & torque control

High load bearing & hollow shaft

Ingress-protection IP66

ANYmal
Combining Dynamic Motion Skills with Large Mobility



Hutter, 2016, Gehring, 2013, Fankhauser, 2014

Outdoor operation
Water-proof & ruggedized design

Fast locomotion
Dynamic gaits at 1 m/s

Modular payload
10 kg payload

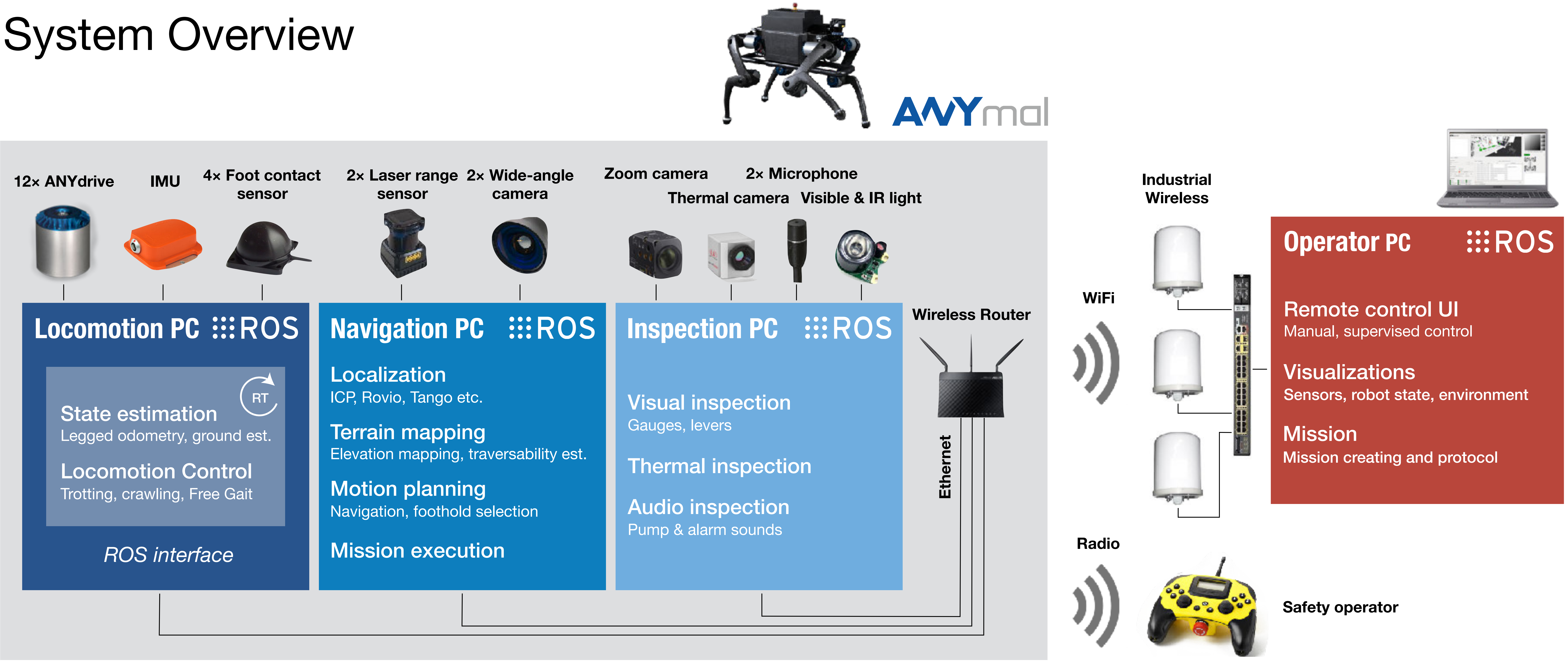
Safe and lightweight
30 kg and force-controlled

Extreme mobility
360° rotation of all joints

Full autonomy
Laser sensors for navigation

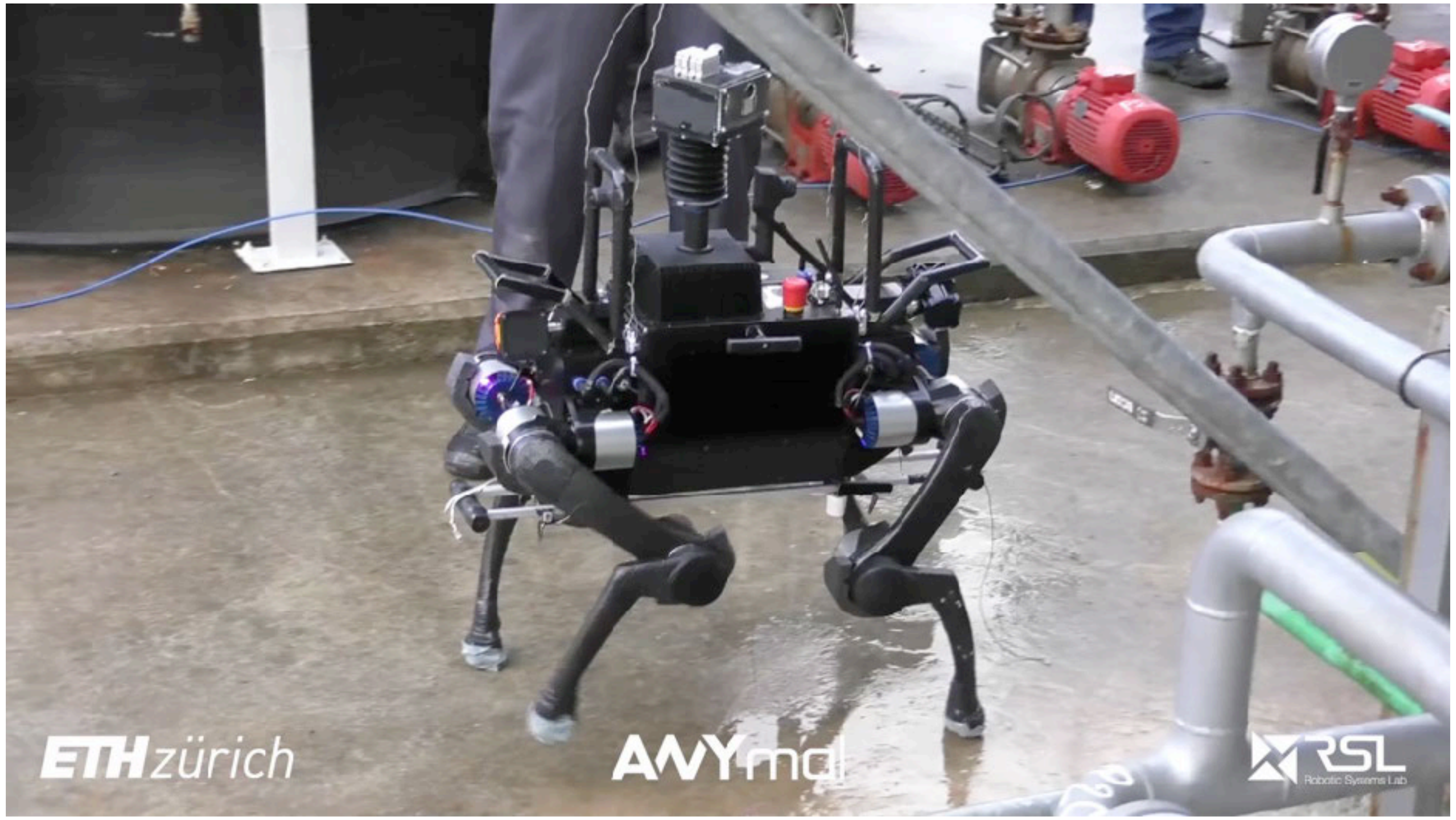
Long endurance
3 h operation

ANYmal
System Overview



Fankhauser, 2016

Thank You



RSL Robotic Systems Lab

Autonomous Systems Lab

www.rsl.ethz.ch

www.asl.ethz.ch

Open-Source Software

github.com/ethz-asl

github.com/leggedrobotics

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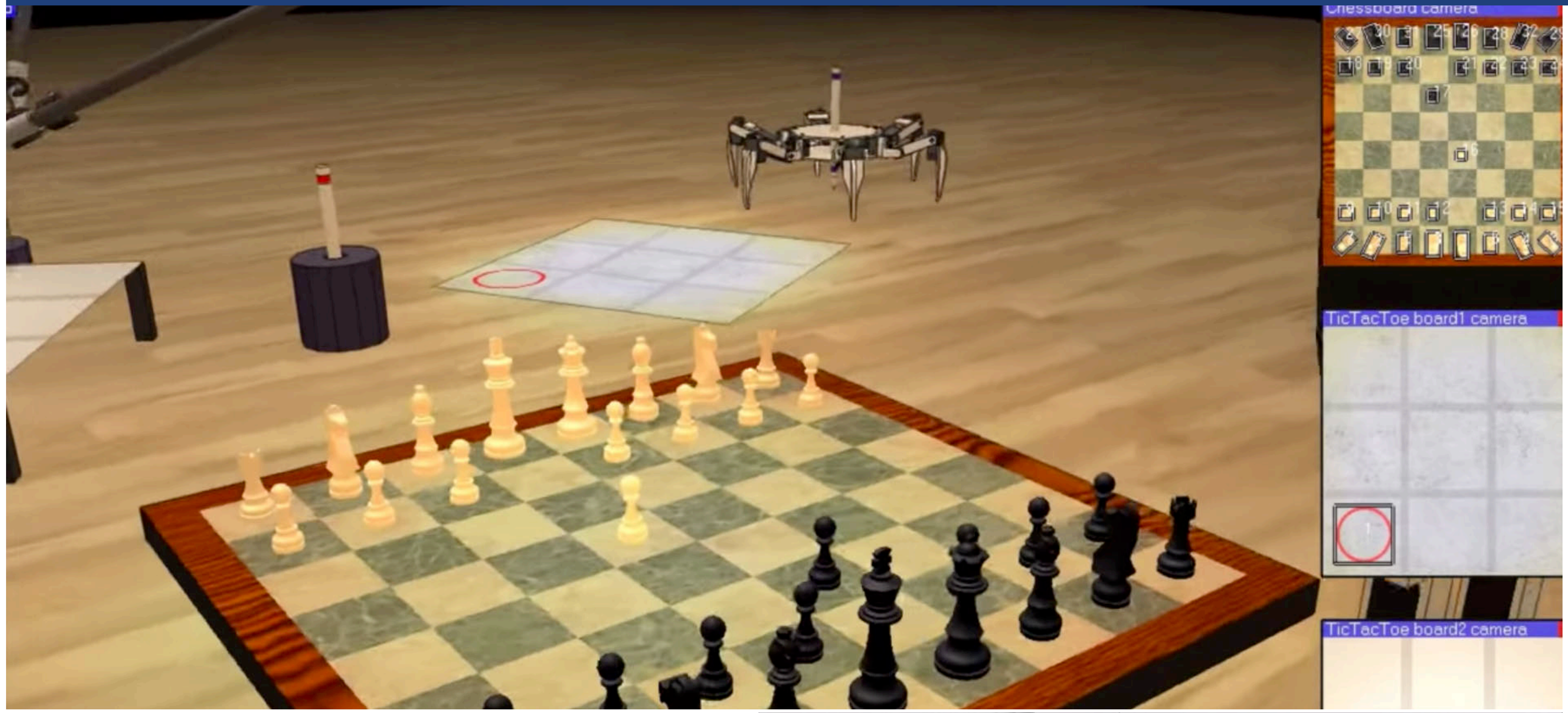
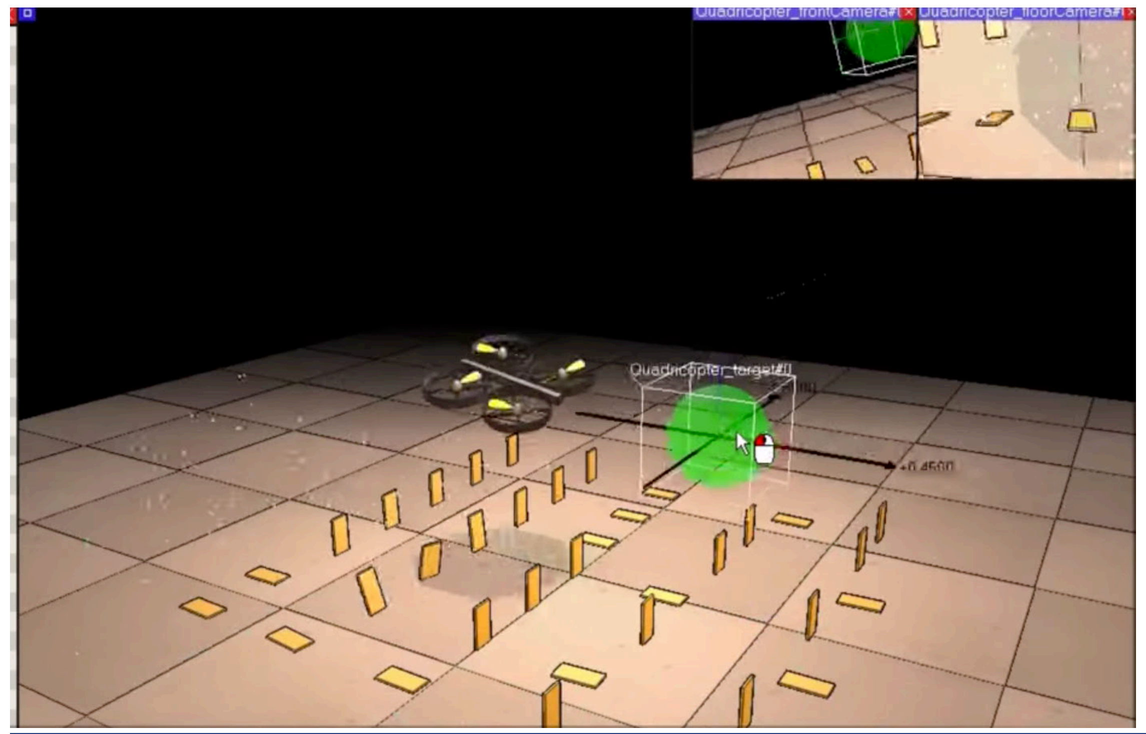
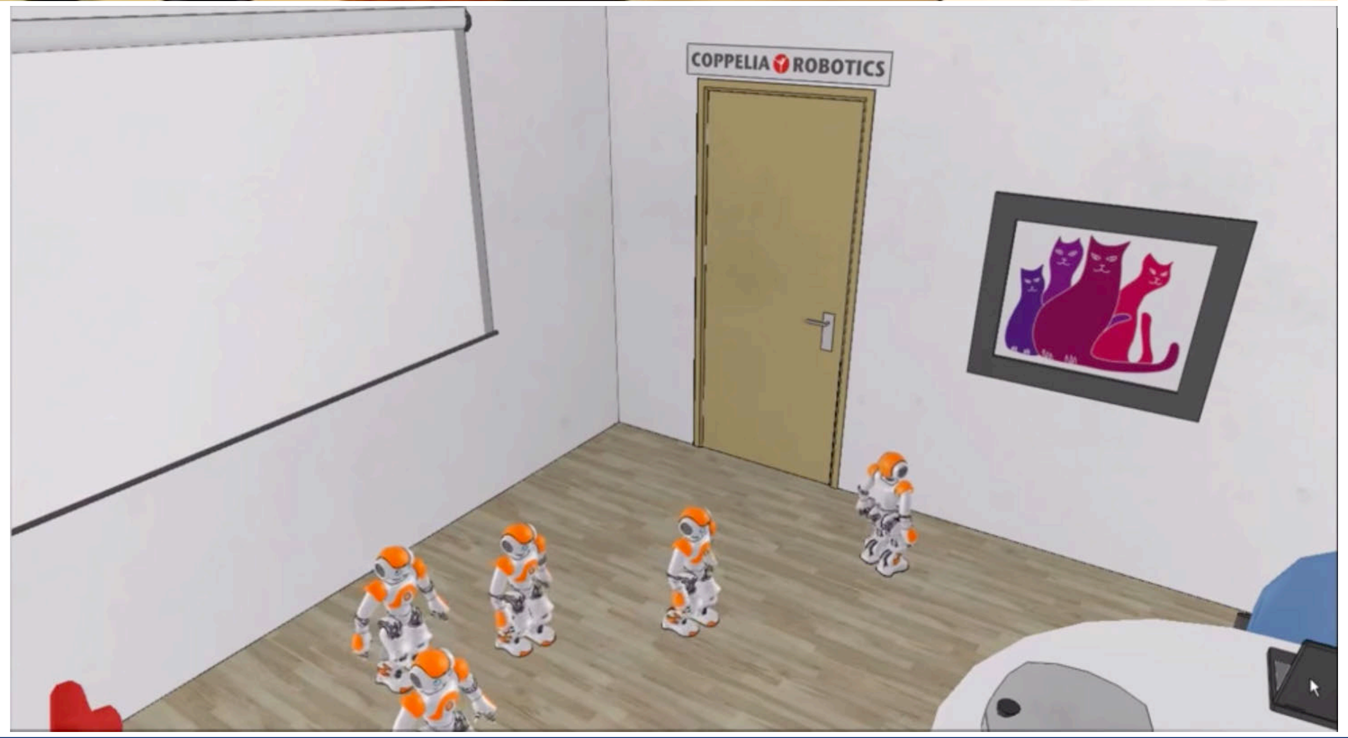
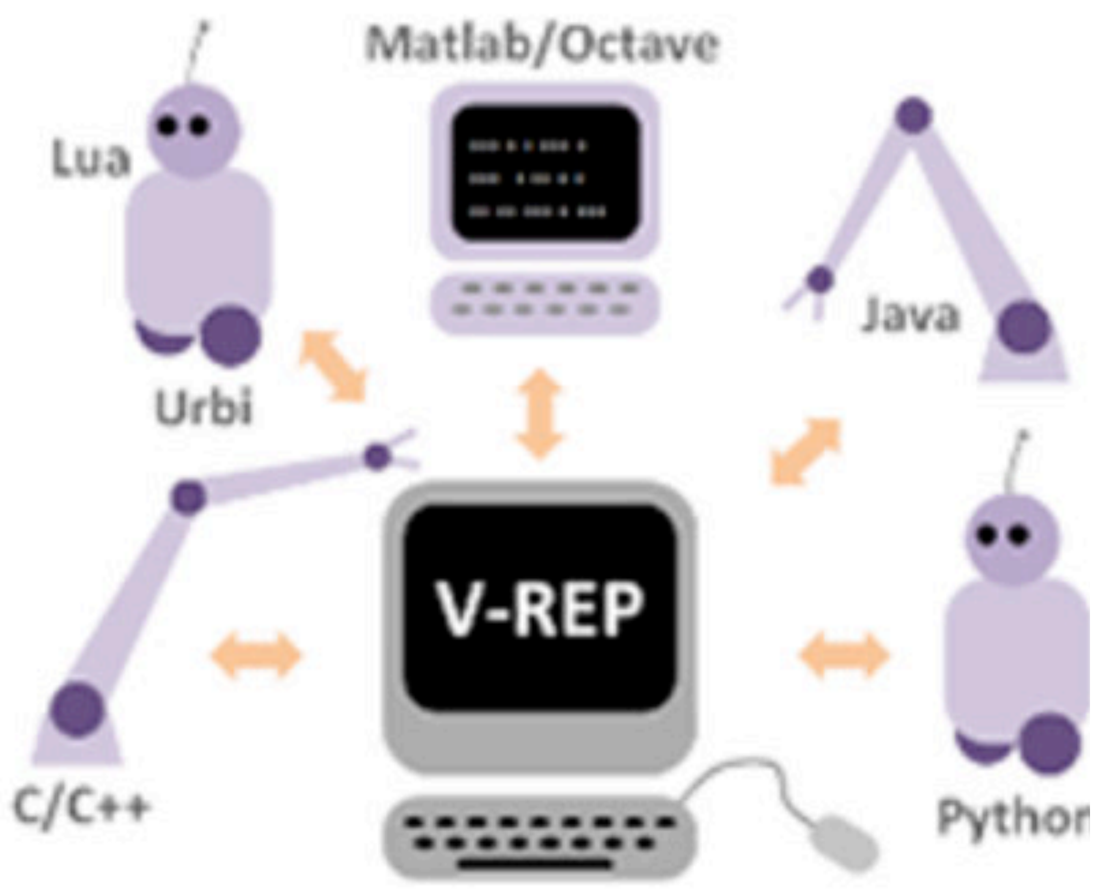
Dominic Jud
Ralf Kaestner
Bruno Kaufmann
Philipp Krüsi
Andreas Lauber
Philipp Leemann
Konrad Meyer
Roland Siegwart
Vassilios Tsounis
Martin Wermelinger









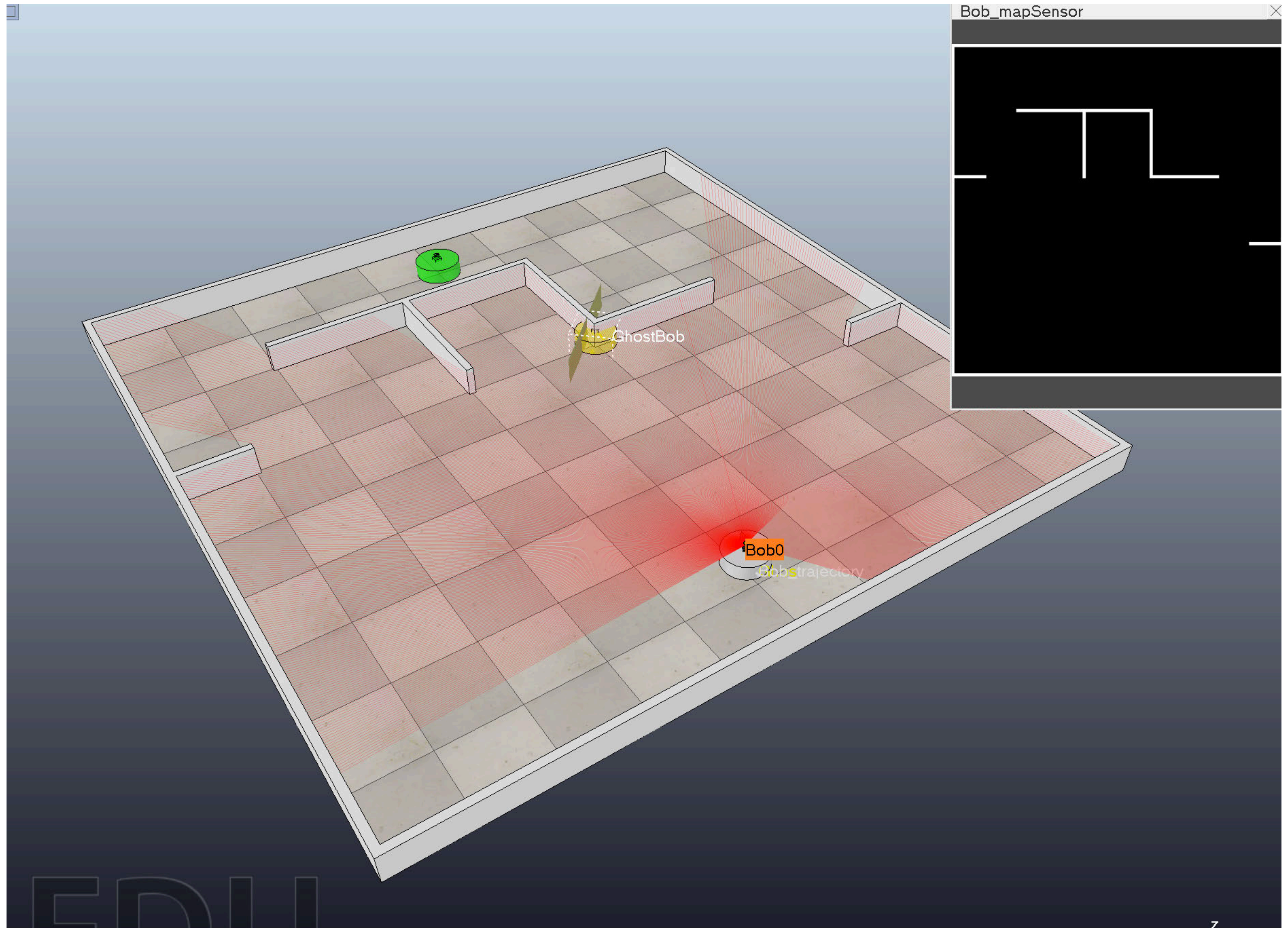
v-rep
virtual robot experimentation platform

Introduction to the V-REP robot simulator

Exercise #1 (14:15-16:00, 28/Feb/2017) in CAB G11

- Introduction of V-REP scene
  - Model browser
  - Scene hierarchy (LUA child script)
- MATLAB remote APIs
  - Obtaining robot pose and sensor measurements and sending control inputs.
- Material can be found from http://www.asl.ethz.ch/education/lectures/autonomous_mobile_robots/spring-2017.html
- You can build your own algorithms based on this.

V-REP scene



Remote API

MATLAB