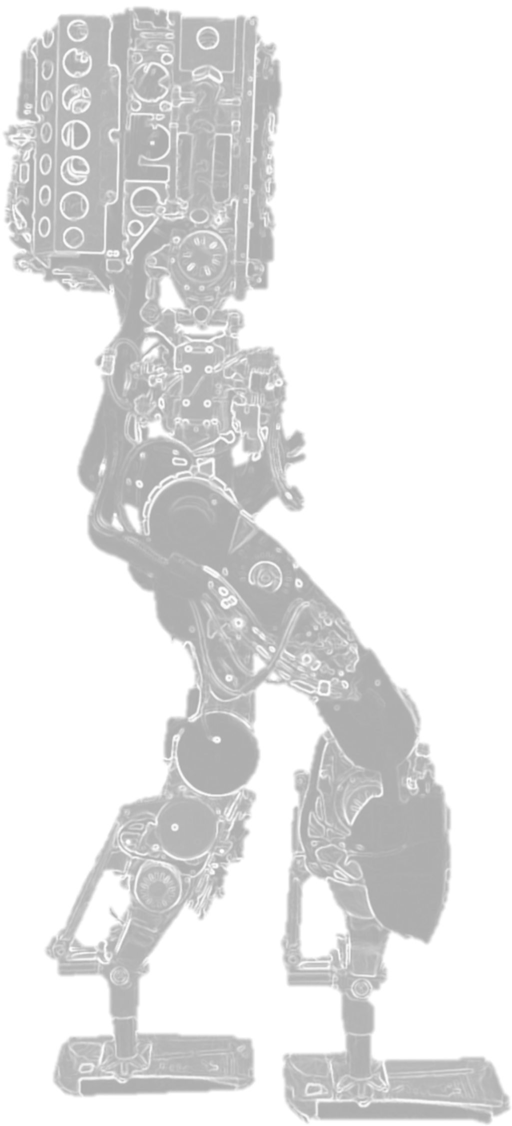


Advanced Mechanical
Bipedal Experimental
Robotics LAB

HISTORY OF WALKING ROBOTS

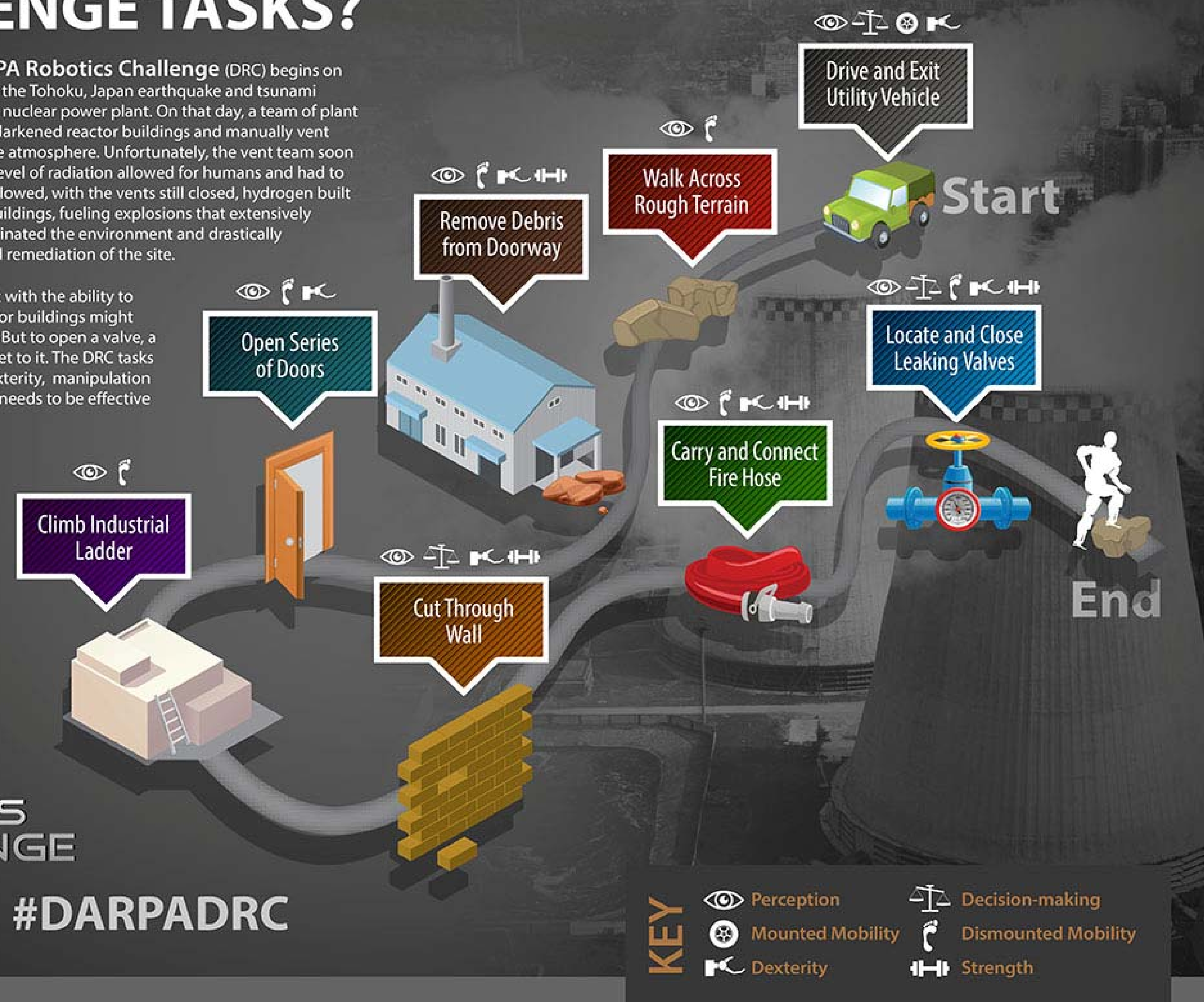
Shishir N. Y. Kolathaya
Postdoctoral scholar
Mechanical and Civil Engineering
California Institute of Technology

Seminar
Bombay, Aug 9

WHY THE DARPA ROBOTICS CHALLENGE TASKS?

The story of the DARPA Robotics Challenge (DRC) begins on March 12, 2011, the day after the Tohoku, Japan earthquake and tsunami struck the Fukushima-Daiichi nuclear power plant. On that day, a team of plant workers set out to enter the darkened reactor buildings and manually vent accumulated hydrogen to the atmosphere. Unfortunately, the vent team soon encountered the maximum level of radiation allowed for humans and had to turn back. In the days that followed, with the vents still closed, hydrogen built up in each of three reactor buildings, fueling explosions that extensively damaged the facility, contaminated the environment and drastically complicated stabilization and remediation of the site.

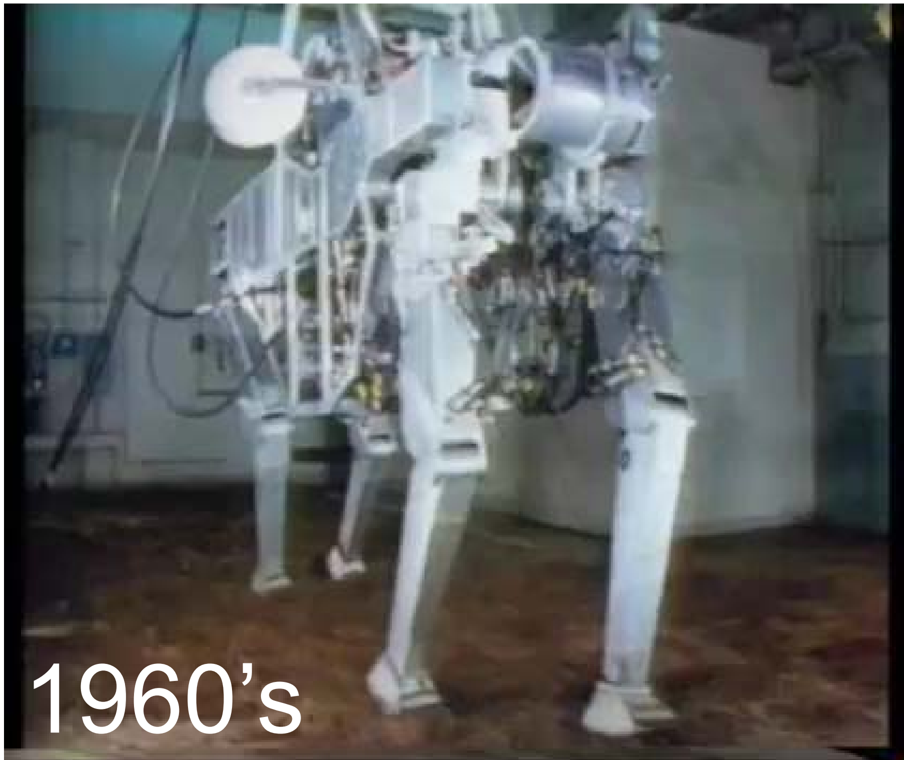
At Fukushima, having a robot with the ability to open valves to vent the reactor buildings might have made all the difference. But to open a valve, a robot first has to be able to get to it. The DRC tasks test some of the mobility, dexterity, manipulation and perception skills a robot needs to be effective in disaster response.



DARPA

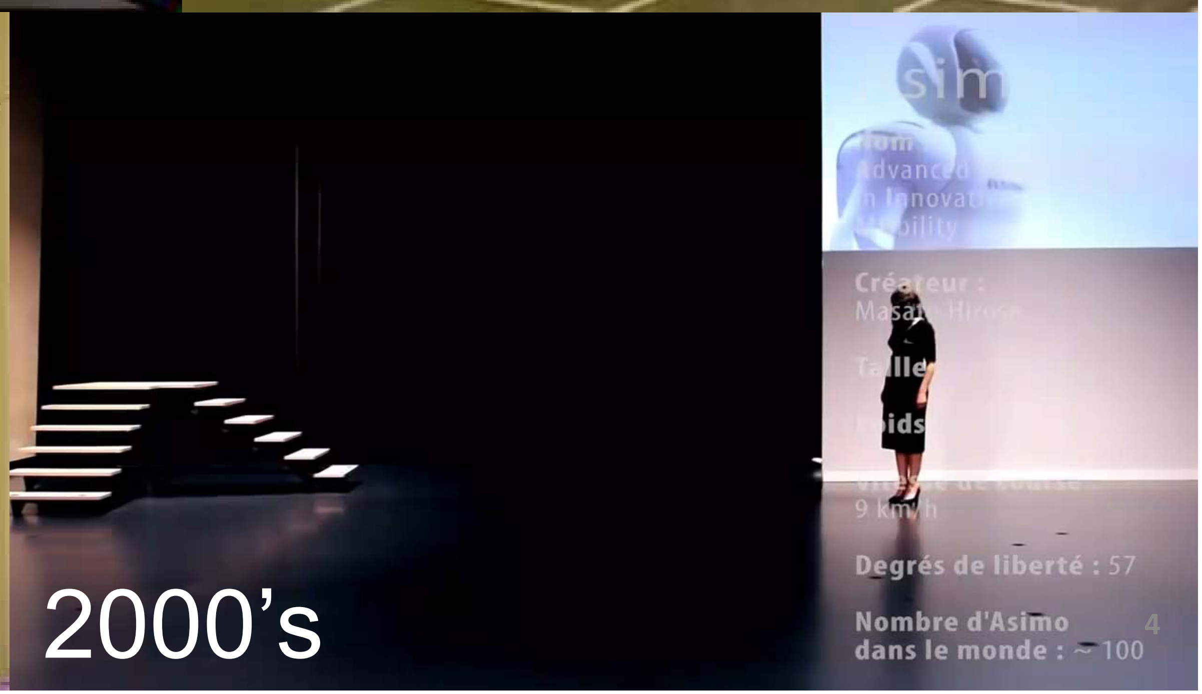
ROBOTICS CHALLENGE 2013 TRIALS

#DARPADRC

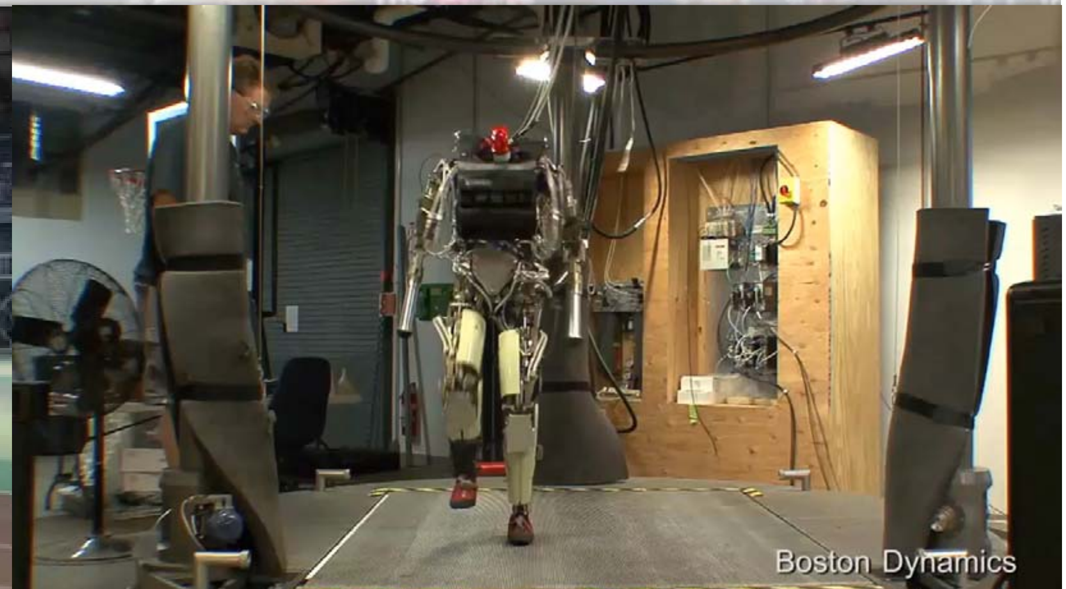

1960’s

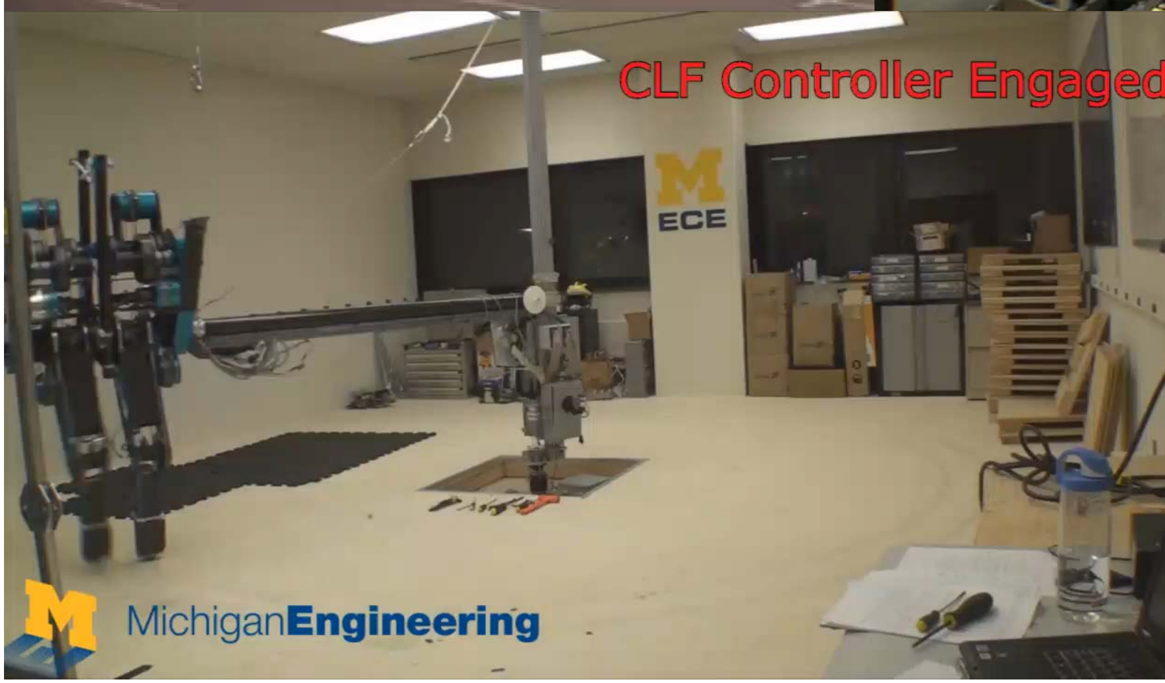

Discovery
1980’s

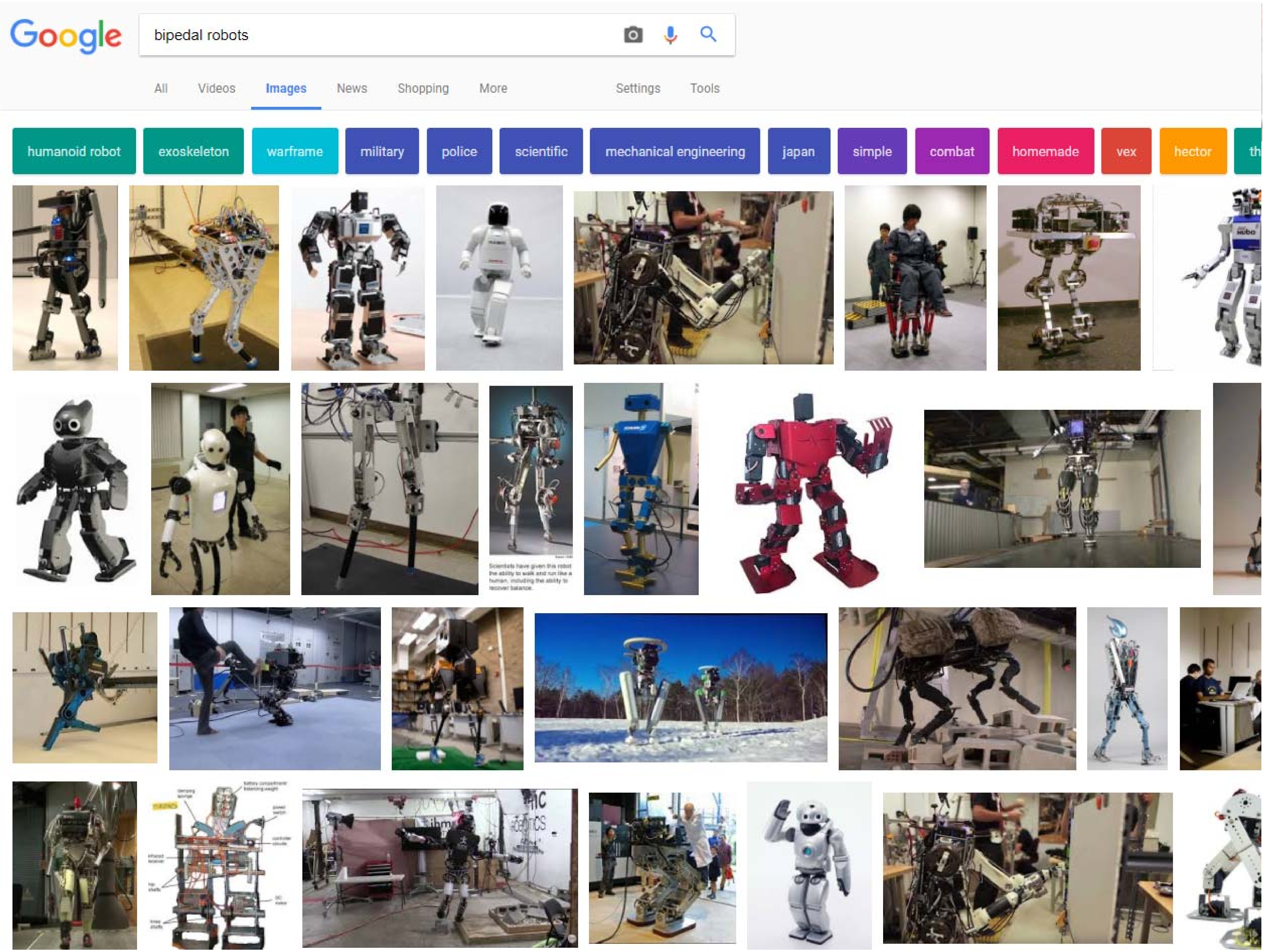

2000’s


2000’s
9 km/h
Degrés de liberté : 57
Nombre d'Asimo
dans le monde : ~ 100

There are quite a few working bipeds today!






Google
bipedal robots
All
Videos
Images
News
Shopping
More
Settings
Tools
humanoid robot
exoskeleton
warframe
military
police
scientific
mechanical engineering
japan
simple
combat
homemade
vex
hector

Approaches used for bipedal walking

Traditional Methods:

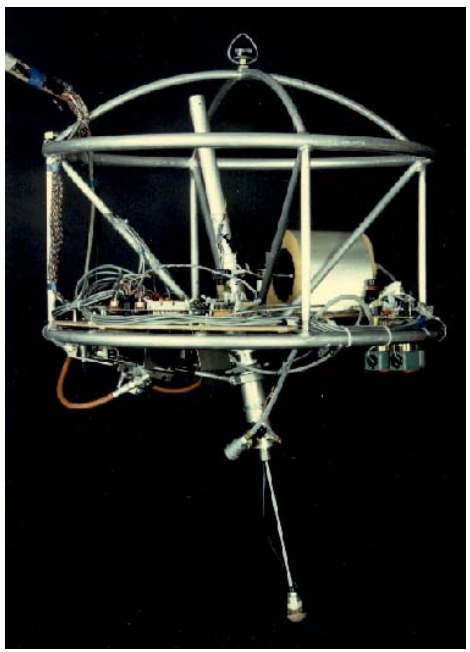
Zero Moment Point (ZMP)

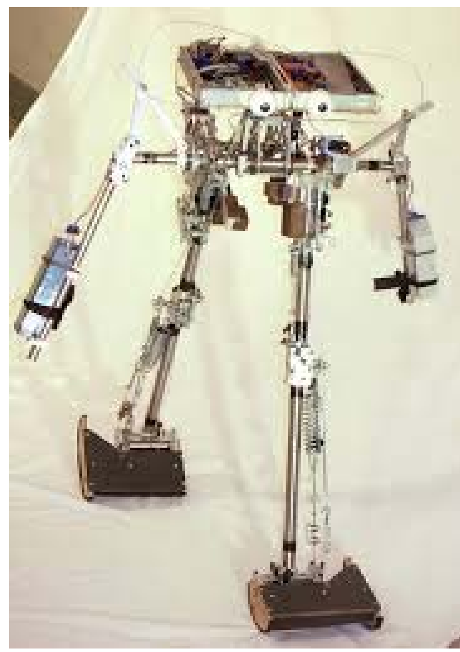
Spring Loaded Inverted Pendulums (SLIP)

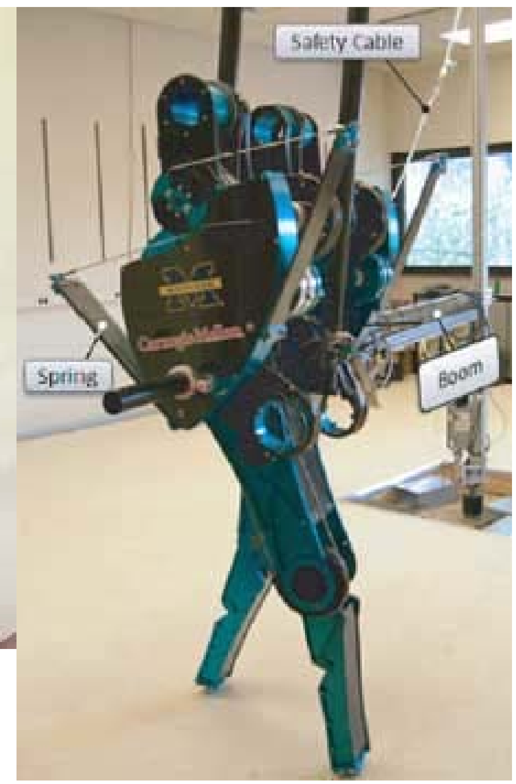
Modern Methods:

Passivity based control

Hybrid Zero Dynamics (HZD)







Outline of the talk

History of methods for walking

1. Zero Moment Point (ZMP)
2. Spring Loaded Inverted Pendulums (SLIP)
3. Passivity based control
4. Hybrid zero dynamics (HZD)

Our approaches for walking

1. Gait design:
   Direct collocation based trajectory optimization
2. Controller design:
   Input-to-state stabilizing controllers

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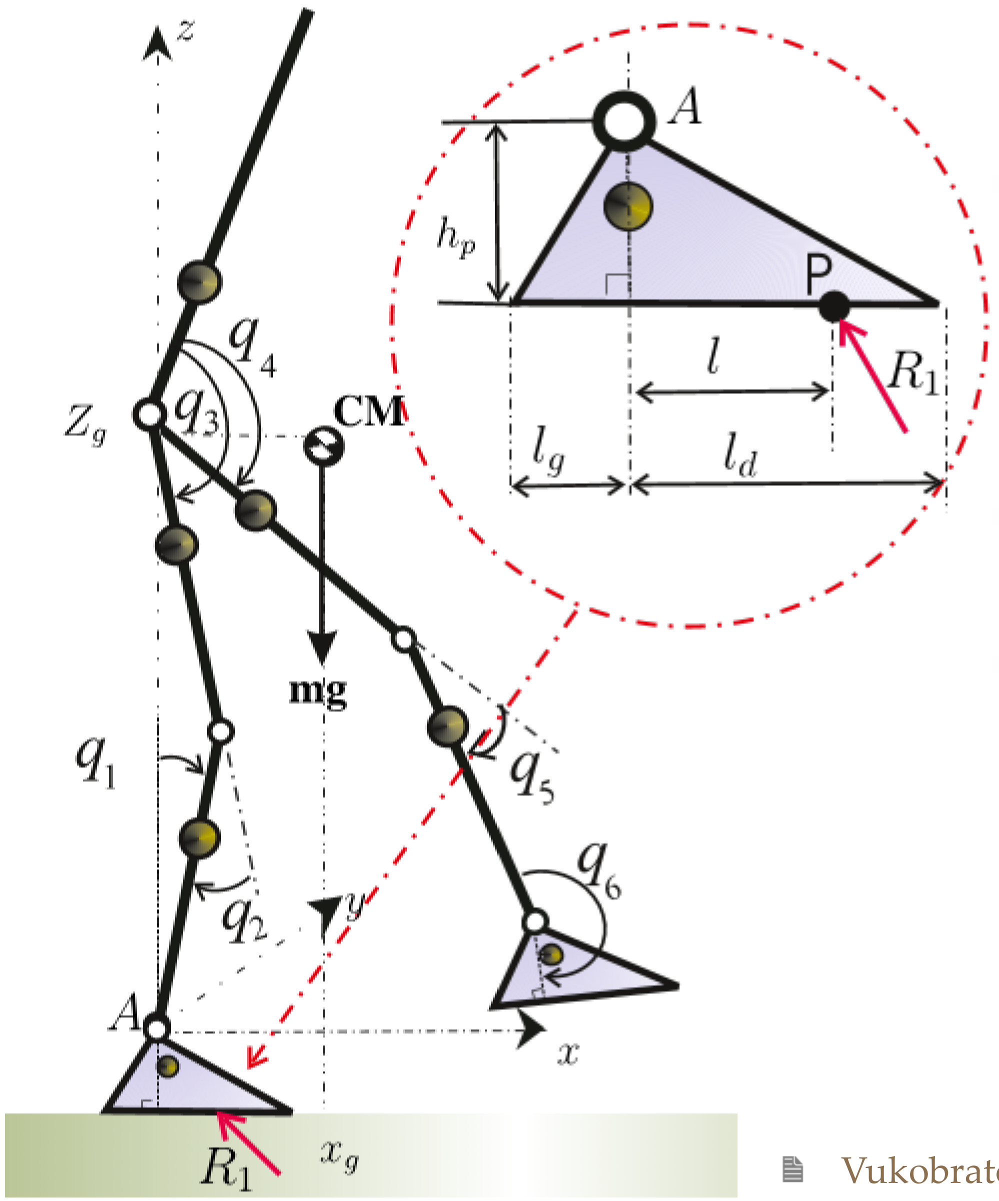
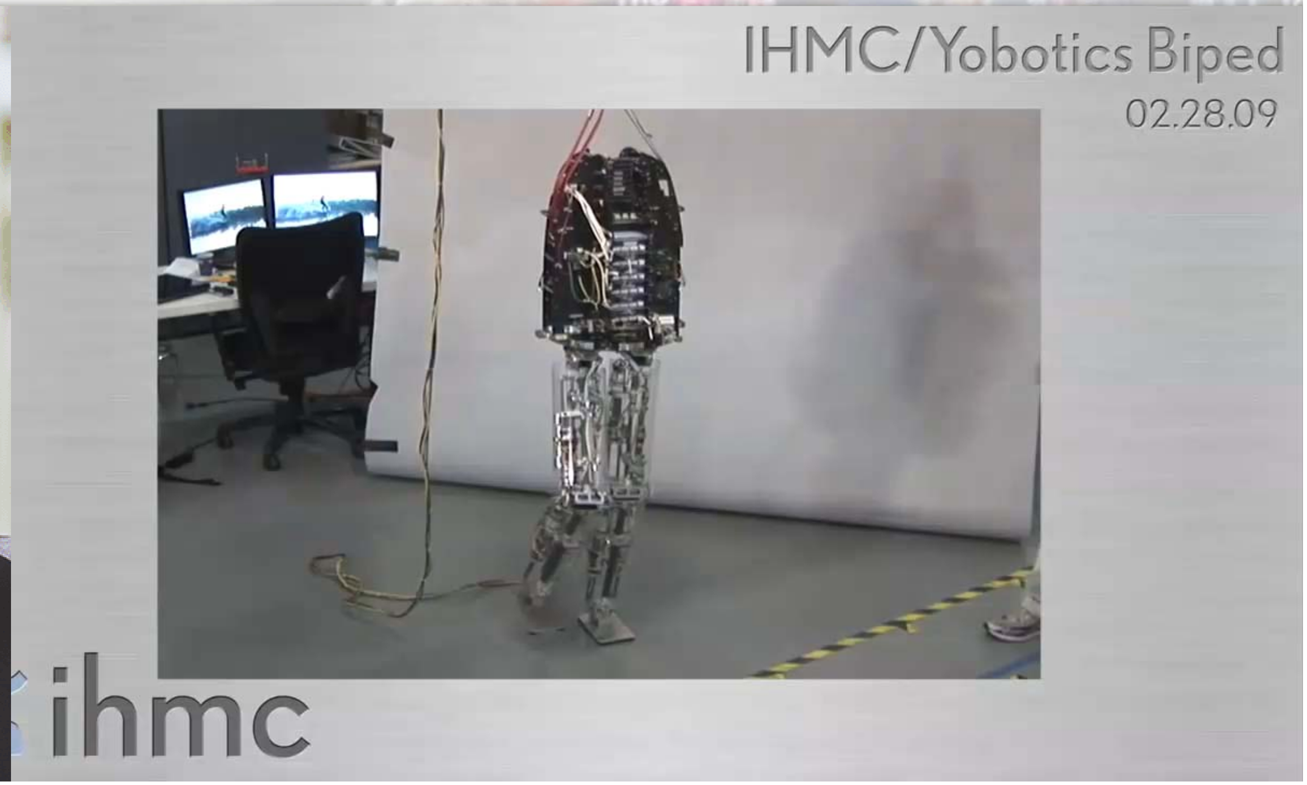
Zero Moment Point (ZMP)



Vukobratovic et. al, IEEE Transactions on Bio-Med 1969

Capture points

Jerry Pratt



Pratt et. al, IEEE International Conference on Humanoid Robots 2006

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Spring Loaded Inverted Pendulums (SLIP)

Marc Raibert

Raibert, IEEE Journal of Robotics and Automation 1986

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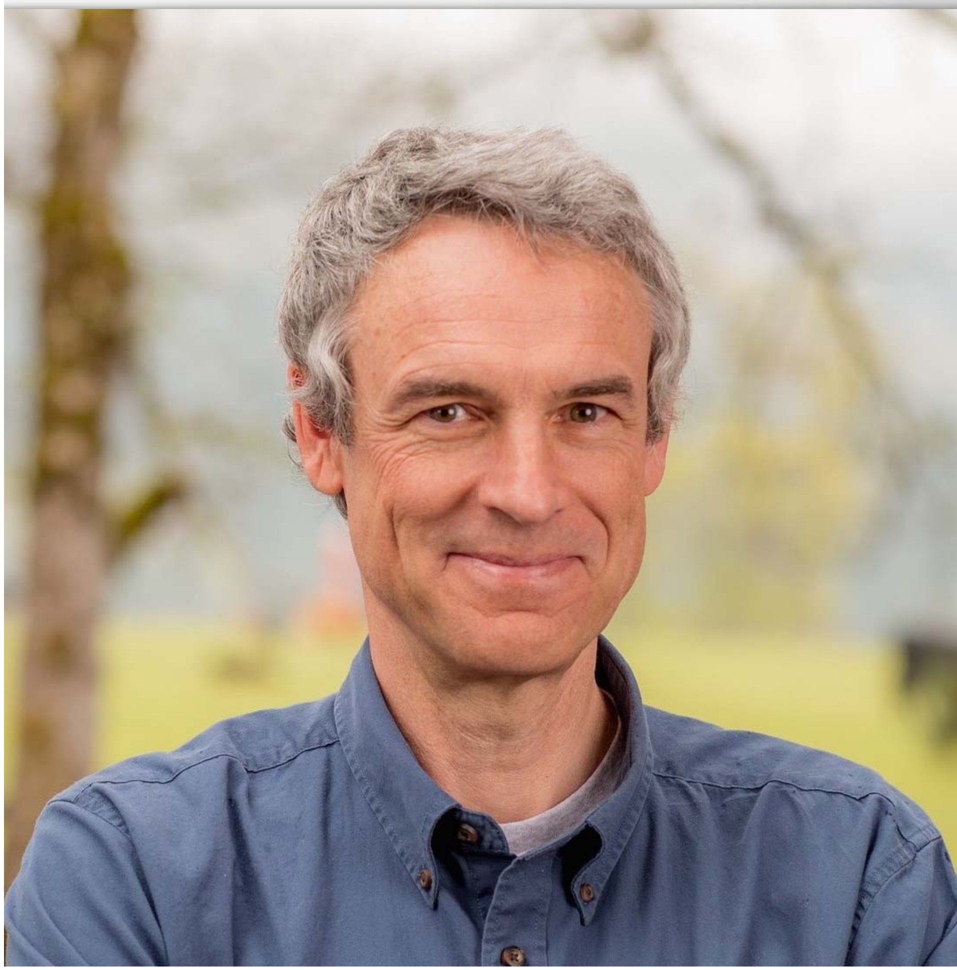
Passivity based control



Tad McGeer

McGeer, IJRR 1990

Slope change as a group action

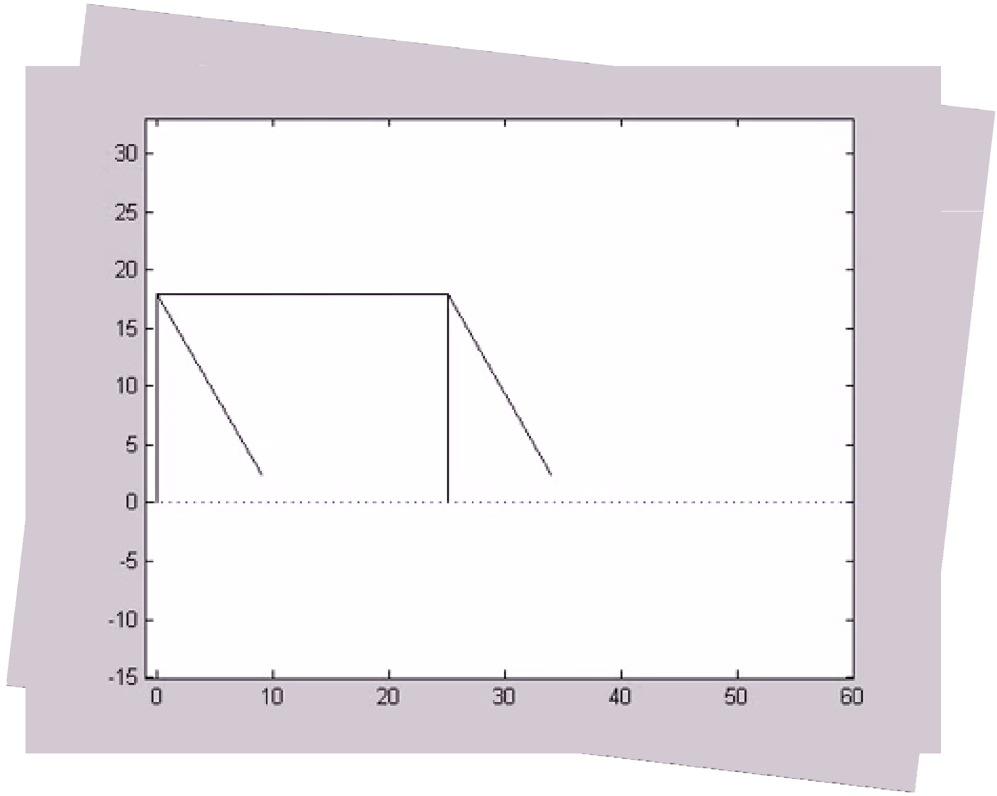
$Q \subset \mathbb{R}^n, \quad G \subset \mathbb{R}_{\geq 0}$

θ : Slope angle of the plane

q : Robot configuration

Slope change is a group action

$\Phi : G \times Q \rightarrow Q$



The dynamics undergo a controlled symmetrical transformation under the slope change

Spong et.al, TAC 2005

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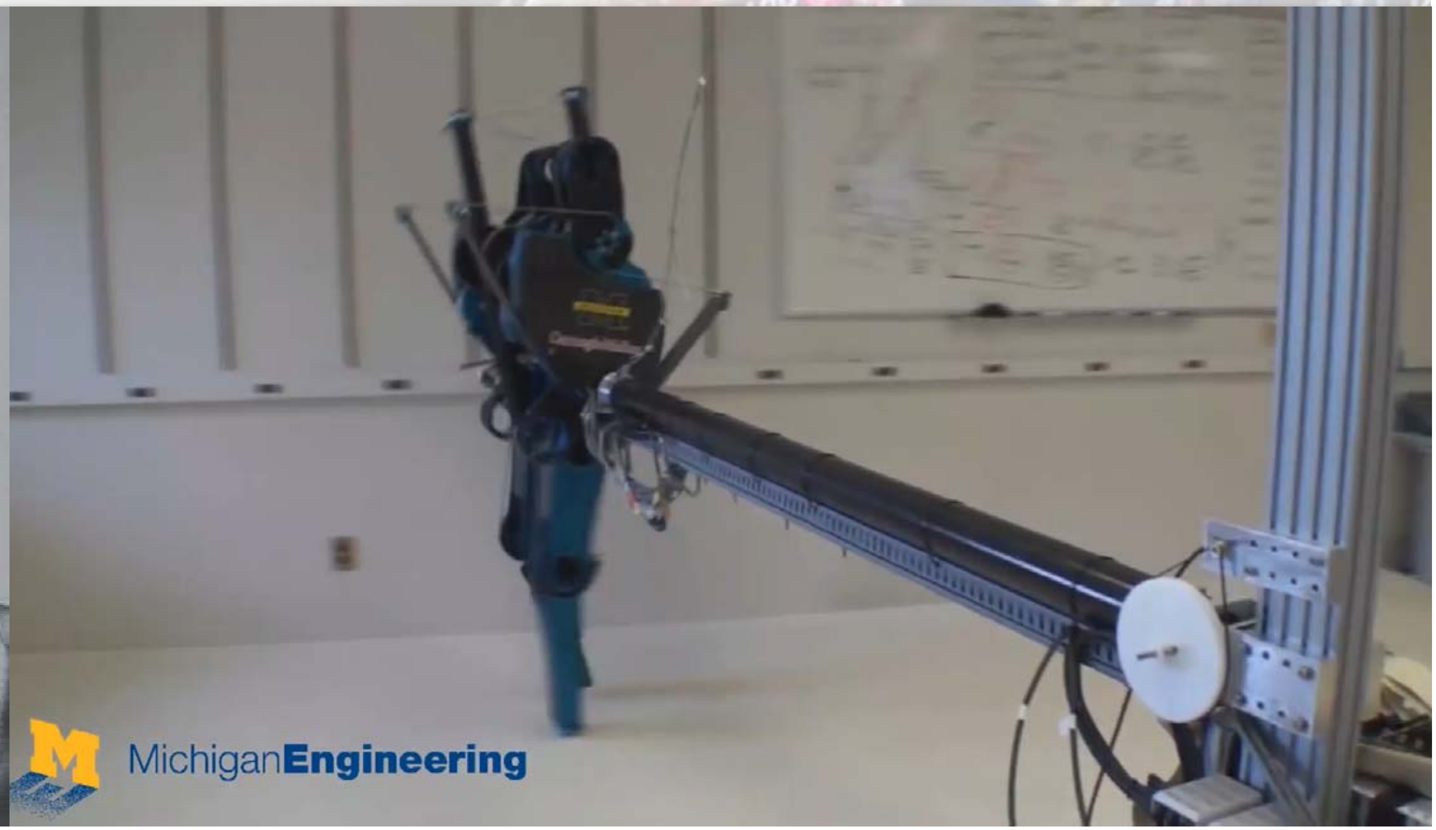
Hybrid zero dynamics



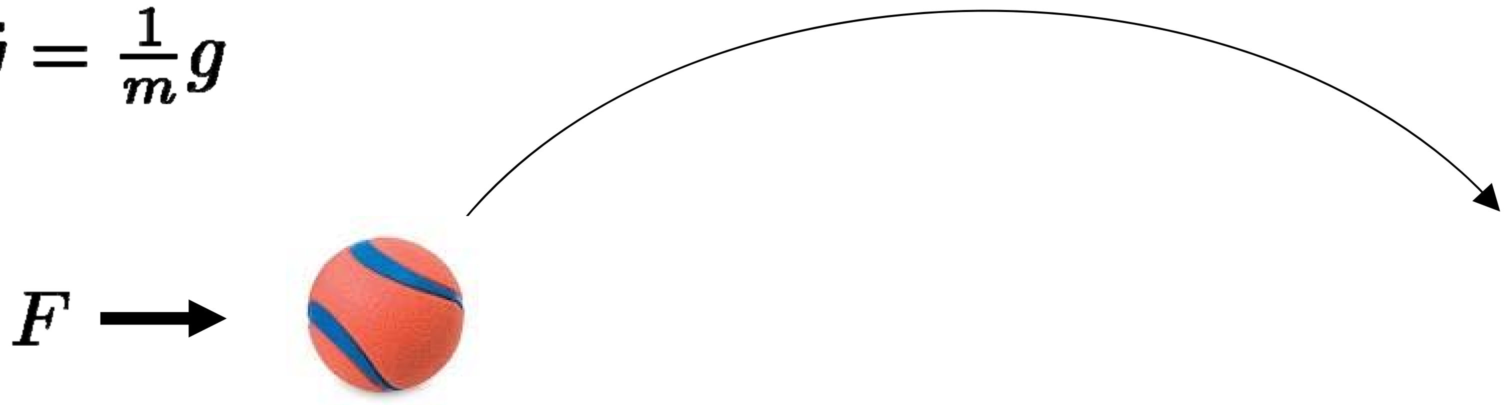
Jessy Grizzle

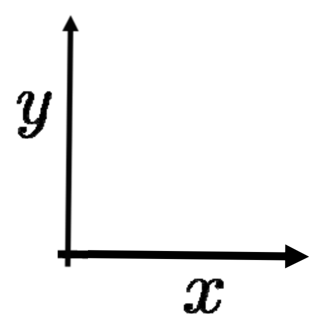
Grizzle et.al, CDC 2003

Zero dynamics <> Underactuated systems

$$\ddot{x} = 0 \qquad \ddot{x} = \frac{1}{m}F$$

$$\ddot{y} = \frac{1}{m}g$$

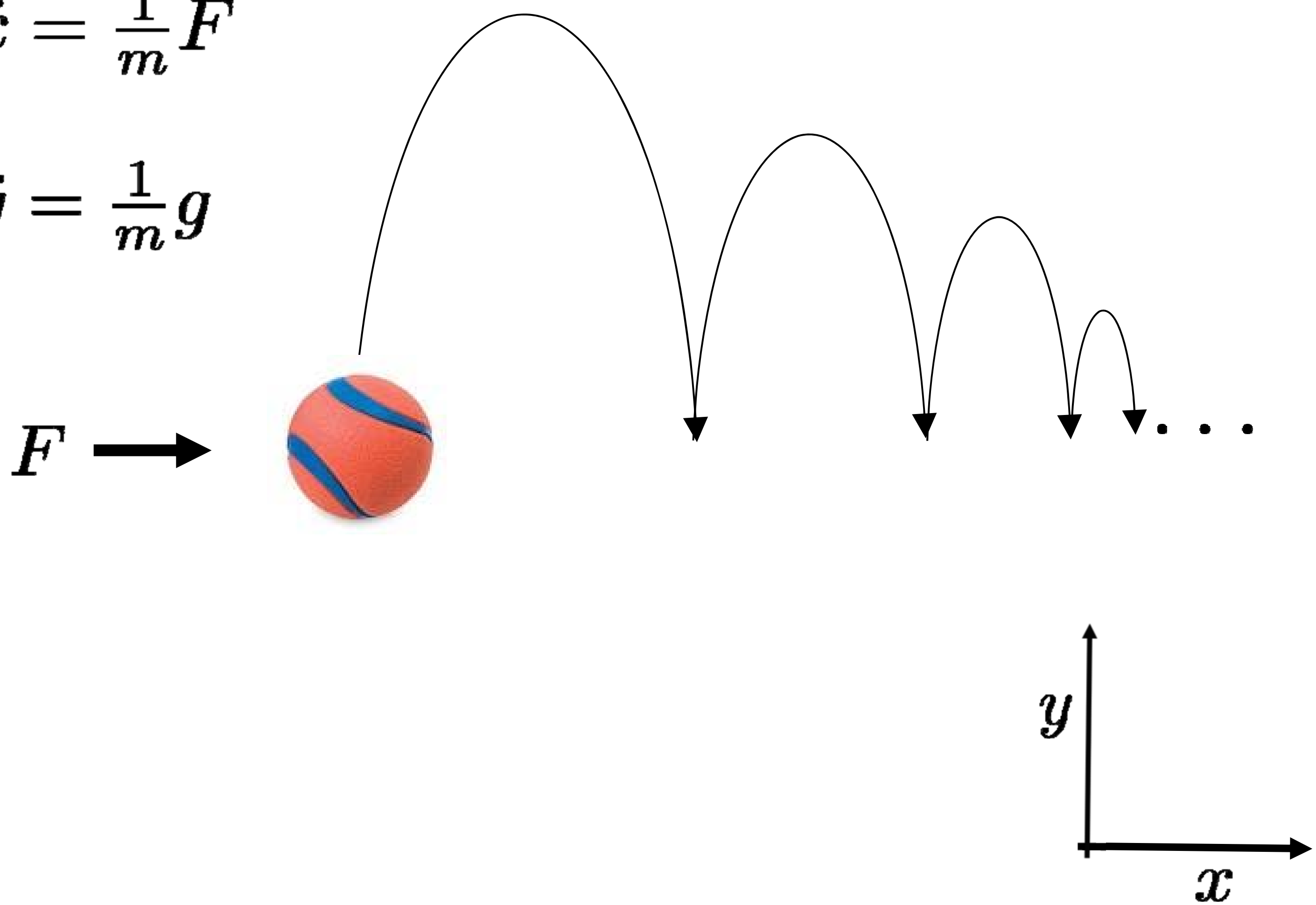




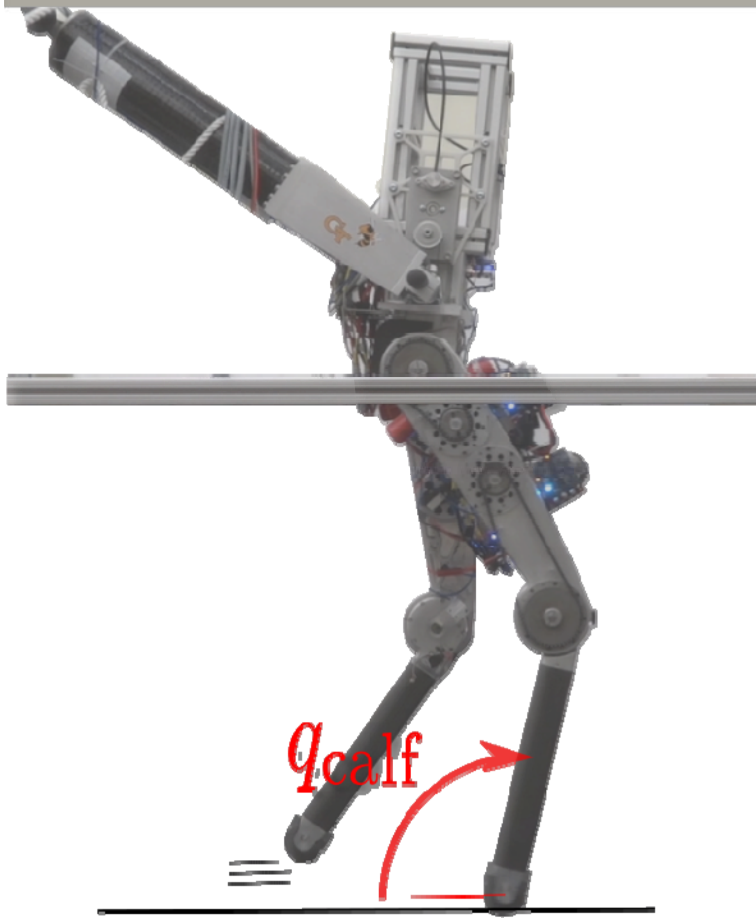
Hybrid zero dynamics <> Underactuated systems

$$\ddot{x} = \frac{1}{m} F$$

$$\ddot{y} = \frac{1}{m} g$$



Hybrid zero dynamics <> Underactuated systems



Tracking control:

Actual outputs and desired outputs:

$y_a(q)$: *linear combination of joint angles*

$y_d(q, \alpha)$: *desired polynomial trajectory*

Example:

$$y_a = \begin{bmatrix} q_{sk} \\ q_{nsk} \\ q_{sh} \\ q_{nsh} \end{bmatrix}$$

$$y_d(q, \alpha) = \begin{bmatrix} polynomial_1 \\ polynomial_2 \\ polynomial_3 \\ polynomial_4 \end{bmatrix}$$

$$polynomial_i = \alpha_{i1}t^4 + \alpha_{i2}t^3 + \alpha_{i3}t^2 + \alpha_{i4}t + \alpha_{i5}$$

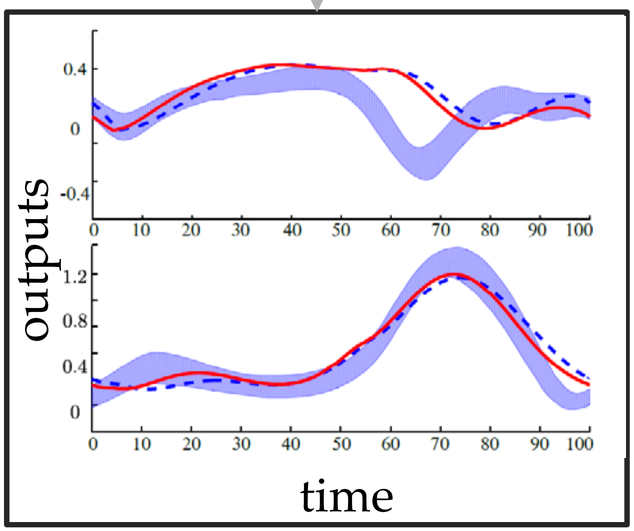
Hybrid zero dynamics <> Underactuated systems

Control Objective:

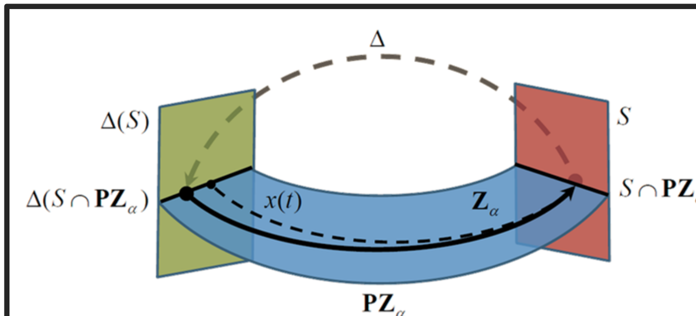
Drive the actual behavior of the robot to the desired behavior: $y_\alpha(q) = y_a(q) - y_d(q,\alpha) \to 0$

$y_d(q,\alpha)$

$y_a(q)$



$y_a(q) \to y_d(q,\alpha)$



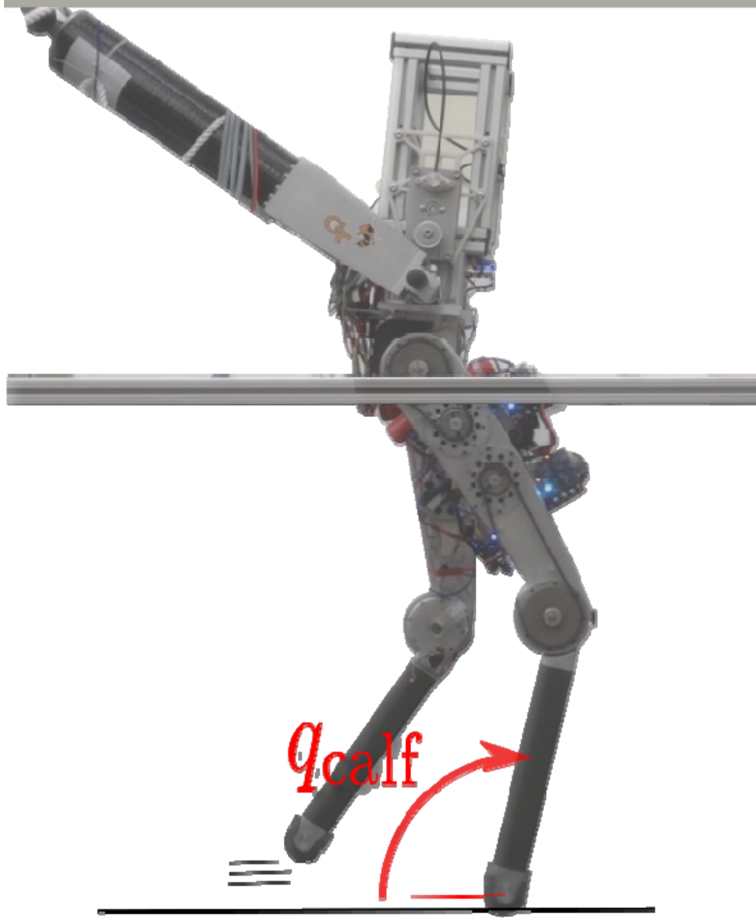
$$\alpha^* = \underset{\alpha \in \mathbb{R}^{5n-4}}{\text{argmin}} \ \text{Cost}_{\text{HD}}(\alpha)$$

$$\text{s.t} \quad \Delta(S \cap \mathbf{PZ}_\alpha) \subset \mathbf{PZ}_\alpha$$

Hybrid Zero Dynamics

- Grizzle et al., TAC 2001 & TAC 2003
- Ames, ROMOCO 2011

Hybrid zero dynamics <> Underactuated systems



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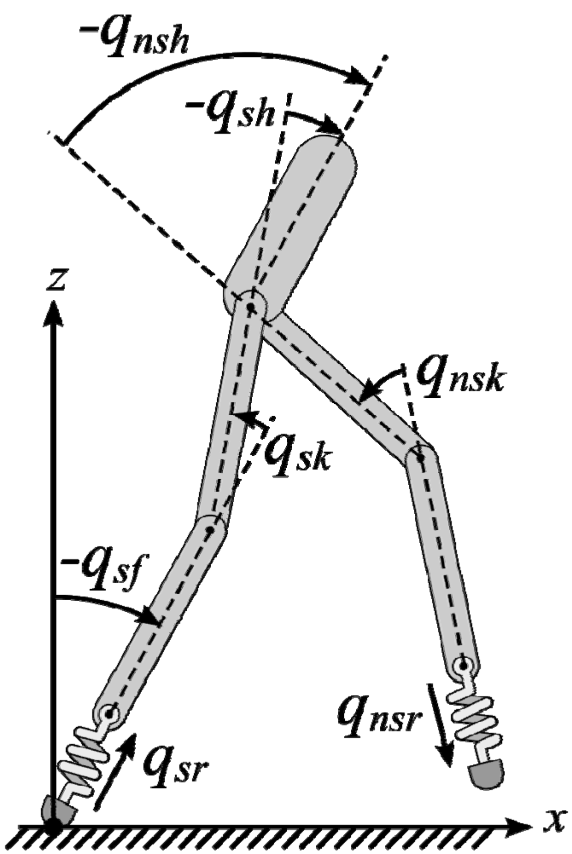
$$y_d(q, \alpha) = \begin{bmatrix} polynomial_1 \\ polynomial_2 \\ polynomial_3 \\ polynomial_4 \end{bmatrix}$$

$$polynomial_i = \alpha_{i1}\tau(q_{\text{calf}})^4 + \alpha_{i2}\tau(q_{\text{calf}})^3 + \alpha_{i3}\tau(q_{\text{calf}})^2 + \alpha_{i4}\tau(q_{\text{calf}}) + \alpha_{i5}$$

Hybrid zero dynamics <> Underactuated systems



Tracking control:

Actual outputs and desired outputs:

$y_a(q)$: *linear combination of joint angles*

$y_d(q, \alpha)$: *desired polynomial trajectory*

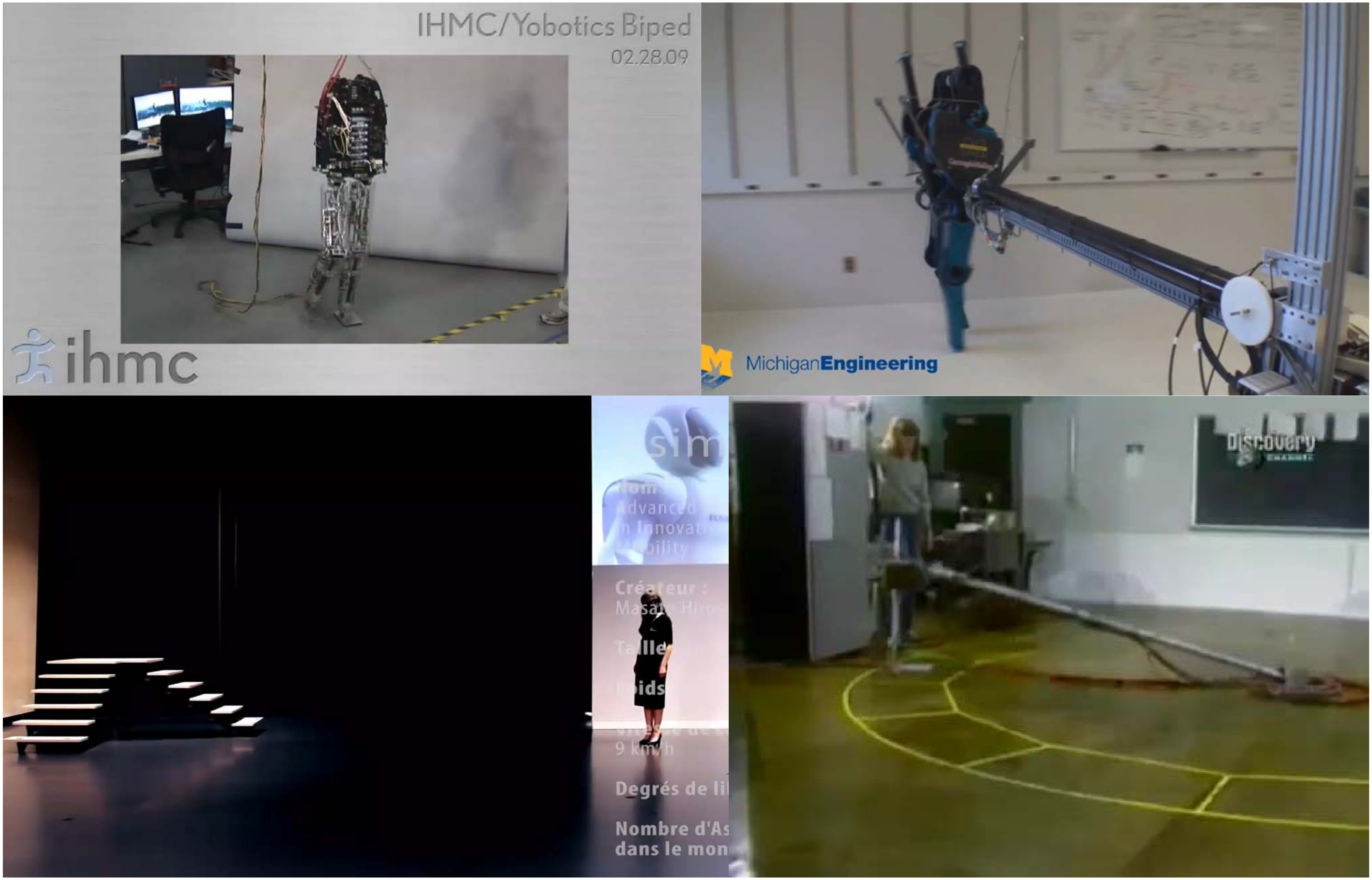
Example:

$$\begin{bmatrix} \dot{y}_\alpha \\ \ddot{y}_\alpha \end{bmatrix} = f(y_\alpha, \dot{y}_\alpha) + g(y_\alpha, \dot{y}_\alpha)u$$ *Output dynamics*

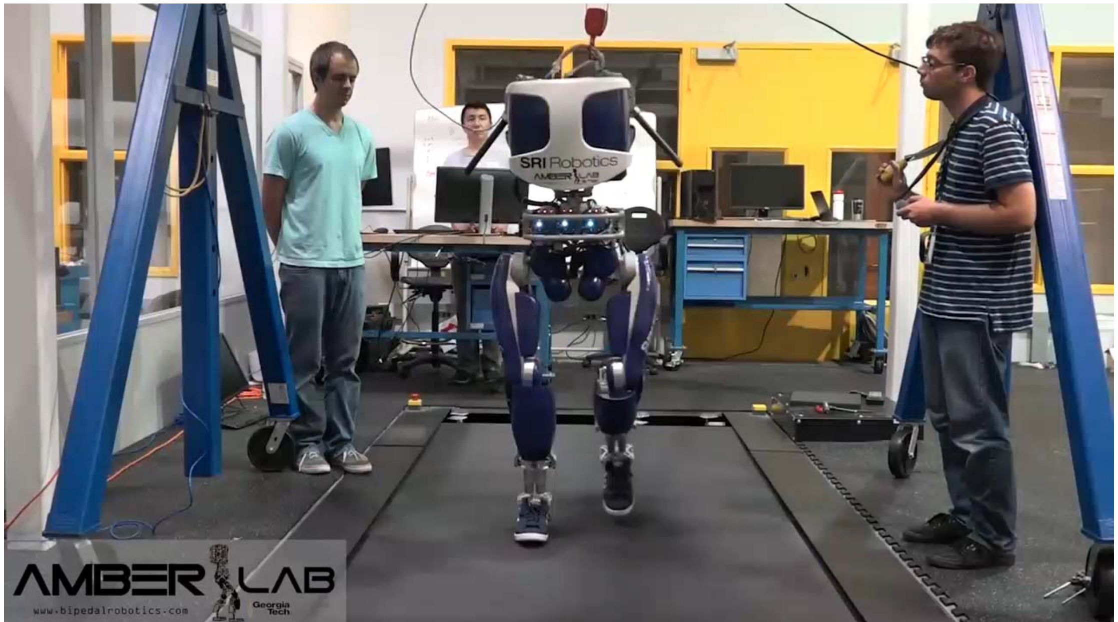
$$\dot{z} = \Psi(y_\alpha, \dot{y}_\alpha, z)$$ *Passive dynamics*

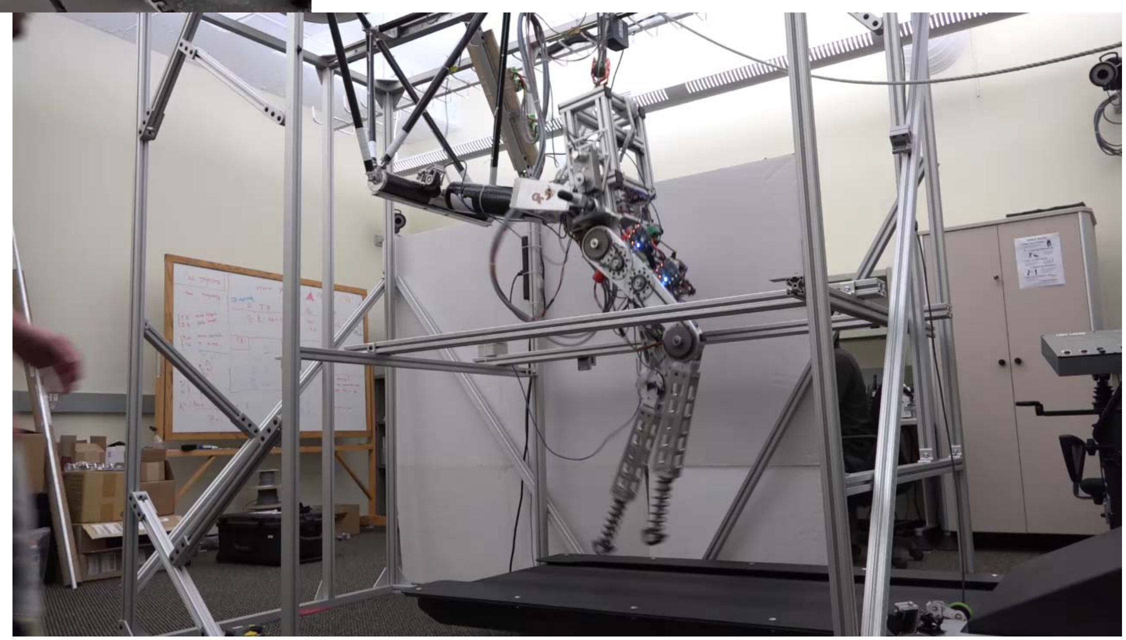
Gait design *Control design*

We have progressed from this



To this…


SRI Robotics
AMBER LAB
www.bipedalrobotics.com
Georgia Tech



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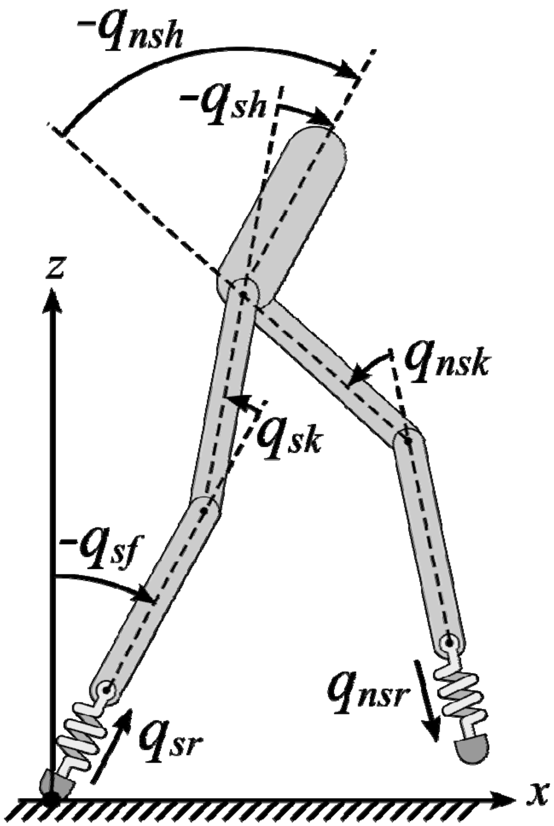
Gait design <> Trajectory Optimization

We need fast trajectory optimization: Limit cycle in simulation does not imply limit cycle in experiment.

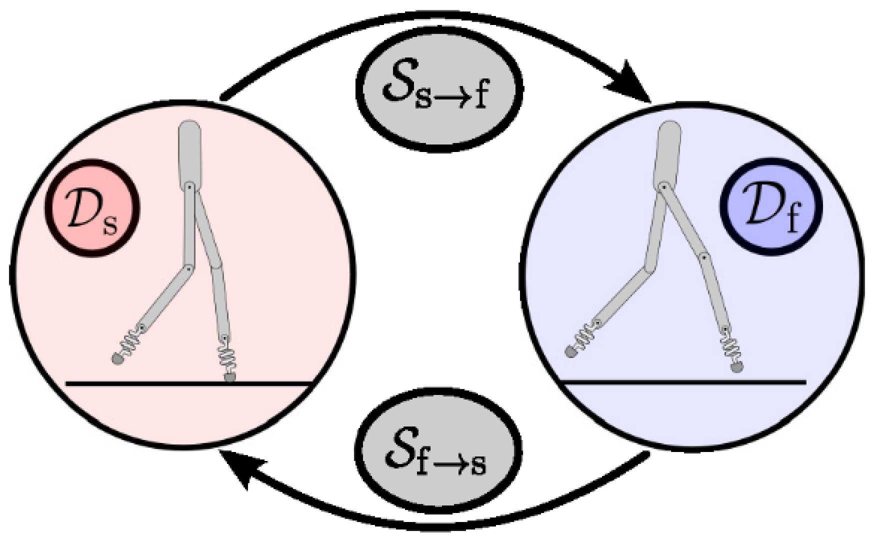
Trajectory Optimization

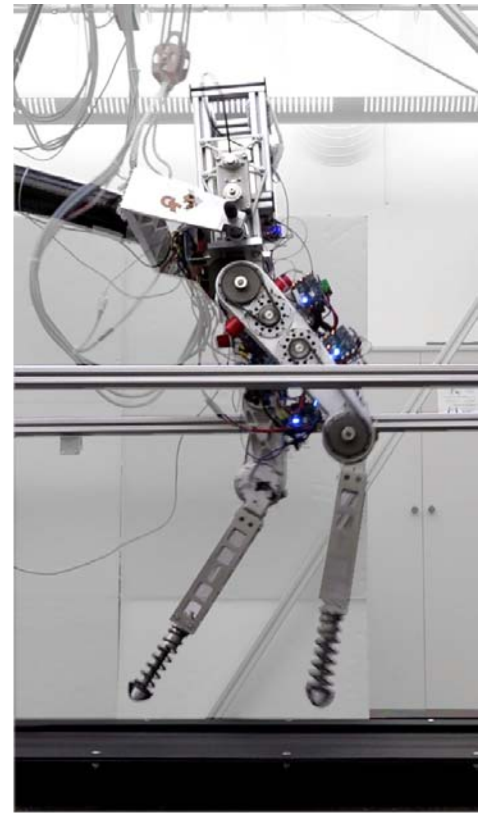


$$q \in \mathbb{R}^n, u \in \mathbb{R}^m, F \in \mathbb{R}^l$$

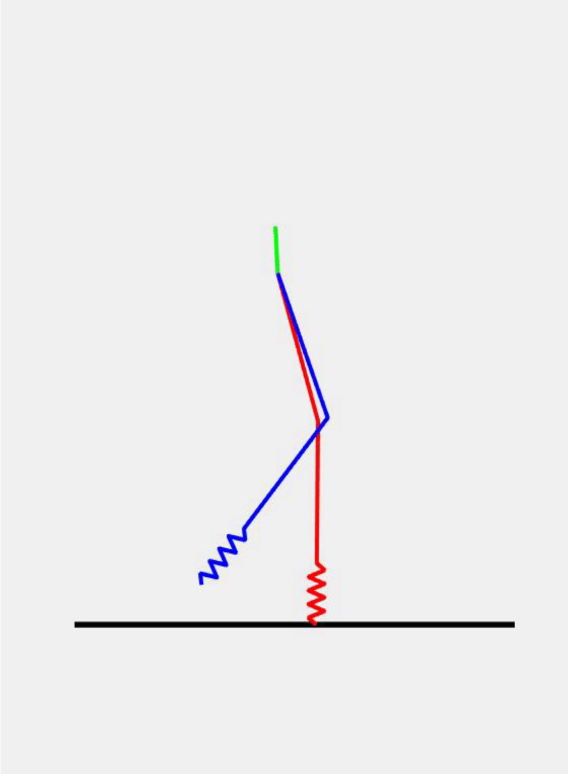
$$v \in \{\mathrm{s}, \mathrm{f}\}, \quad e \in \{\mathrm{s} \to \mathrm{f}, \mathrm{f} \to \mathrm{s}\}$$

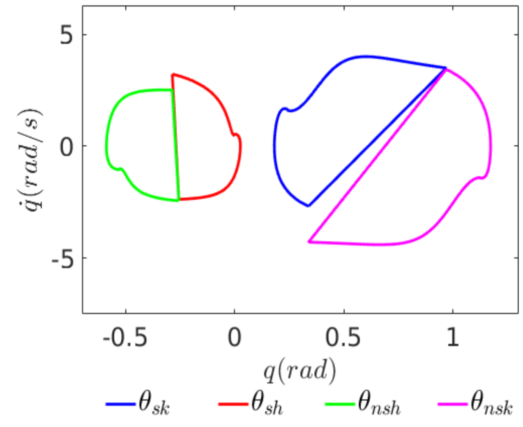
$$\{\mathcal{D}_\mathrm{s}, \mathcal{D}_\mathrm{f}\}, \quad \{\mathcal{S}_{\mathrm{s}\to\mathrm{f}}, \mathcal{S}_{\mathrm{s}\to\mathrm{s}}\}$$





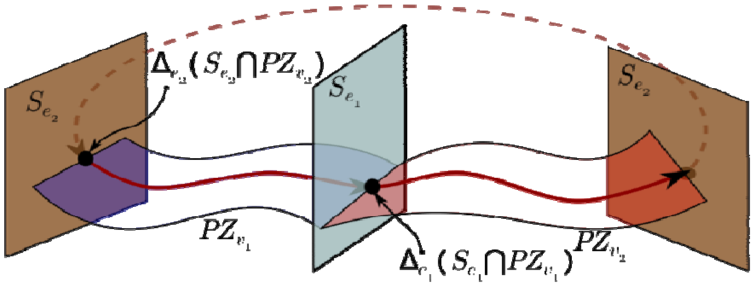
Optimization performance



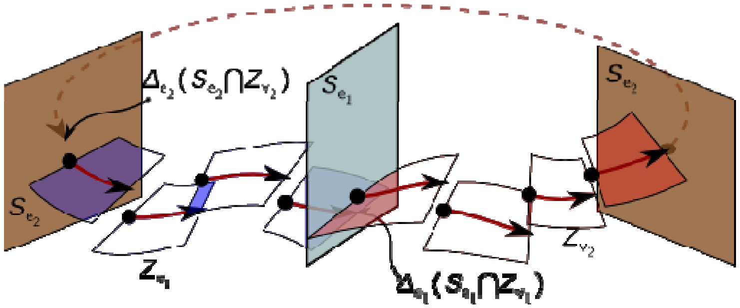


Periodic orbit $\mathcal{O}$

Single shooting



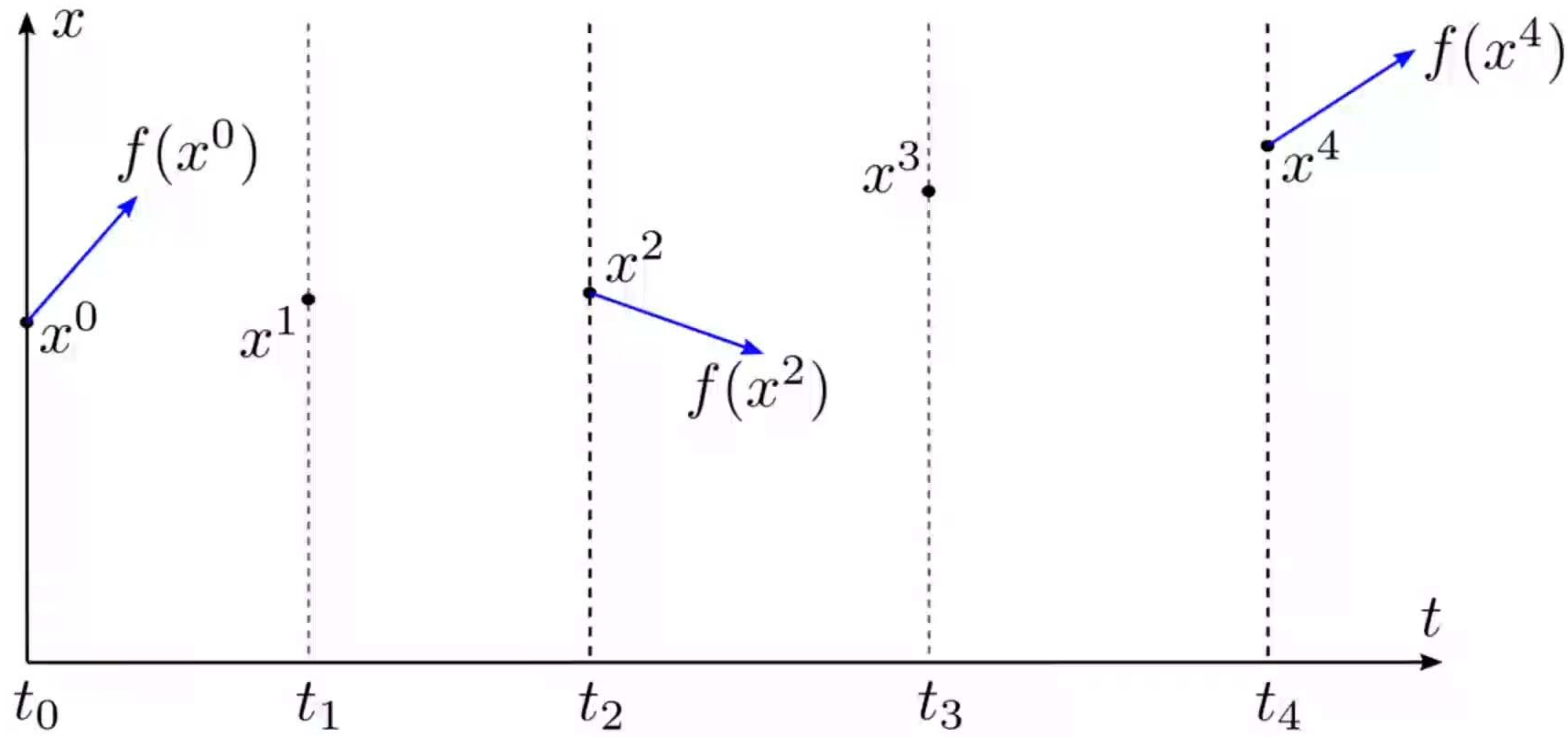
Multiple shooting



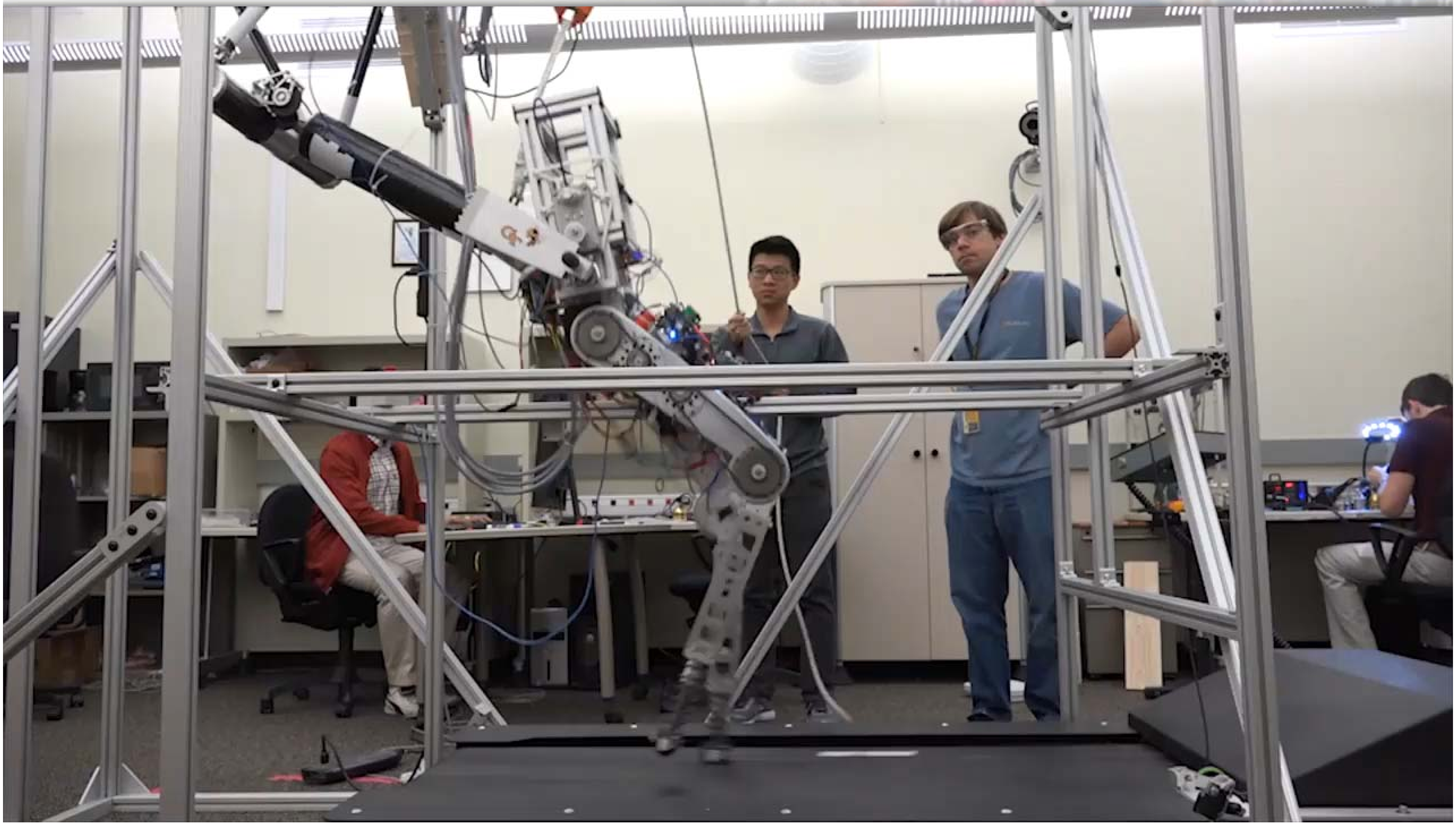
1. Single shooting method: >2 hours, solution not found
2. Multiple shooting method: 13 hours, solution found
3. **Direct collocation:** <1 min, solution found

Trajectory Optimization

Direct Collocation



Trajectory Optimization



We need fast trajectory optimization for testing different gaits.

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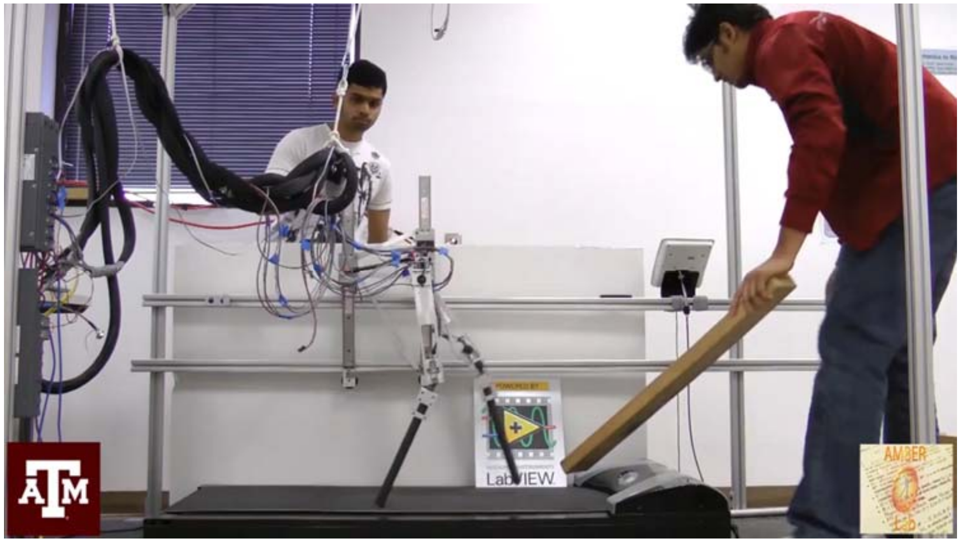
Controller design plays an important part!

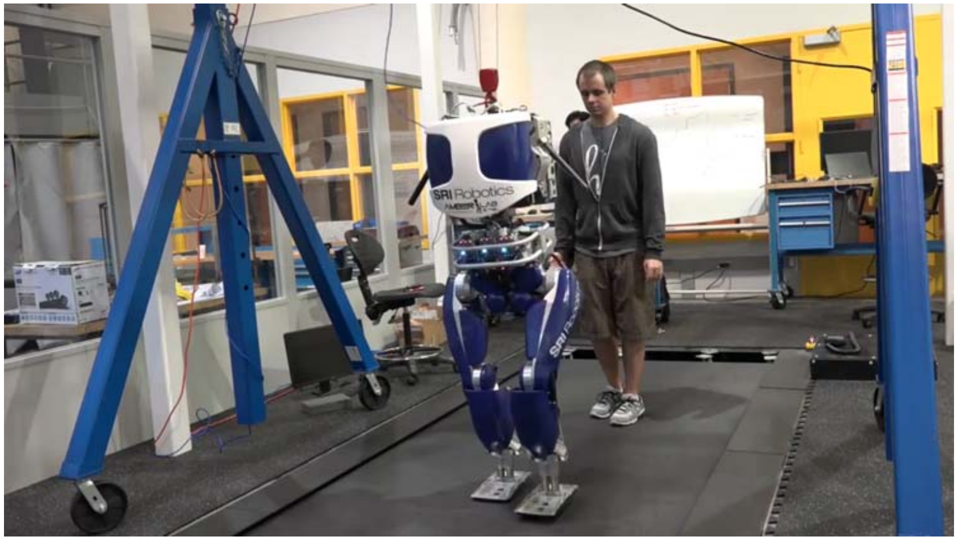
Dec 2011



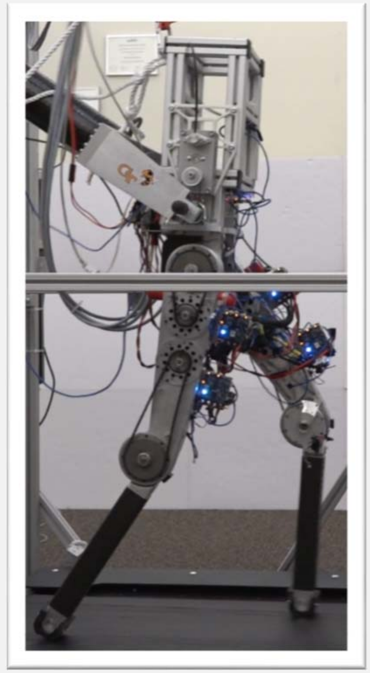
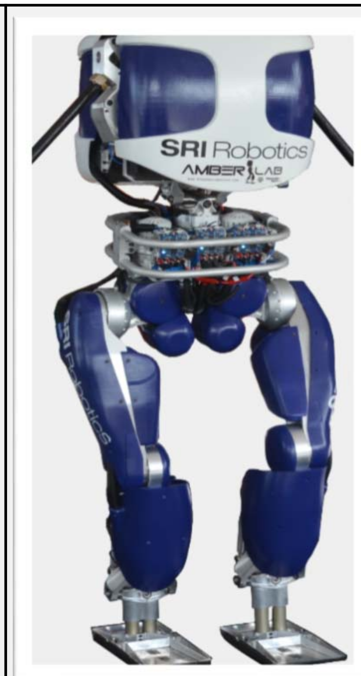
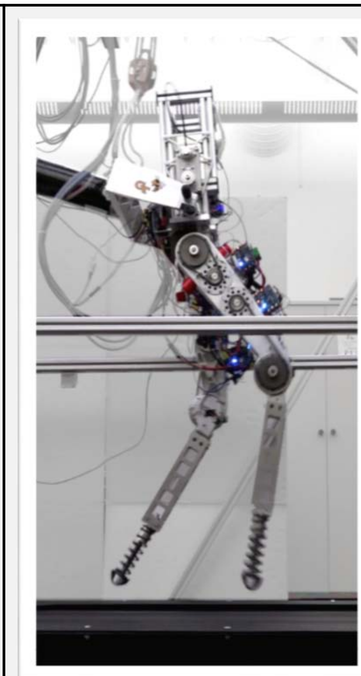
Nov 2013

Jun 2015

Jun 2016

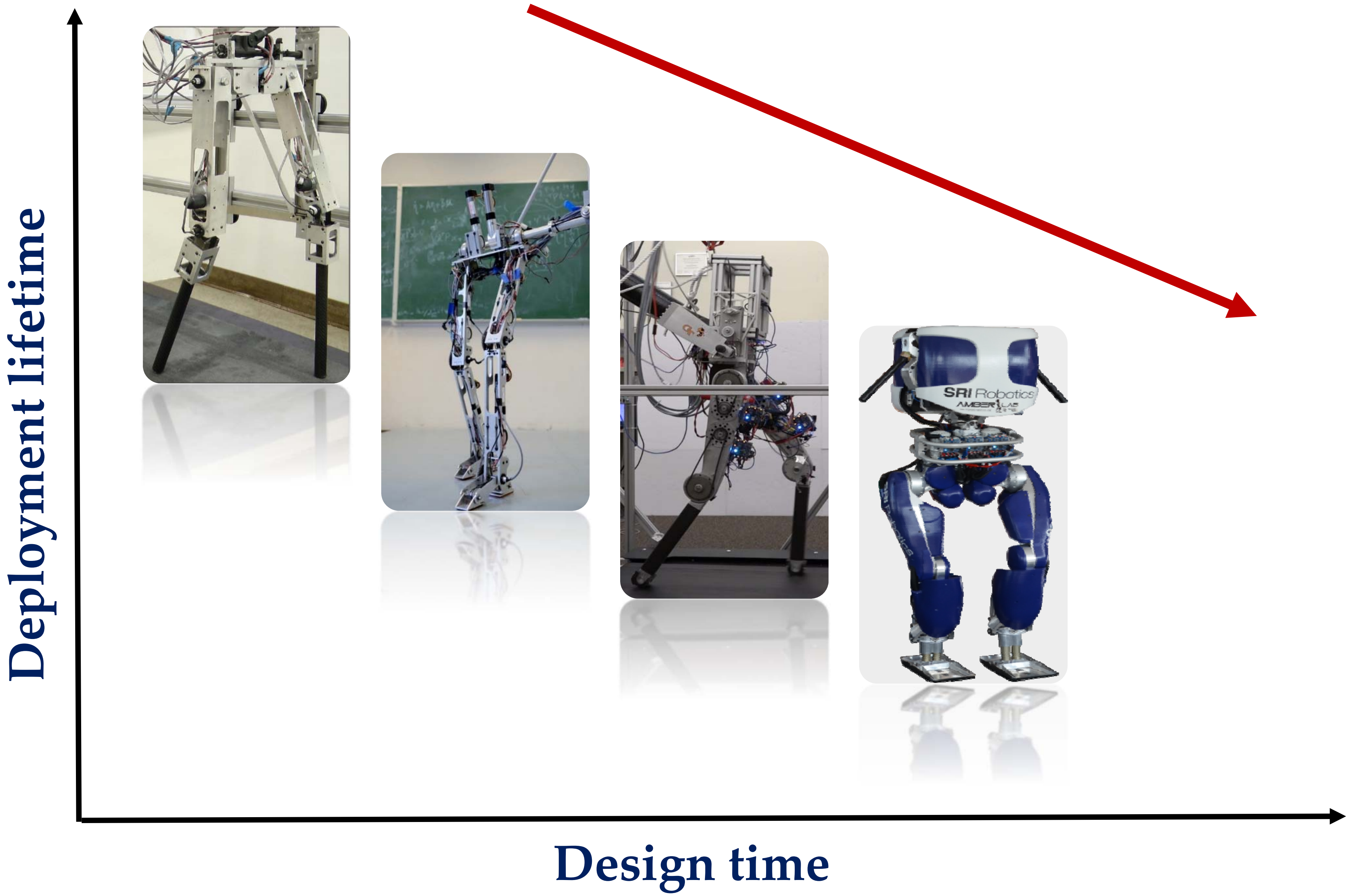


Controller design plays an important part!

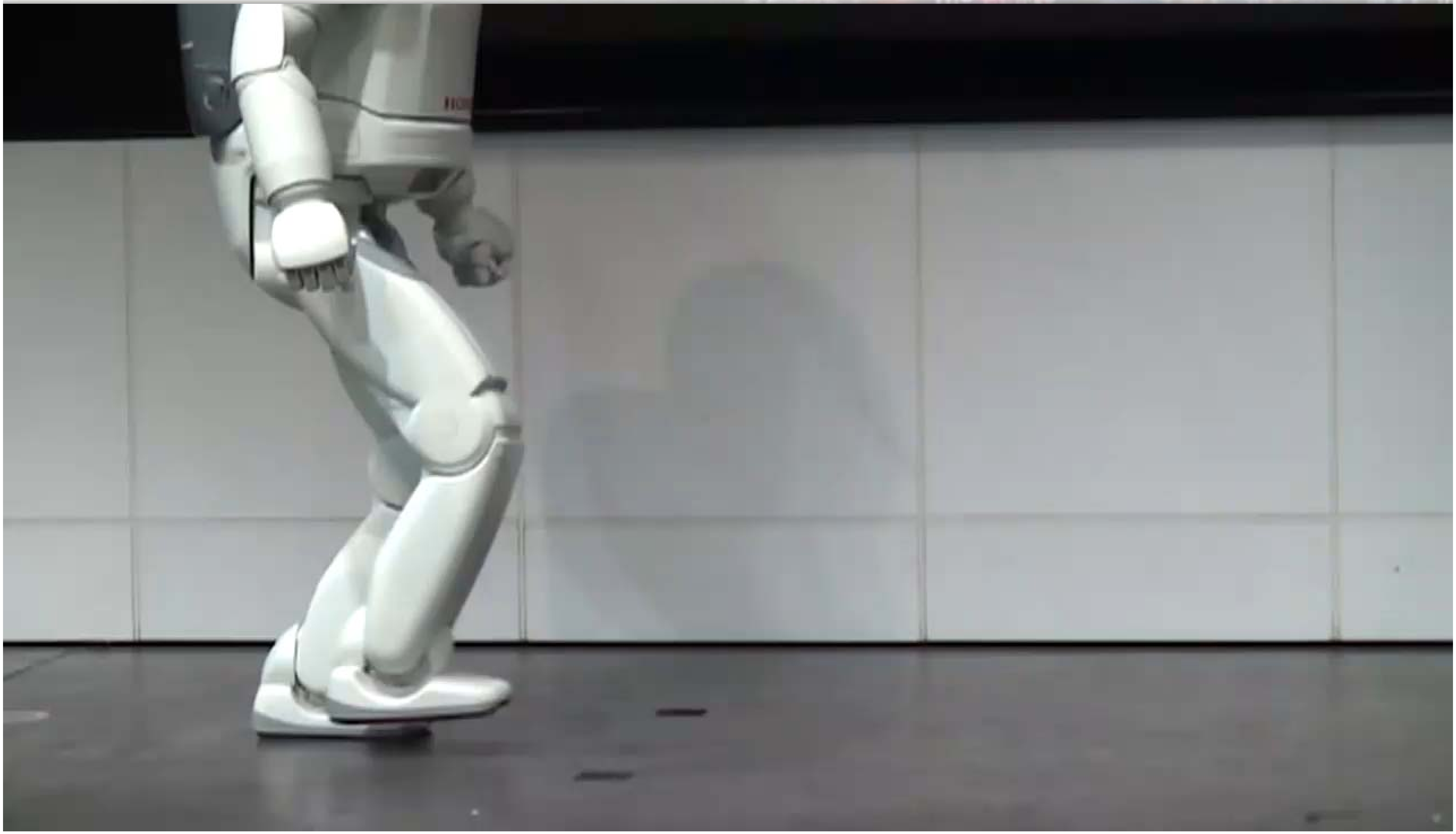
				
AMBER1	**AMBER2**	**PROXI**	**DURUS**	**DURUS-2D**
P Voltage Control	PD current control	PD current control	PD current control+Regulators, Time based parameterization	PD current control, Time+state based parameterization
2011	2013	2014	2015	2016

→ **Increasing complexity!**

Controller design plays an important part!



Returning to basics!



Watch how the hip is always maintained at a constant height.

Returning to basics!

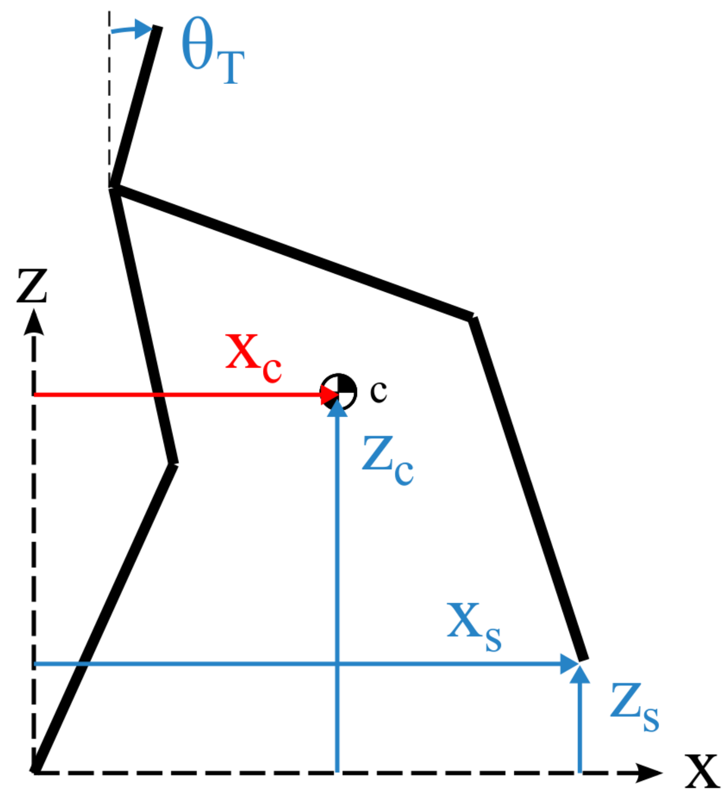
$$L_y = m z_c \dot{x}_c - m x_c \dot{z}_c + H_c$$

Take the derivative and substitute for $\dot{L}_y = m g x_c$

$$m g x_c = m \dot{z}_c \dot{x}_c + m z_c \ddot{x}_c - m \dot{x}_c \dot{z}_c - m x_c \ddot{z}_c + \dot{H}_c$$

Assuming constant center of mass height and low $\dot{H}_c$

$$m g x_c = m z_c \ddot{x}_c$$



Returning to basics!

Harold Black

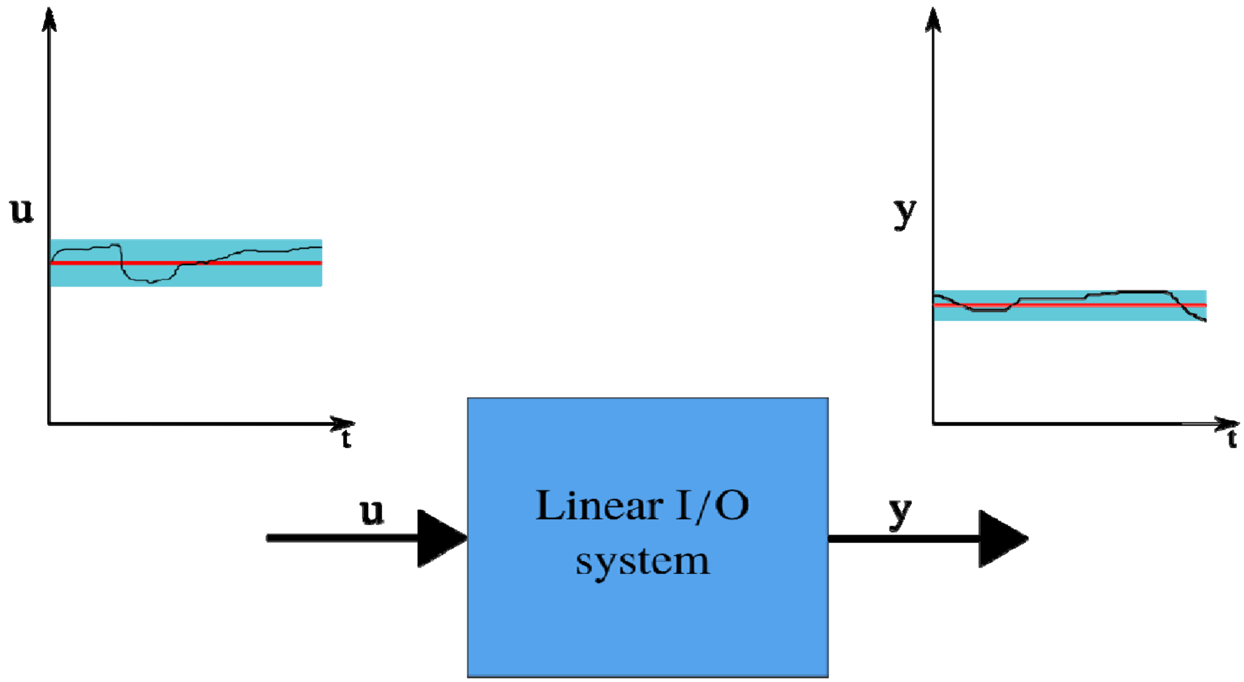
Amplifier

George Zames

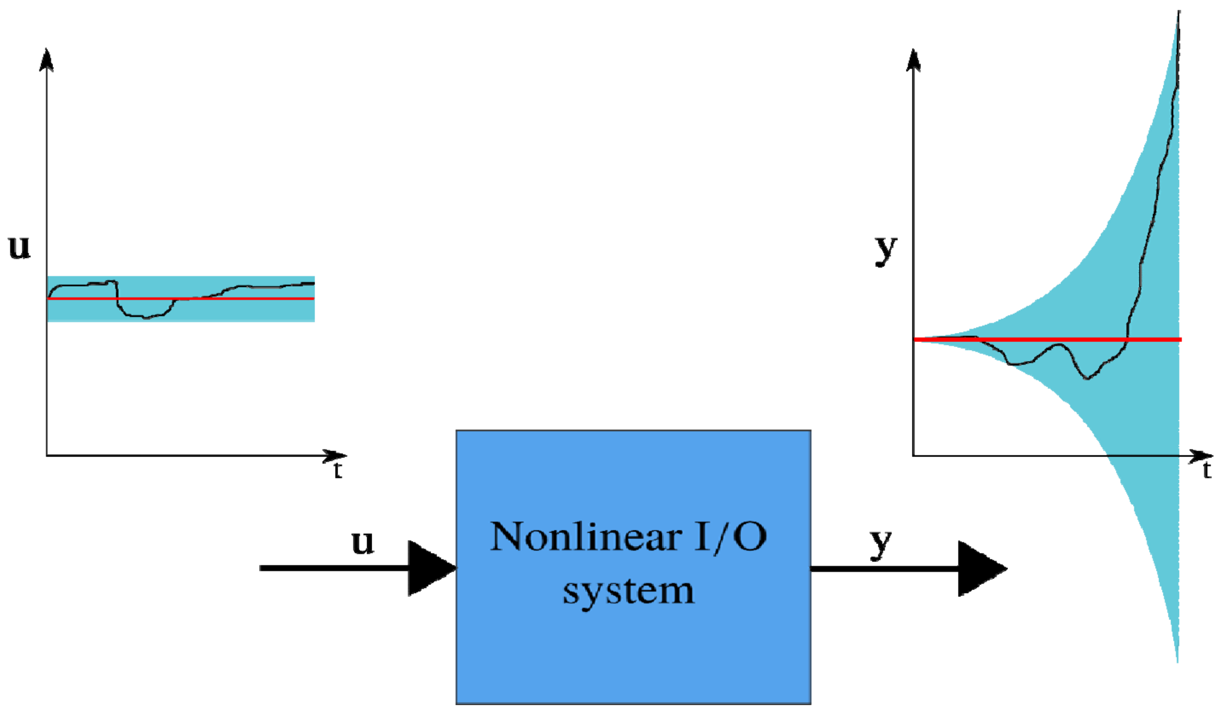
Black: Negative feedback for amplifiers.

Zames: Input/output stability. Operator theory.

Returning to basics!



Preliminaries on ISS



Preliminaries on ISS

George Zames

+

Aleksandr Lyapunov

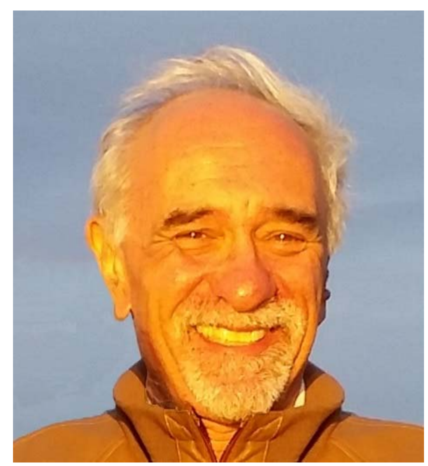
Input/output stability
for linear systems

Lyapunov stability for
nonlinear systems

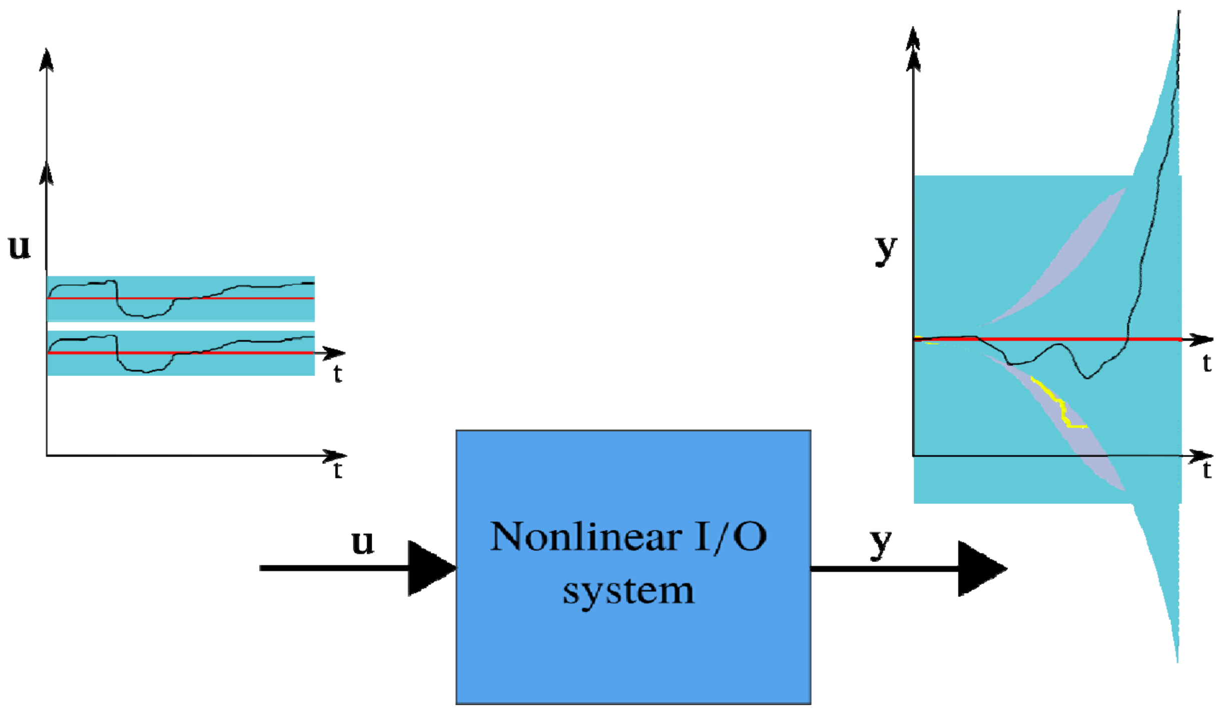
=

Input to state stability
for nonlinear systems

Eduardo Sontag



Preliminaries on ISS



Properties of ISS

ISS is always w.r.t. d.

$$\dot{x} = f(x, k(x) + d), \quad u = k(x) + d, \quad x(0) = x_0$$

If $\dot{x} = f(x, k(x))$ is asymptotically stable, then $u = k(x)$ is the stabilizing controller.

If $\dot{x} = f(x, k(x) + d)$ is input to state stable, then $u = k(x)$ is the input to state stabilizing controller.

How to obtain ISSing controllers?

Linear feedback laws

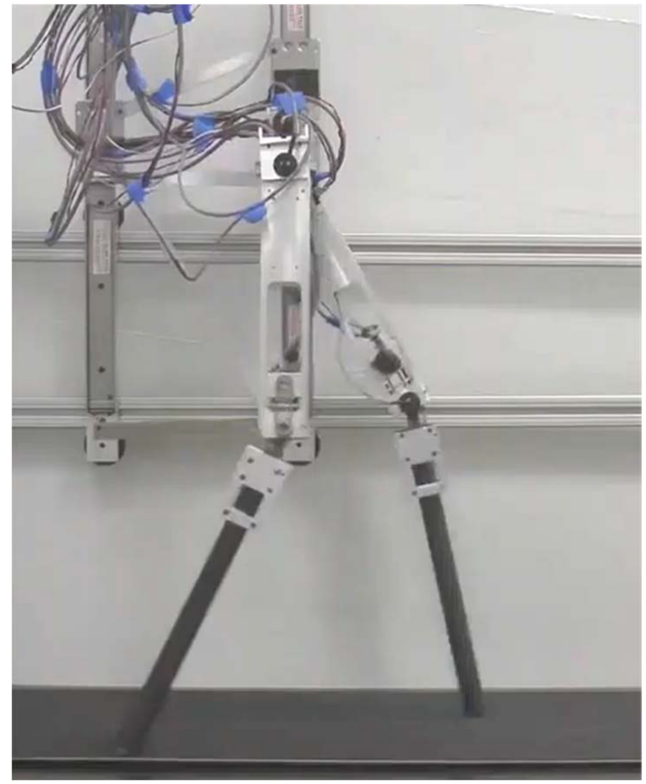
$$D(q)\ddot{q} + \boxed{C(q,\dot{q})\dot{q} = d\; G(q)} = BK_p(q_d - q) + BK_d(\dot{q}_d - \dot{q})$$

Stabilizing controller

+

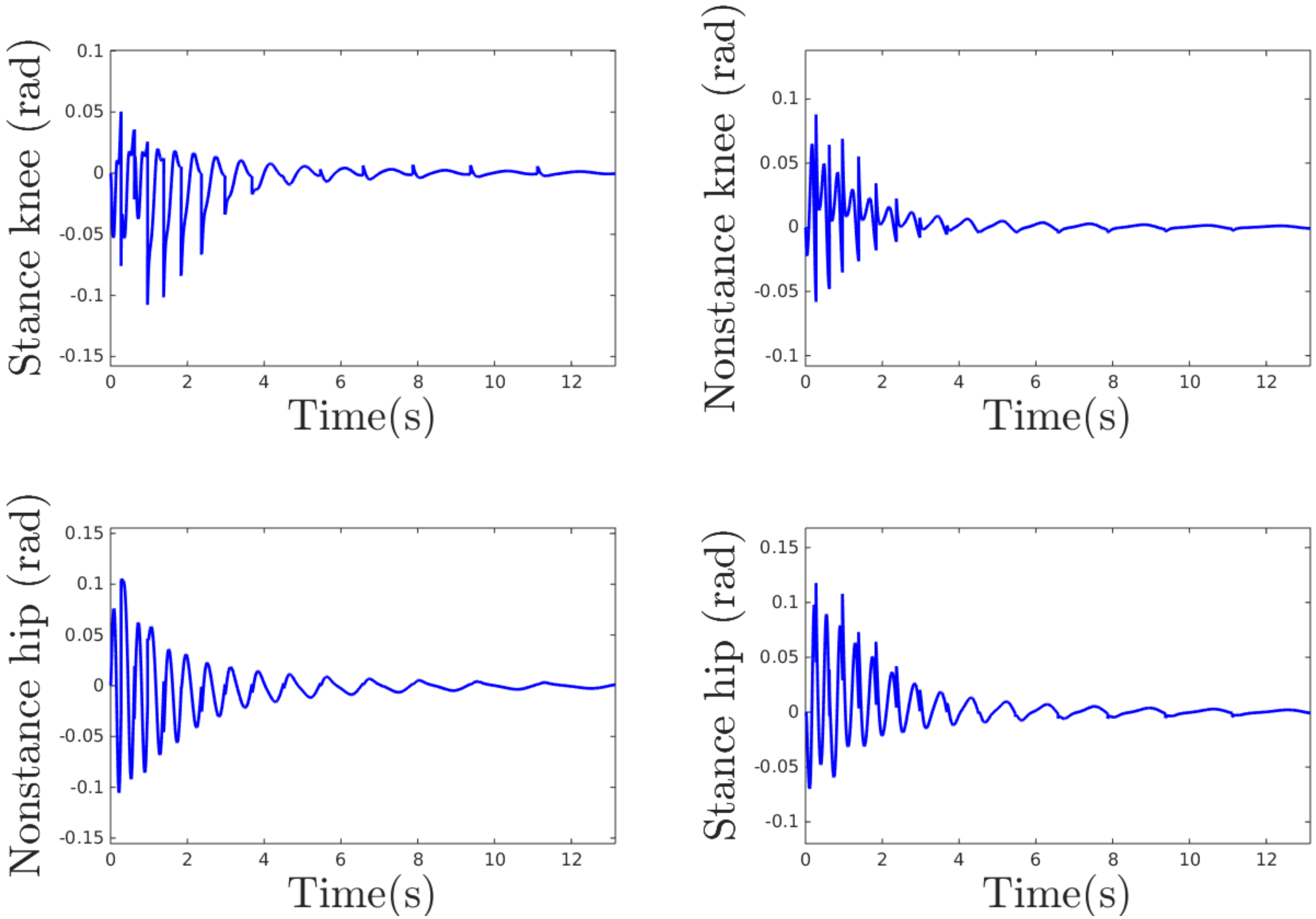
Hybrid invariance

= Output stability



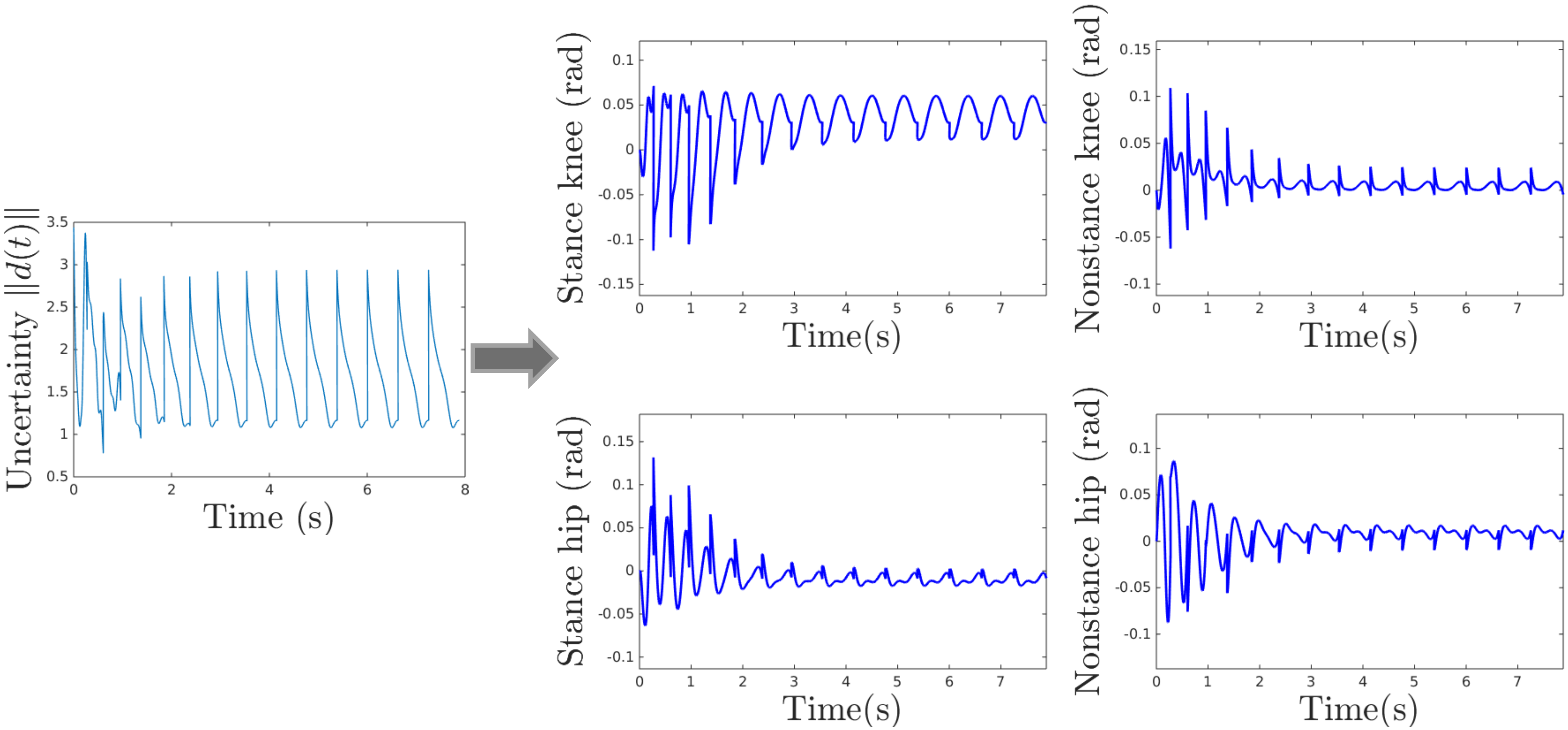
Yadukumar et. al, WAFR 2010.

$d = 0$



Stance knee (rad)
0.1
0.05
0
-0.05
-0.1
-0.15
0
2
4
6
8
10
12
Time(s)
Nonstance knee (rad)
0.1
0.05
0
-0.05
-0.1
0
2
4
6
8
10
12
Time(s)
Nonstance hip (rad)
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
0
2
4
6
8
10
12
Time(s)
Stance hip (rad)
0.15
0.1
0.05
0
-0.05
-0.1
0
2
4
6
8
10
12
Time(s)

$d \neq 0$



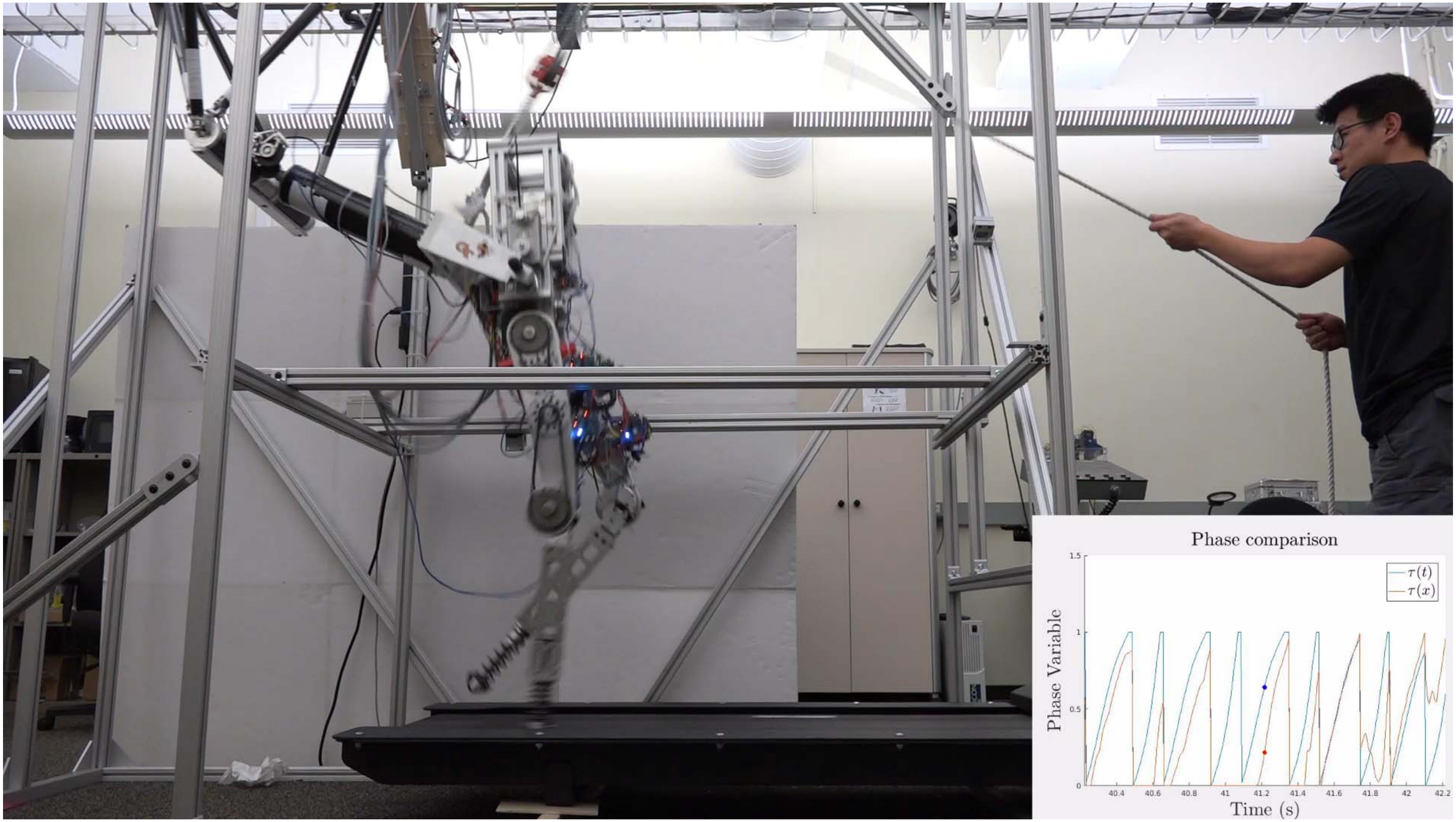
Uncertainty $\|d(t)\|$
Time (s)
Stance knee (rad)
Time(s)
Nonstance knee (rad)
Time(s)
Stance hip (rad)
Time(s)
Nonstance hip (rad)
Time(s)

Phase uncertainty

$$y = y_a - y_d = \begin{bmatrix} y_{sk} \\ y_{sh} \\ y_{nsh} \\ y_{nsk} \end{bmatrix} - y_d(\tau(q))$$

Kolathaya et. al, ACC 2016

DURUS-2D Running with ISS based controllers

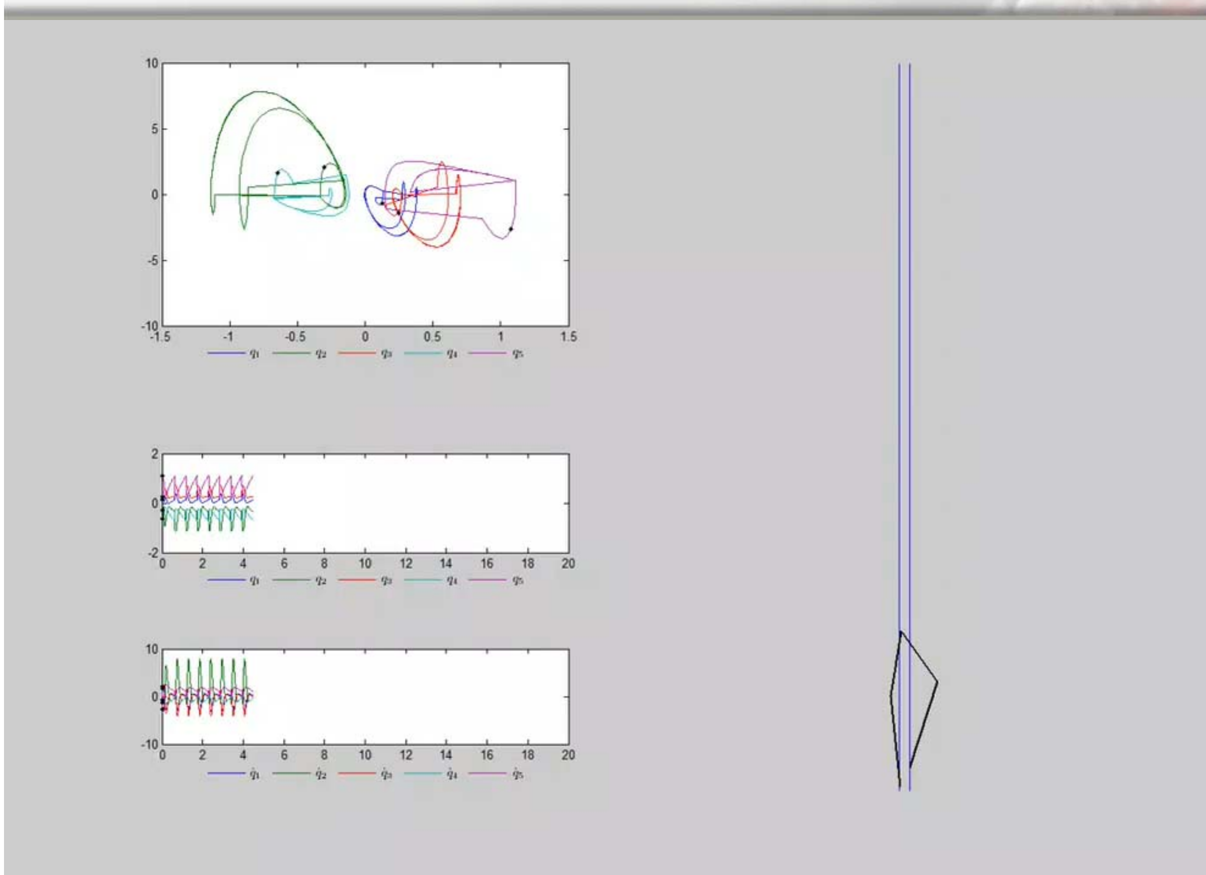


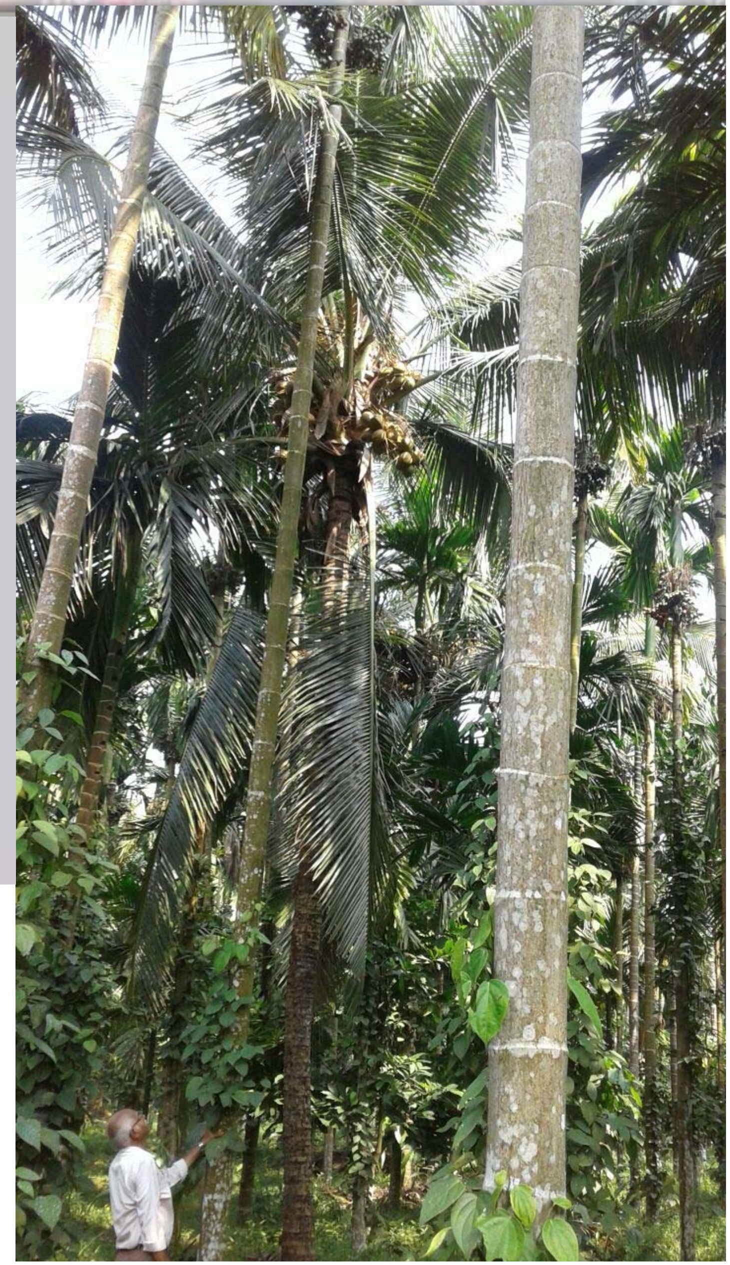
Conclusions

Made a significant step toward bridging the gap between theory and experiment

- Gait design: Demonstrated fast gait generation via collocation methods.
- Controller design: Constructed ISSing controllers to address modeling and phase based uncertainties.

Next steps: Food and agriculture





Challenges

- Hybrid system model
- Underactuation
- Soft contact with trunk


CHANNEL

Robots in agriculture

Farming and mining applications will be the first to receive self-driving tech in India, because the driving patterns are far simpler – no humans and other vehicles in your path to worry about. They're also quick to adopt new technologies. Plus, these industries are key drivers of our country's economy.
-- Dr. Roshy John

Thank you!

Acknowledgements

- NSF, DARPA
- SRI Robotics, National Instruments
- Miso Robotics