ISTITUTO ITALIANO DI TECNOLOGIA

Developing Actuators with Rich Motor Properties for Emerging Humanoids

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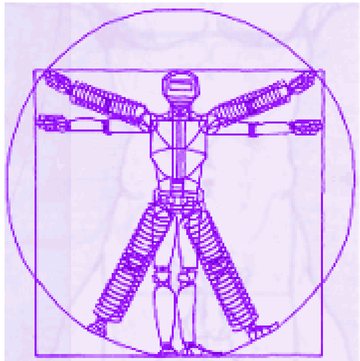
Workshop on New Bodies for Cognitive Humanoids,
Bled, Slovenia, 26th October 2011

Research efforts towards passive compliant systems



VIACTORS

The goal is to design, realize and evaluate new range of actuator groups exhibiting variable stiffness, variable damping or full impedance regulation principles

AMARSI

The goal of AMARSi is a qualitative jump toward rich motor behaviour where novel mechanics, control and learning solutions are integrated with each other

AMARSI project

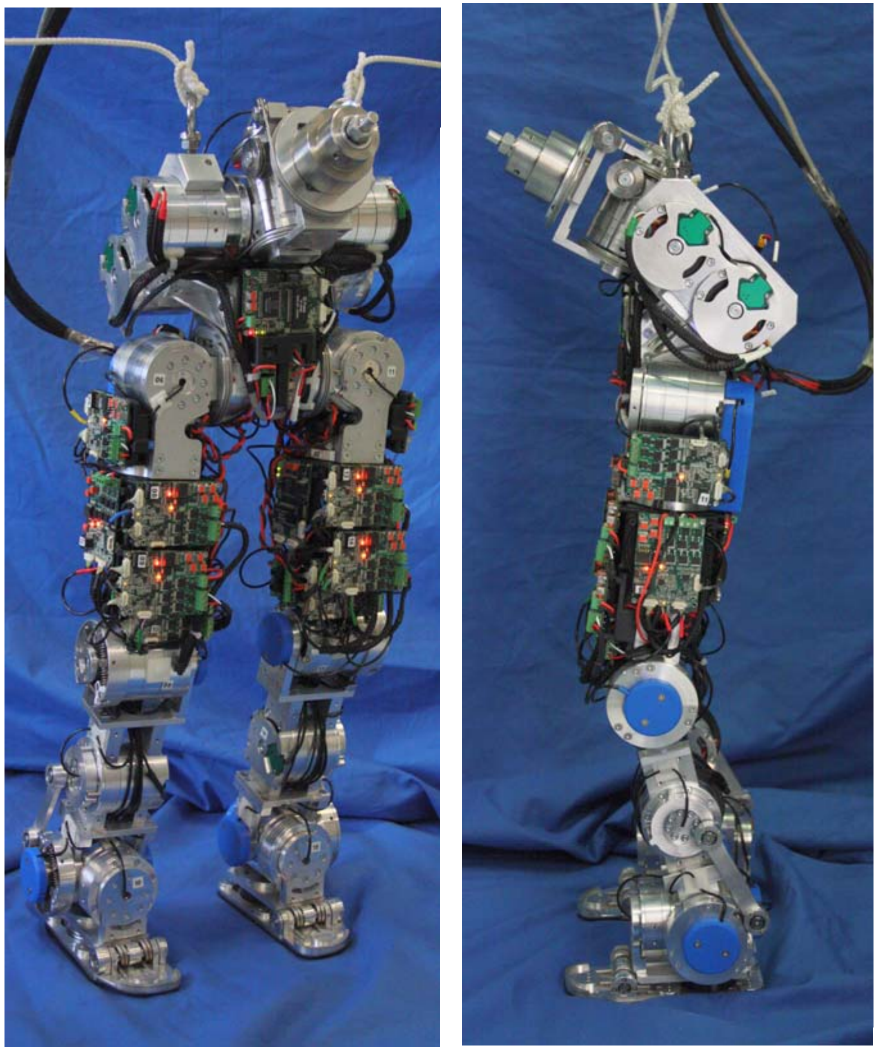
- Aims to design, realize and test a new generation of humanoid and quadruped robotic platforms, powered by compliant actuators

- To study how compliance can be exploited through learning for more natural locomotion, safer interaction and reduced energy consumption.

COmpliant HuMANoid (COMAN)
Summary of features

COMAN passive compliant humanoid

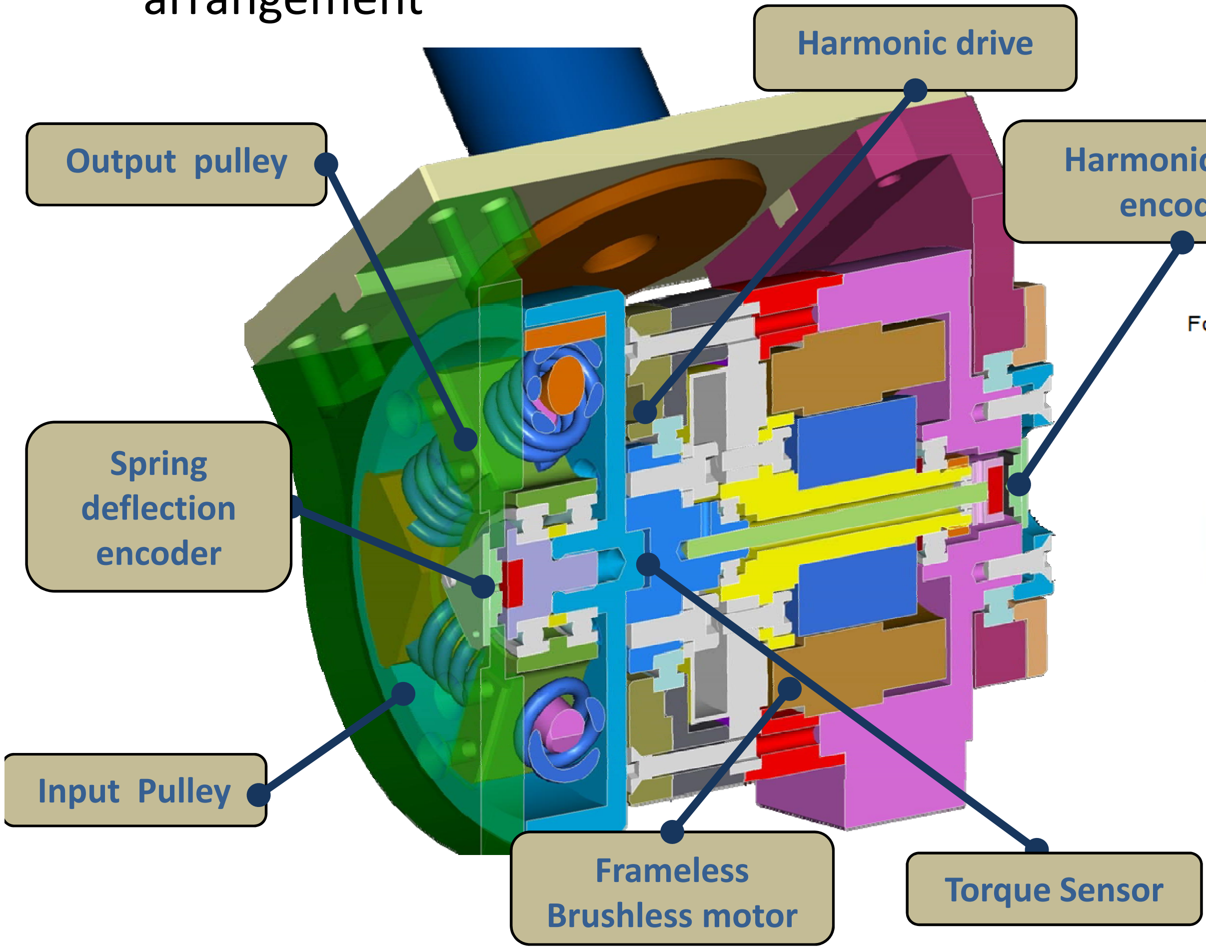
- a full humanoid robot with a height of 110cm.
- 32 + (1) major degrees of freedom of freedom (arms/legs and torso and neck)
- intrinsic passive compliance in the actuation
- Joint torque sensing/active compliance

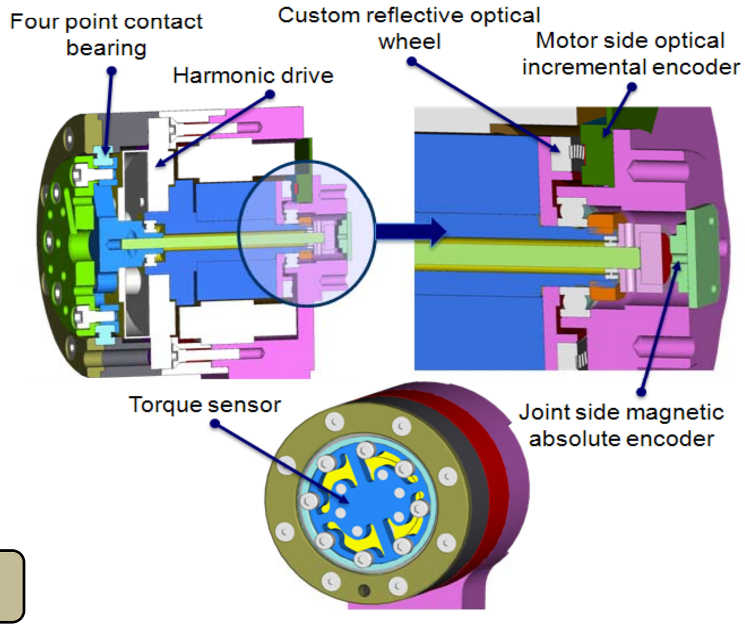


Tsagarakis et al, ICRA 2011

The CompAct™ Unit: A fixed passive compliance actuator

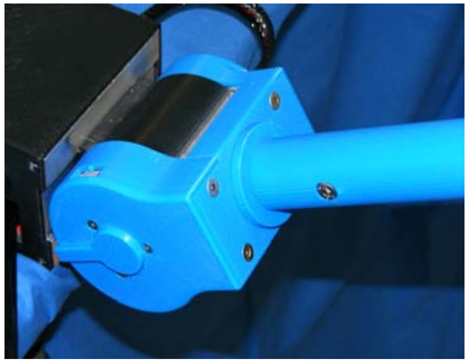
- **Input pulley**: rigidly linked with the gear's outer shaft
- **Output three spoke part**: linked with the external pulley through a spring arrangement

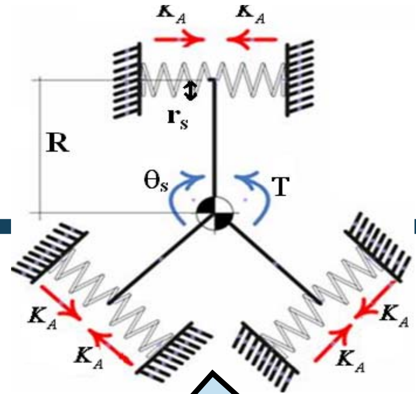


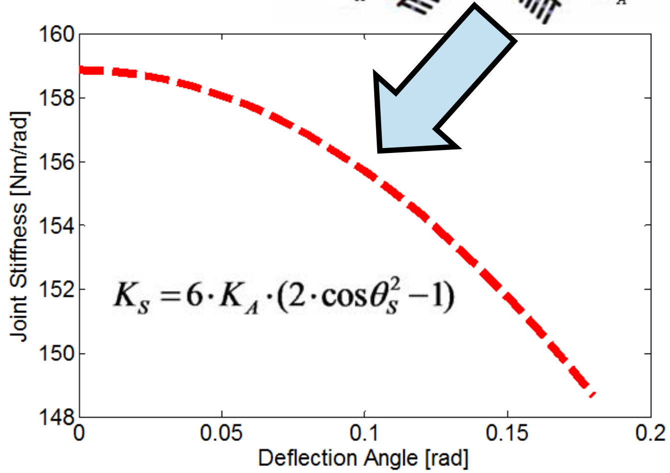


Tsagarakis et al, ICRA 2009

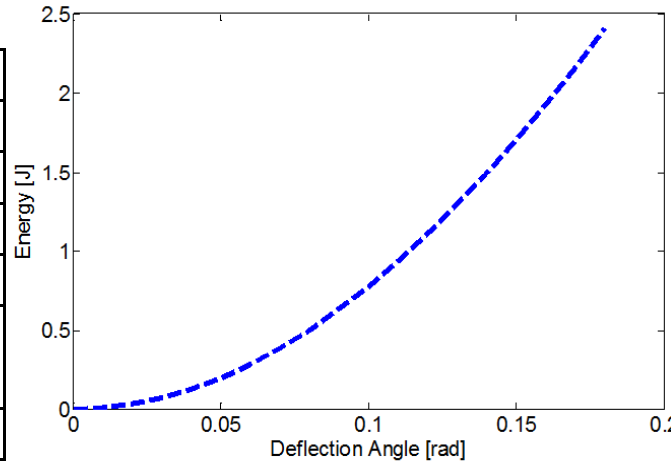
Fixed compliance actuator



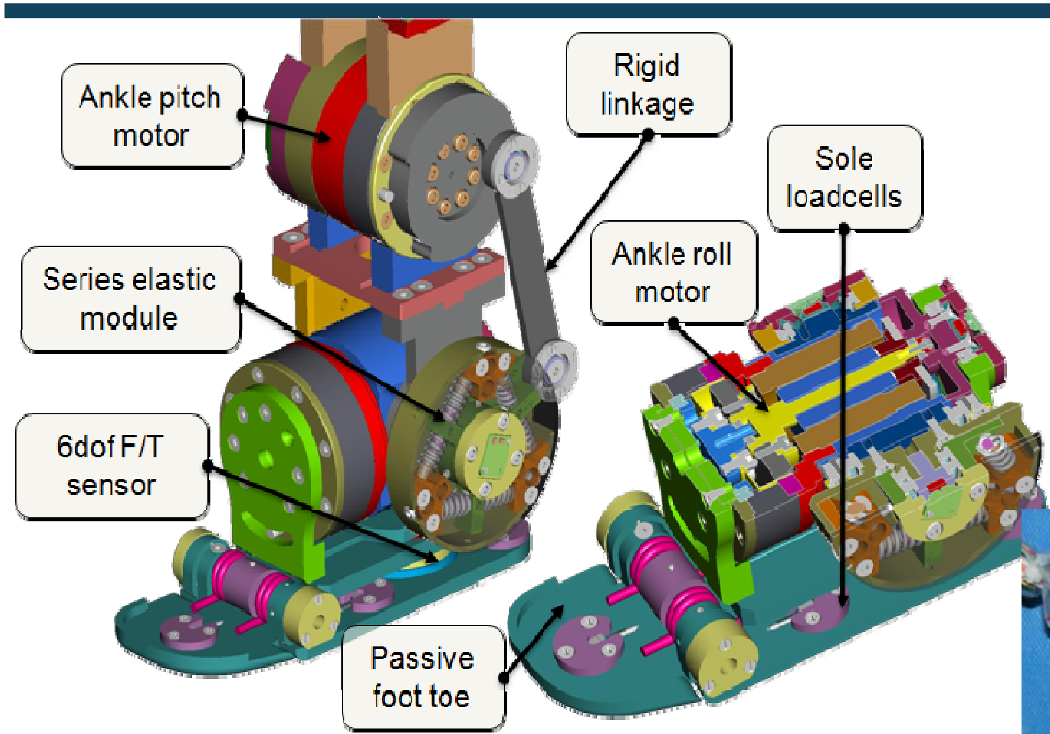


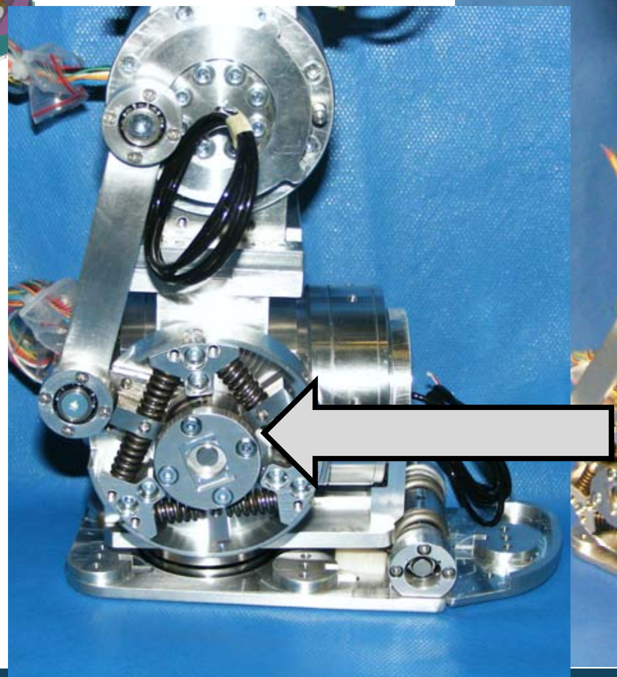


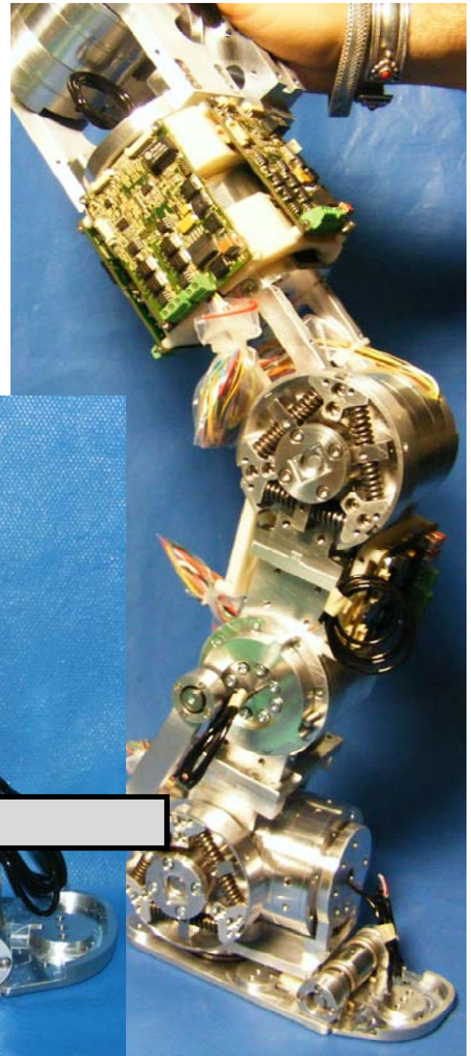
Diameter	70mm
Length	80mm
Power	190W
Gear Ratio	100:1
Peak torque	55Nm
Max rotary passive deflection	+/-0.18rad
Weight	0.52Kg



Leg mechanics

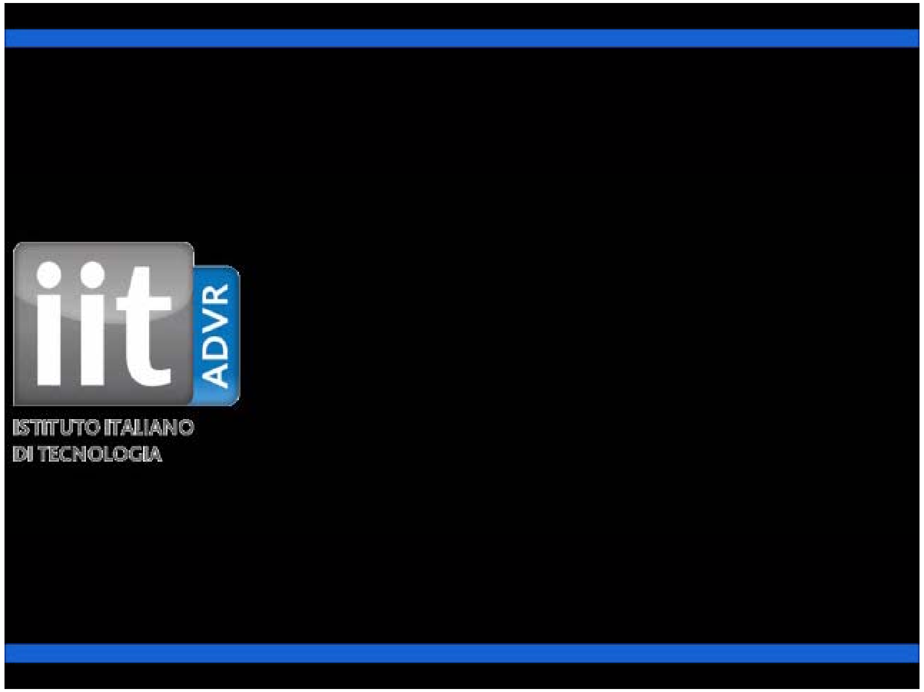


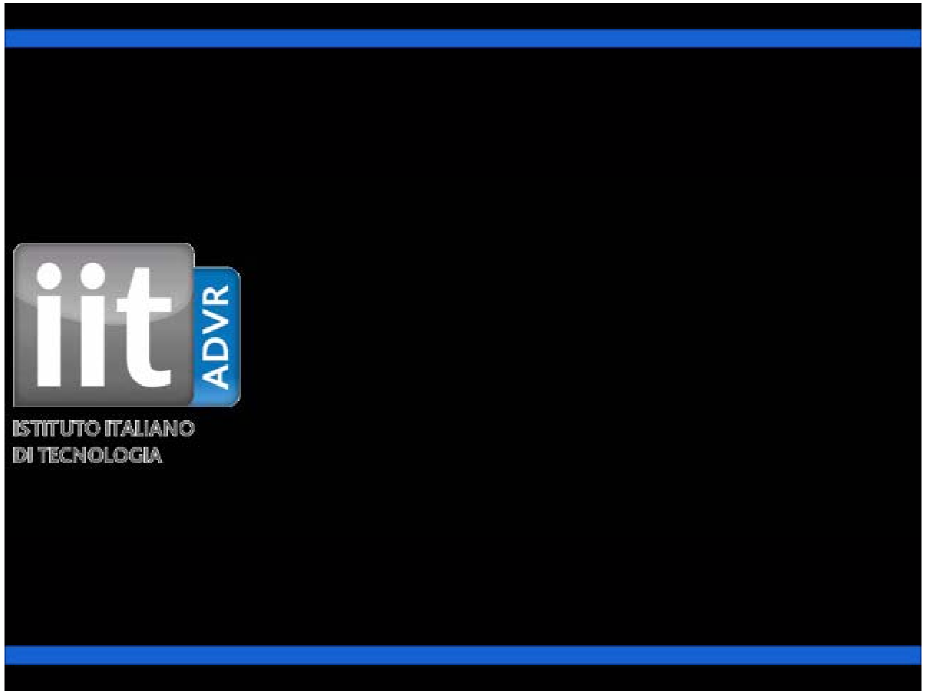




Compliant legs –First static steps

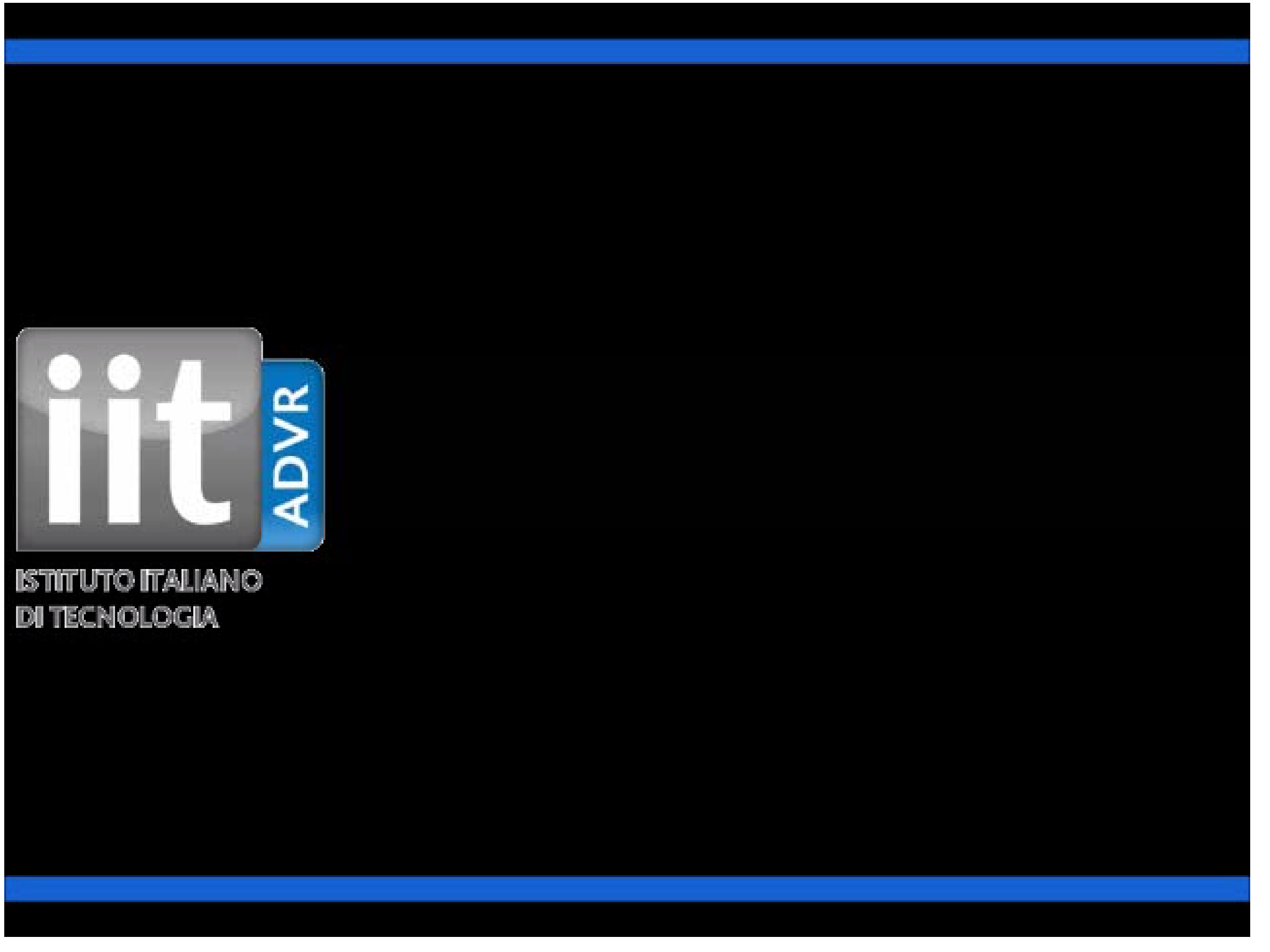
October 2010



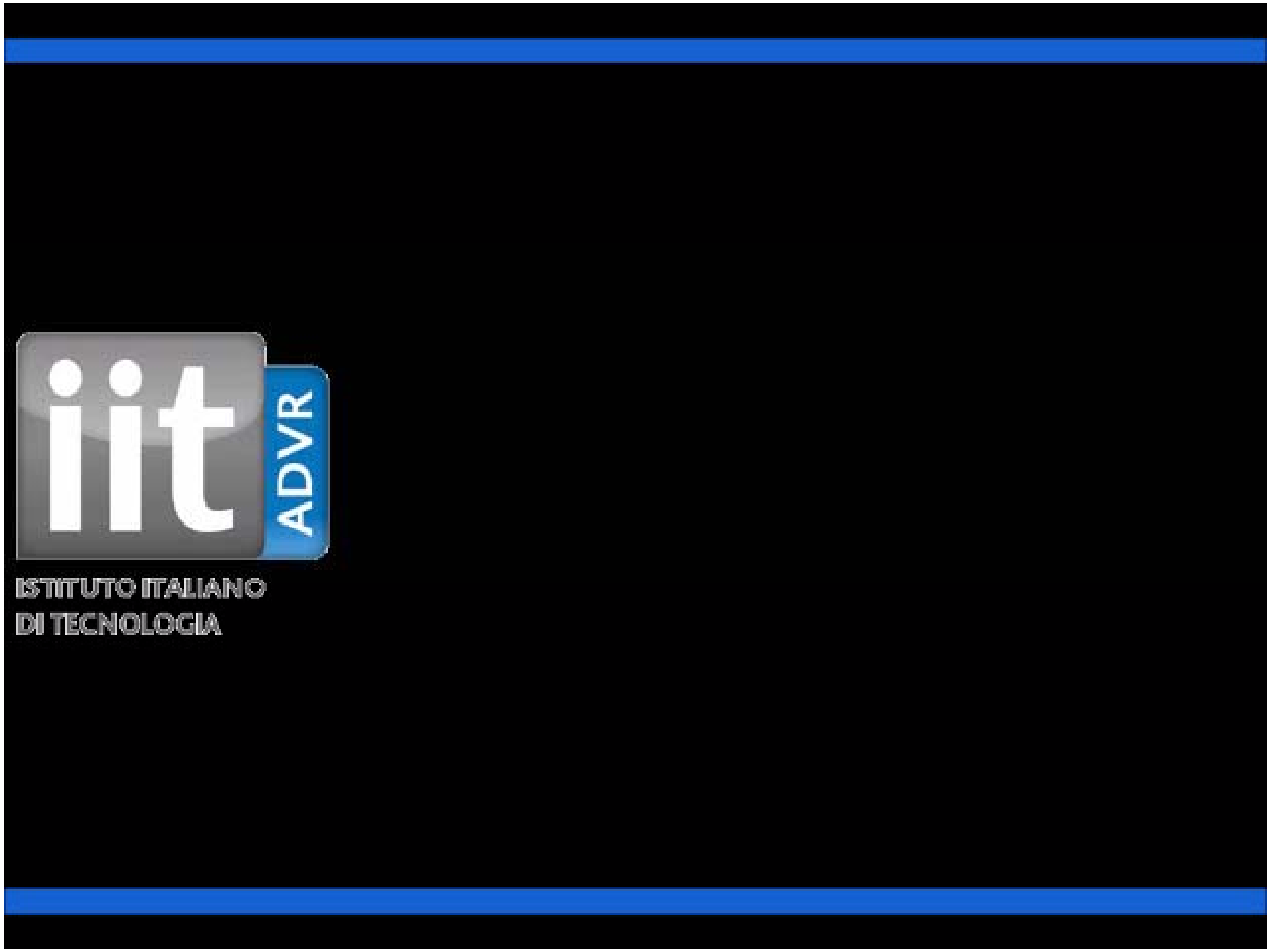


Compliant legs-Dynamic walking

January 2011

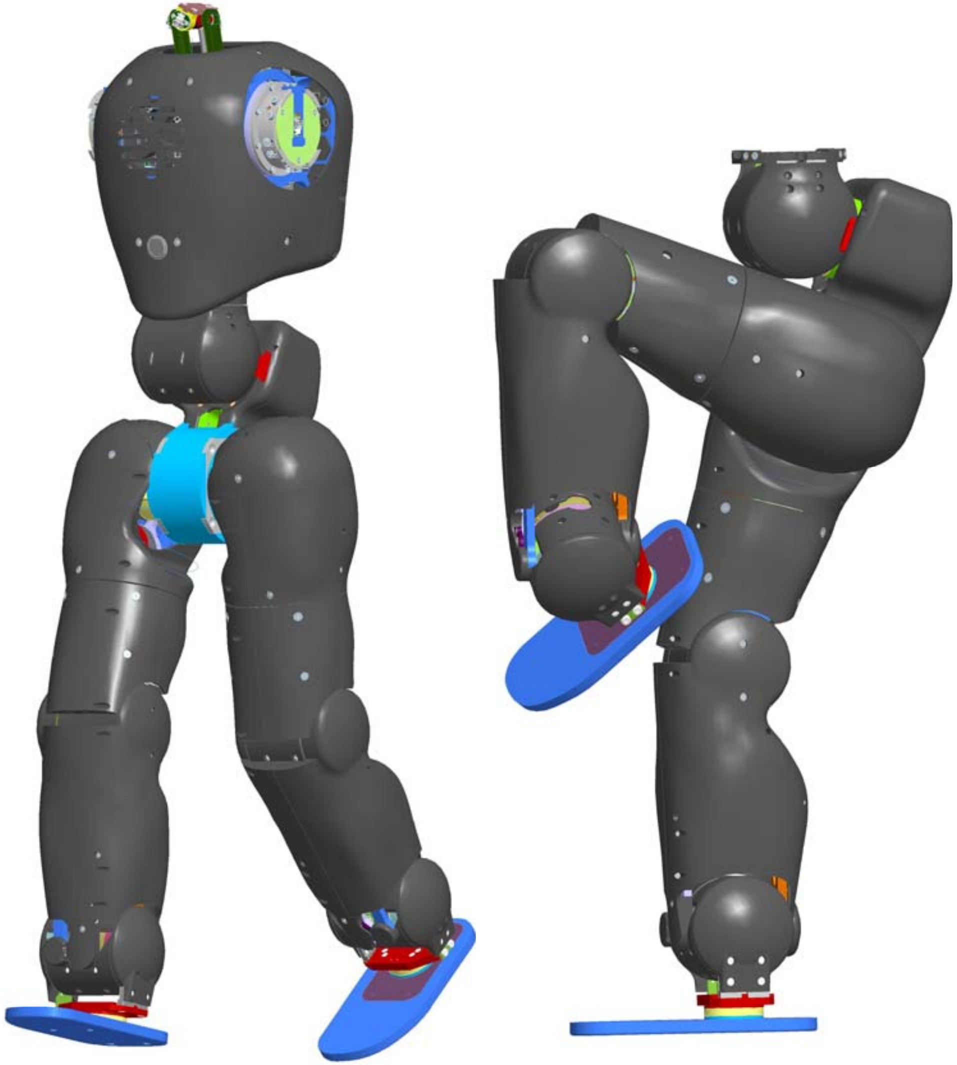


COMAN tolerance to impacts



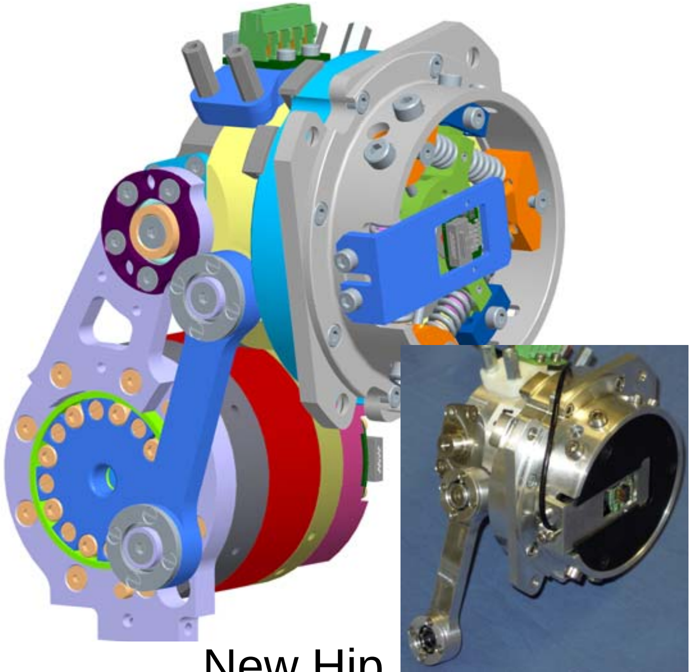
From legs to full body COmpliant HuMANoid (COMAN): Quick summary of updates

- Passive compliance added to
  - Hip joints
  - Torso joint (Pitch and yaw)
- Upper torso and arms
  - Passive compliance at shoulders and elbow
- On board controller
- Battery + BMS



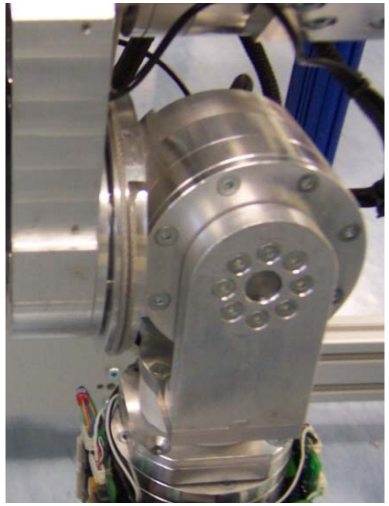
Hip joint

- Serial mechanism
- Passive compliance at the hip flexion / extension



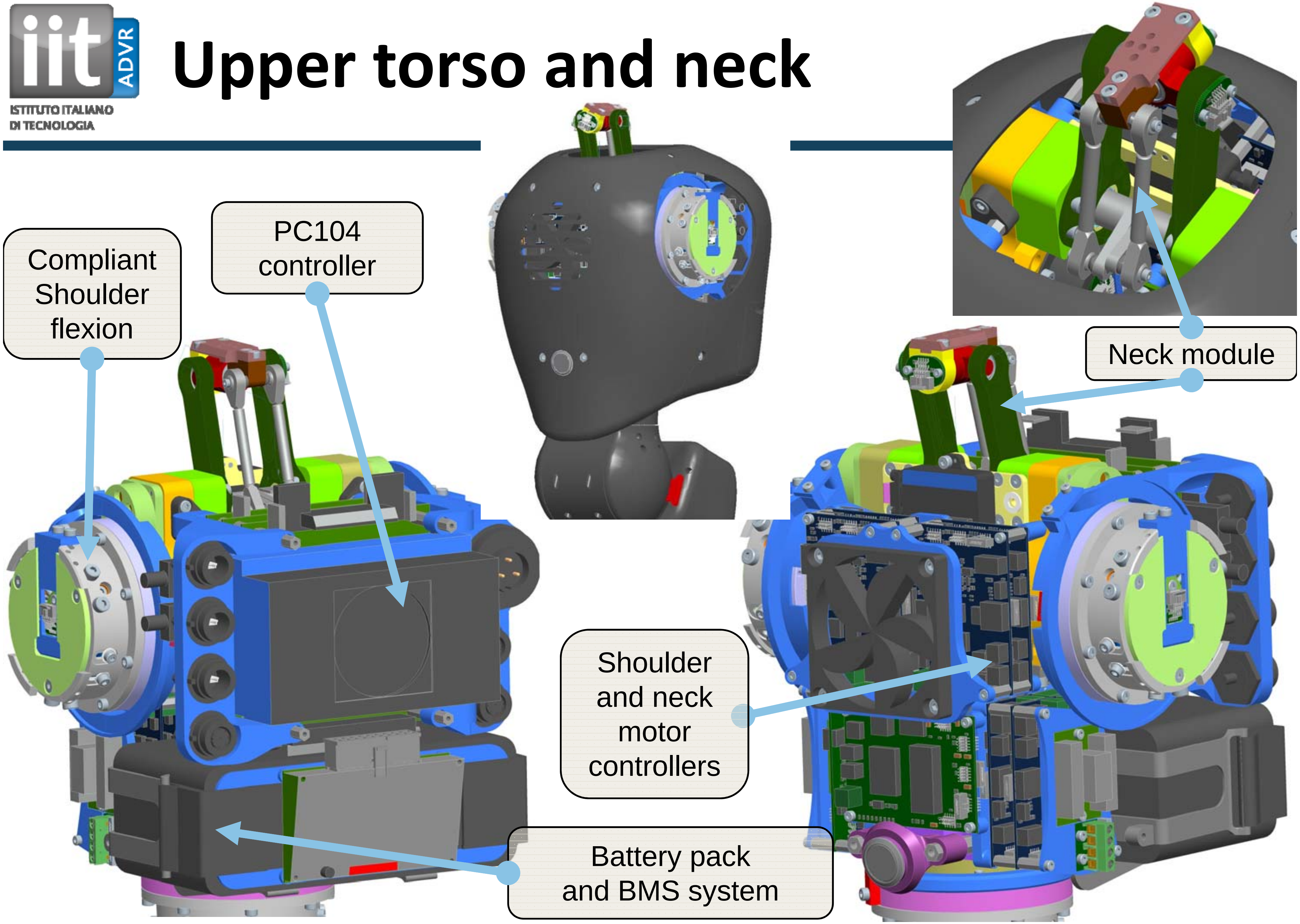
New Hip

Old design



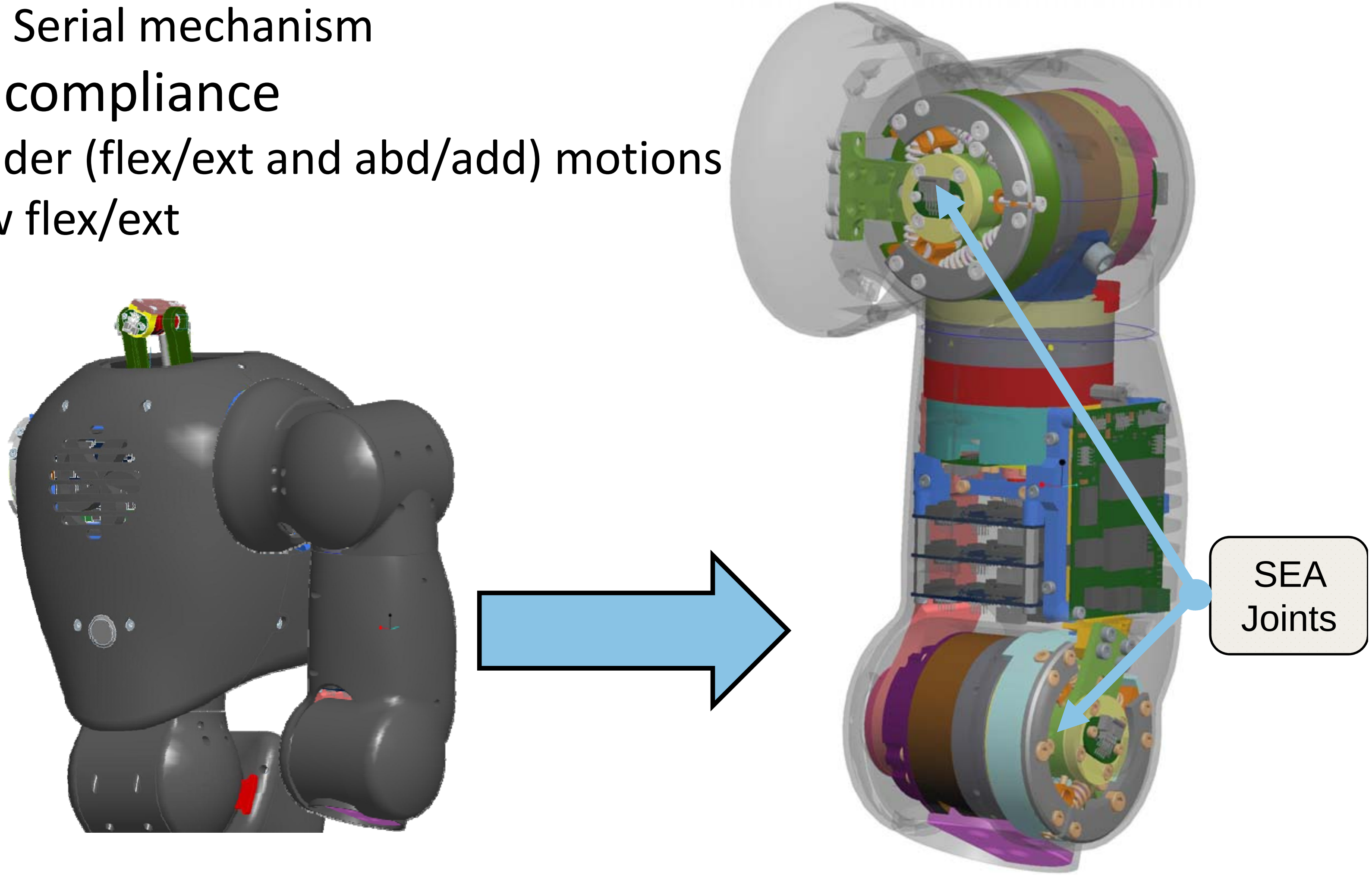
Joint	New Hip		First Prototype	
	Motion Range **(°)**	Torque (Nm)	Motion Range **(°)**	Torque (Nm)
Flex/Ext	+110, -45	55	-110, -45	55
Abd/Add	-60, +20	55	-90, +17	55
Rotation	+50, -50	55	-80, +80	55

Upper torso and neck



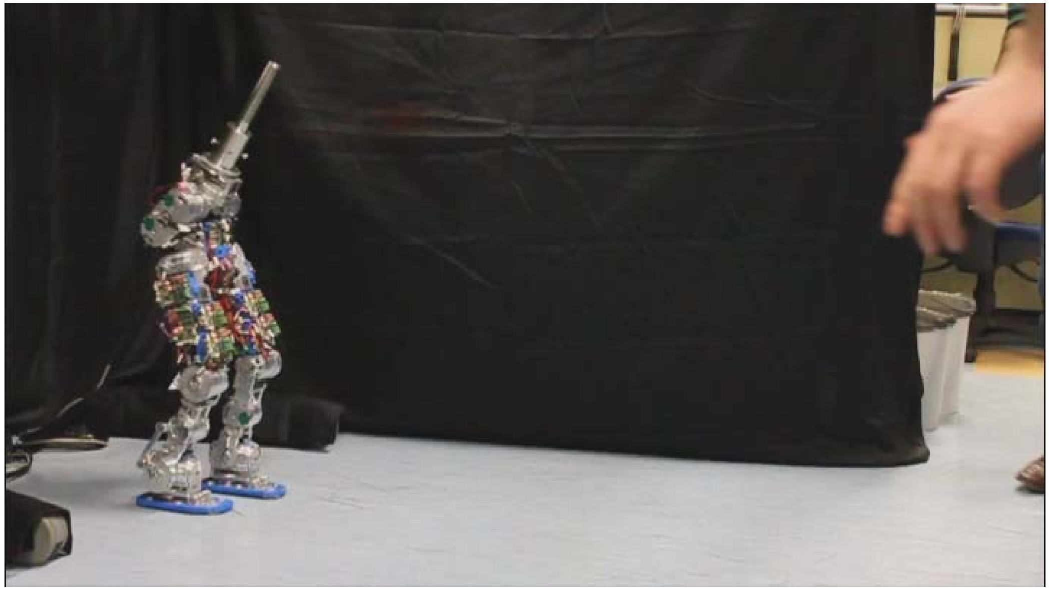
Upper arm

- Fully decoupled
  - 3DOF Serial mechanism
- Passive compliance
  - Shoulder (flex/ext and abd/add) motions
  - Elbow flex/ext

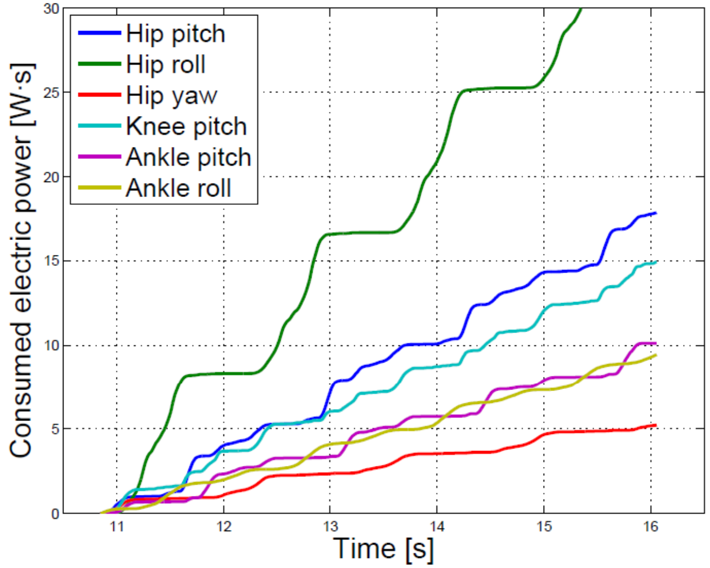


Walking with efficiency

Conventional ZMP-Fixed and COM Height based walking



Energy consumption

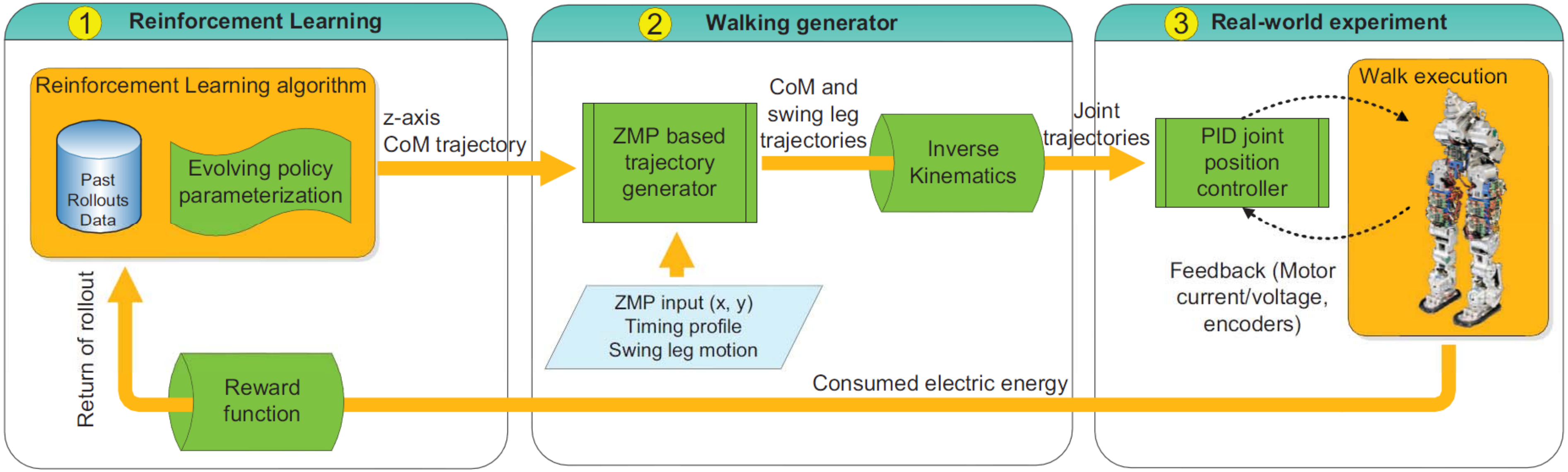


- How to reduce the energy consumption of humanoid walking ?
  - Passive-dynamic walkers
  - Active Systems - Efficient trajectories
  - Use passive compliance to re-use energy

Learn efficient trajectories

Walking with efficiency through Reinforcement Learning of COM

Passively-compliant robot COMAN learning to walk with varying CoM-height

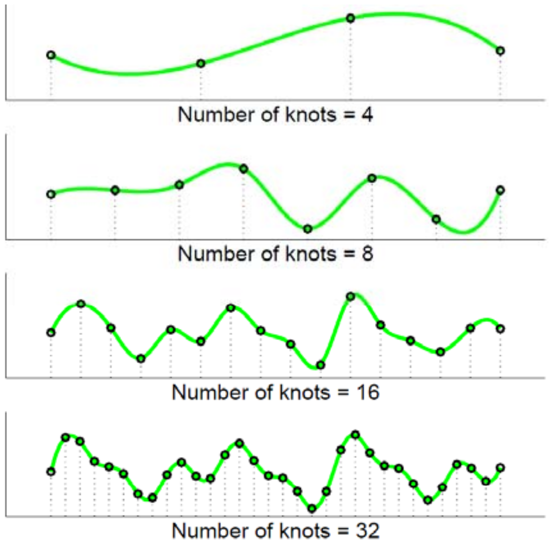


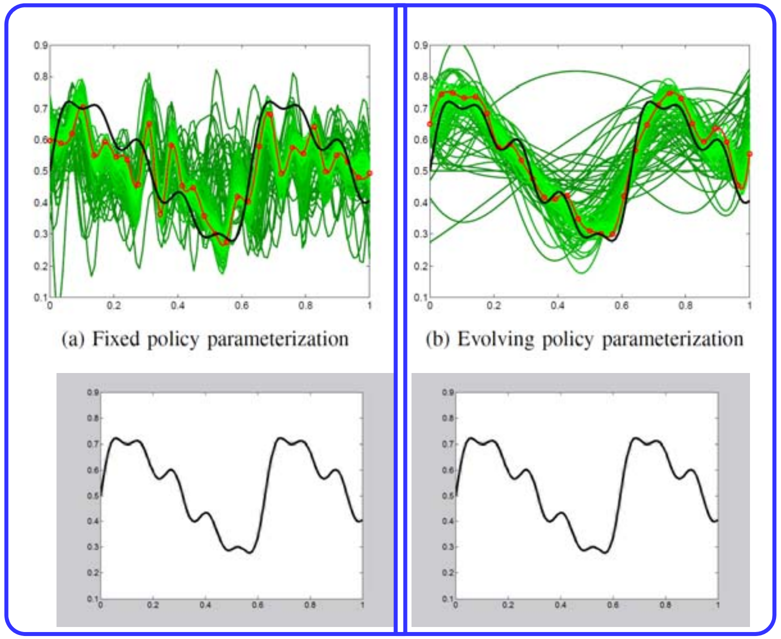
Kormushev et. al., IROS 2011

Evolving policy parameterization

~~Fixed number~~ of spline knots

Dynamically changing number of knots





(a) Fixed policy parameterization

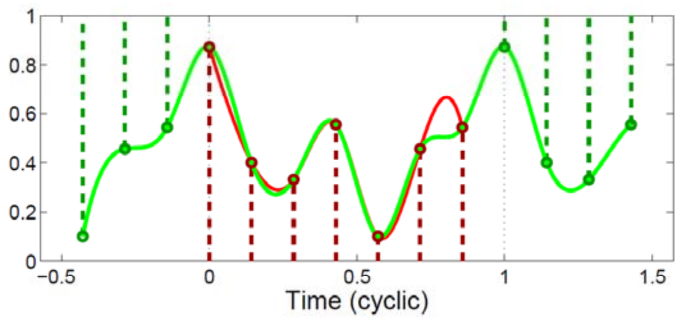
(b) Evolving policy parameterization

Advantages:

- Faster convergence
- Efficient exploration
- Avoids local optima
- Decreased computation time

Real-world experiment

Cyclic trajectories



SEQUENCE OF WALKING PHASES

No.	Phase description	Start time[s]	Duration[s]
1	Wait 1	0.00	1.00
2	Knee bend	1.00	1.00
3	Wait 2	2.00	5.00
4	Transfer phase (Double)	7.00	0.60
5	Right single	7.60	0.50
6	Double	8.10	0.15
7	Left single	8.25	0.50
8	Double	8.75	0.15
9	Right single	8.90	0.50
10	Double	9.40	0.15

Average electric energy consumed per walking cycle

$$E_j(t_1, t_2) = \int_{t_1}^{t_2} I_j(t) U_j(t) \, dt$$

current voltage

$$E(\tau) = \frac{1}{c} \sum_{j \in J} E_j(t_1, t_2)$$

time interval

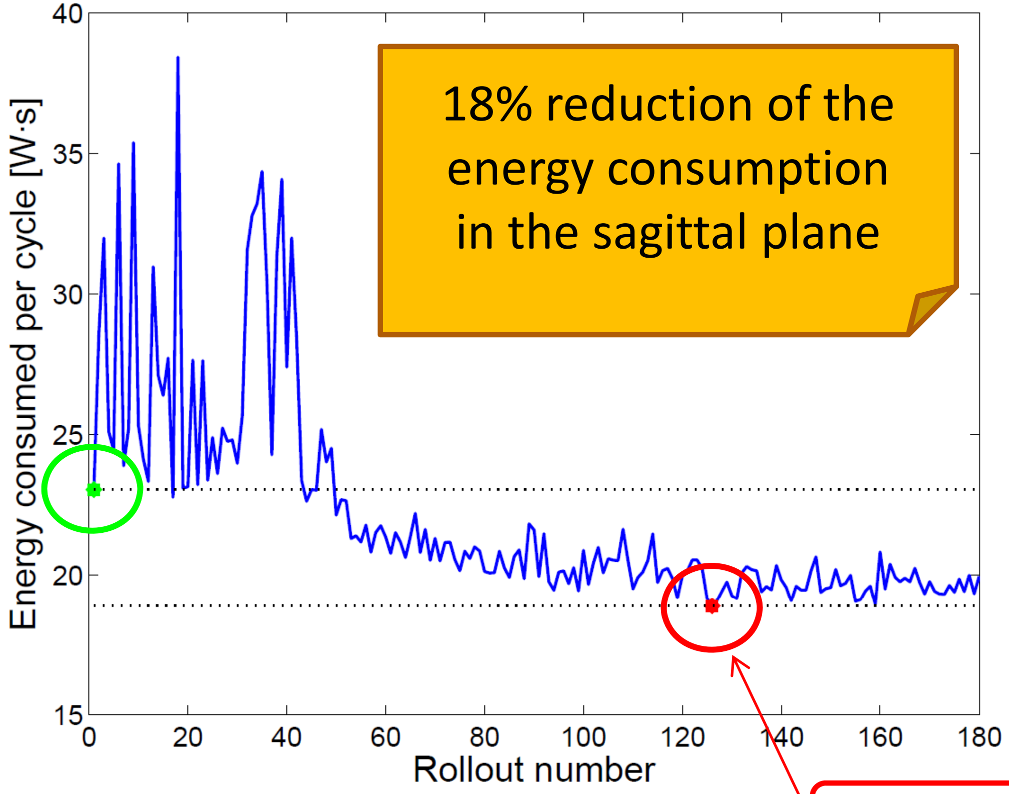
$$R(\tau) = e^{-kE(\tau)}$$

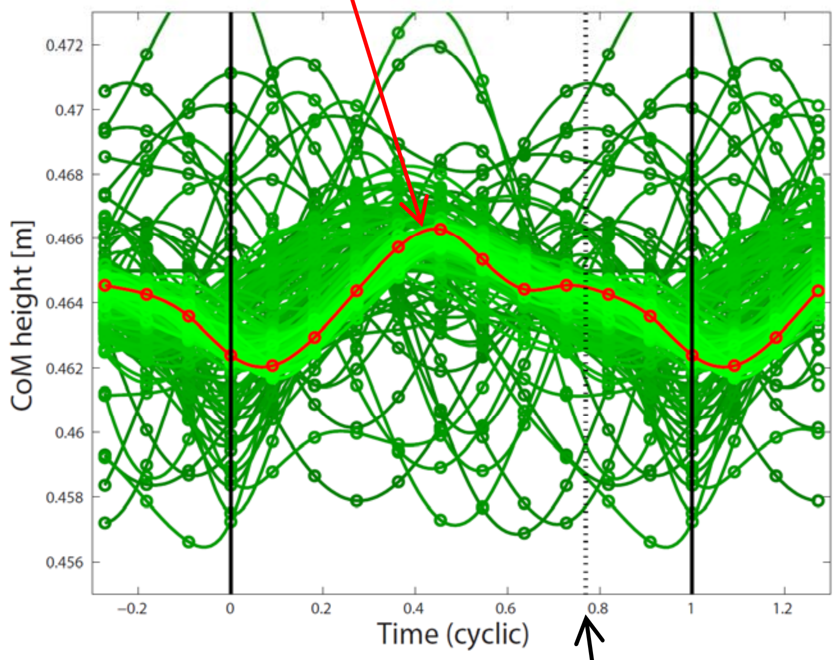
Return of rollout τ

- Number of cycles: $c = 4$ (8 steps)
- Number of joints in sagittal plane: $|J| = 6$

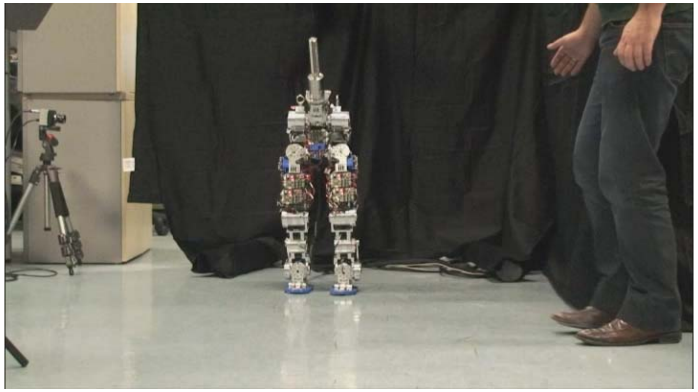
Real-world experiment

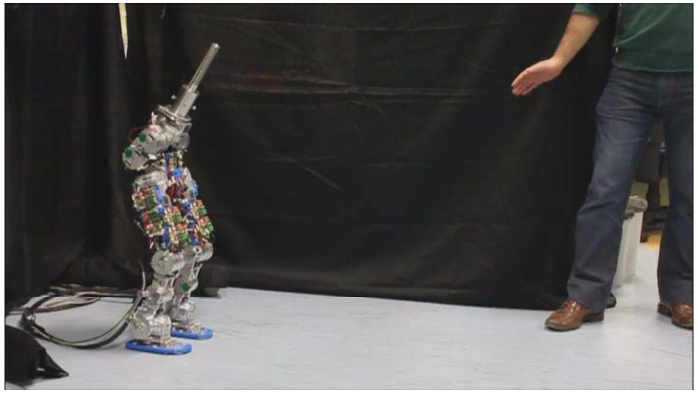
- 180 rollouts later…



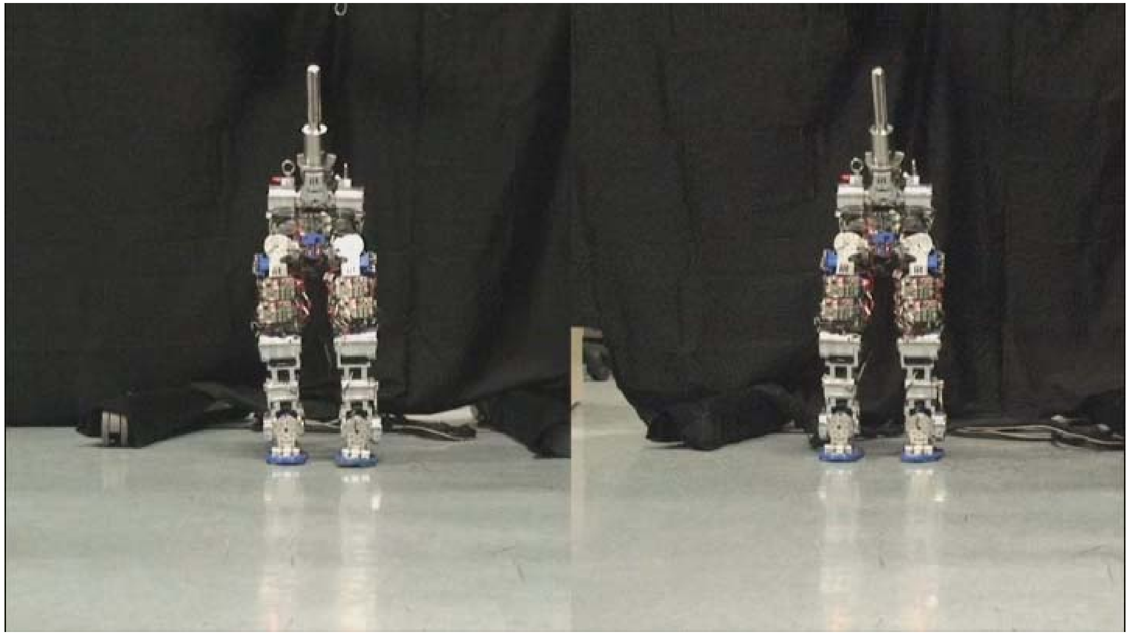


Variable CoM-height walking

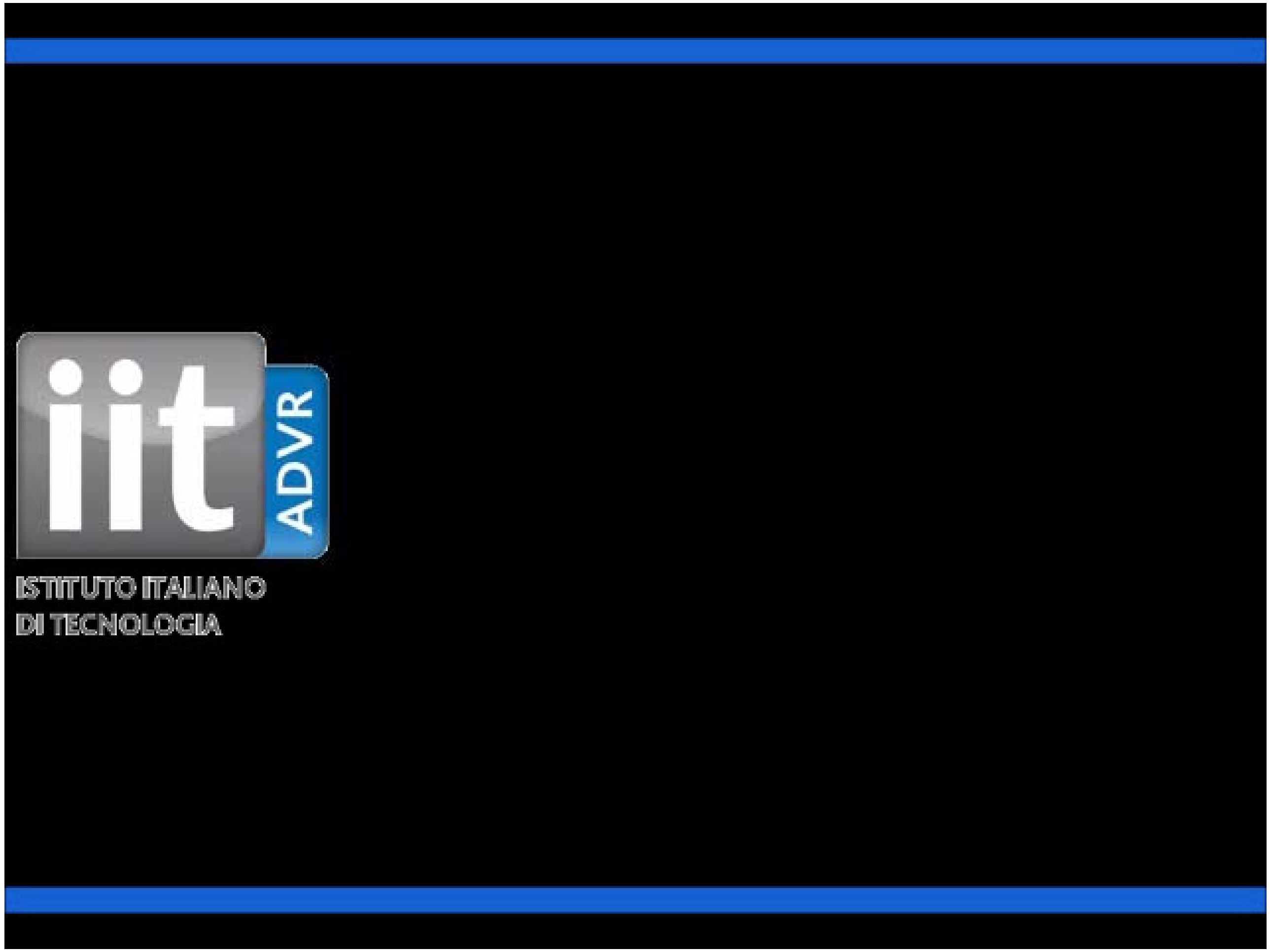




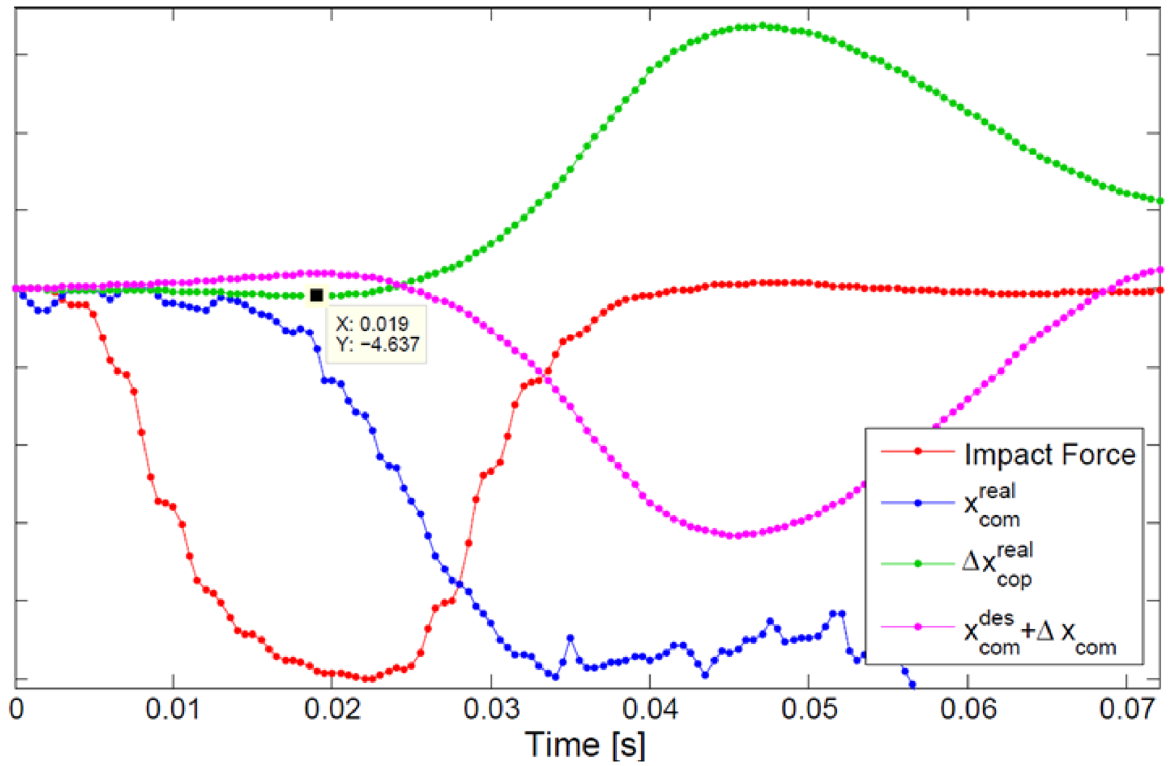
Fixed CoM-height Variable CoM-height



COMAN tolerance to push and terrain disturbances



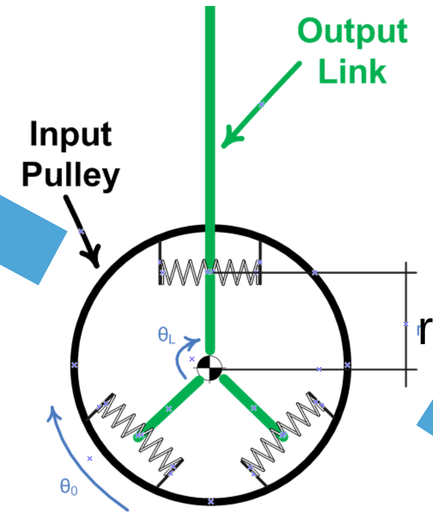
Experimental COM, COP, responses



Actuation:
What is coming next?

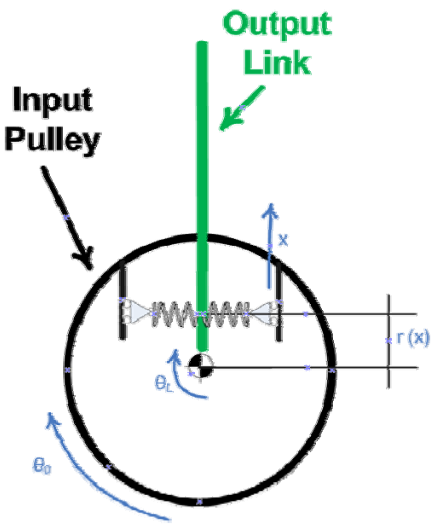
VIACTORS

Fixed stiffness joint

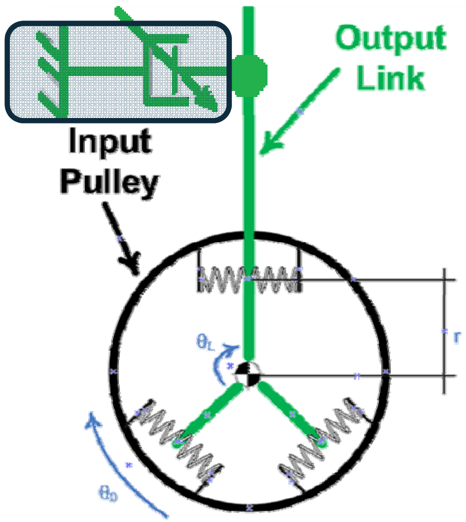


$$K_T = 6 \cdot K_S \cdot f(r^2)$$

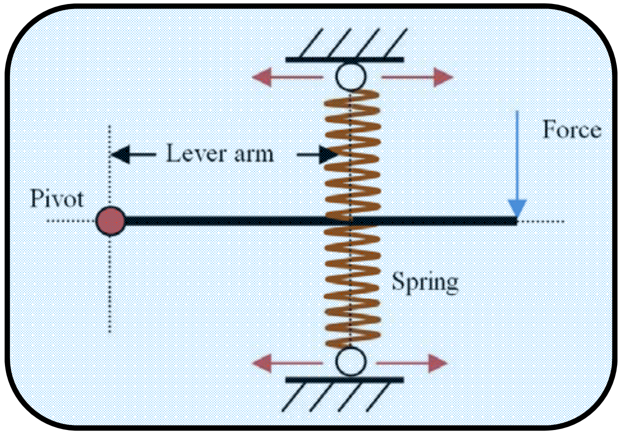
Variable stiffness joint

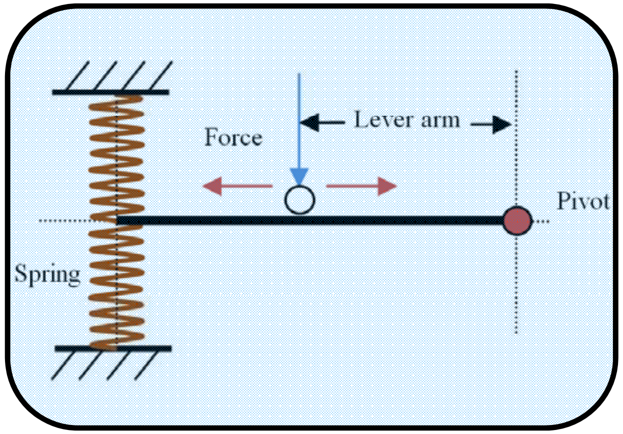


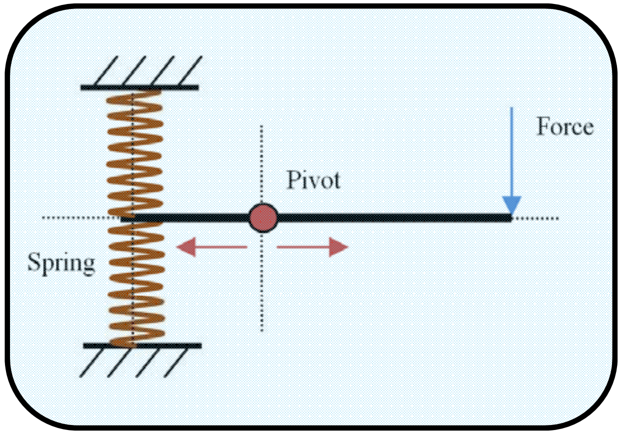
Variable damper



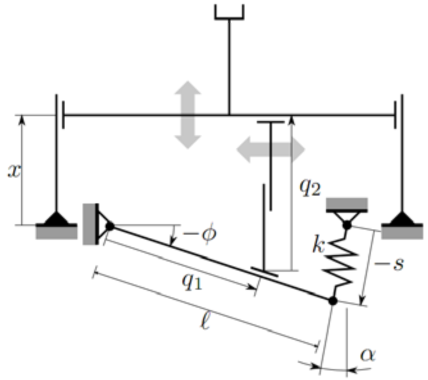
Lever arm principle



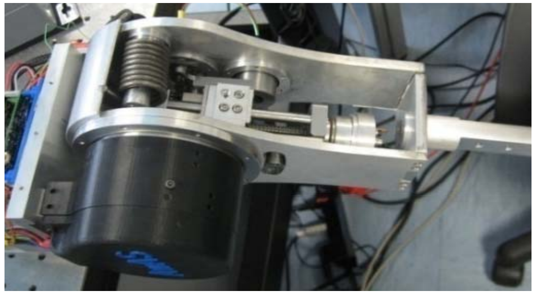




Hybrid actuator:
Byeong-Sang Kim et al., ICRA 2010



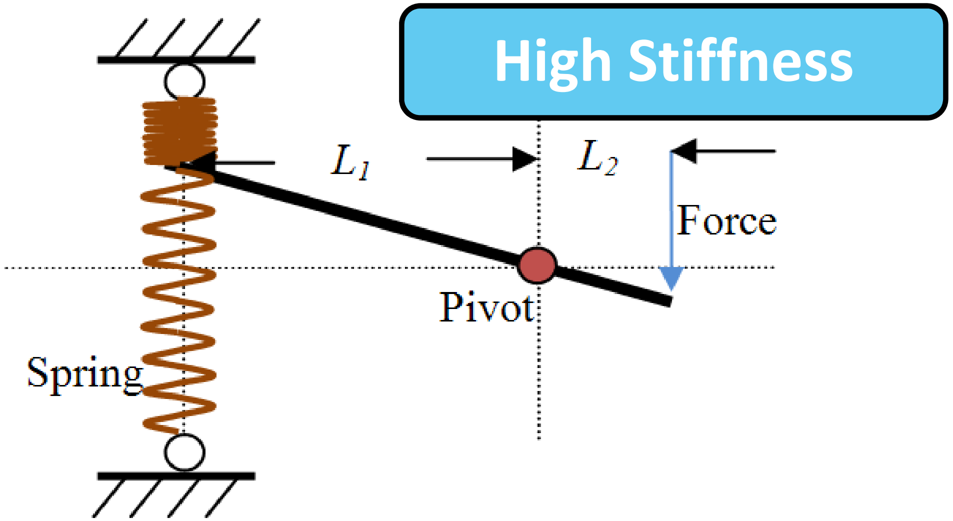
Energy Efficient VSA:
L.C. Visser *et al*., ICRA 2010

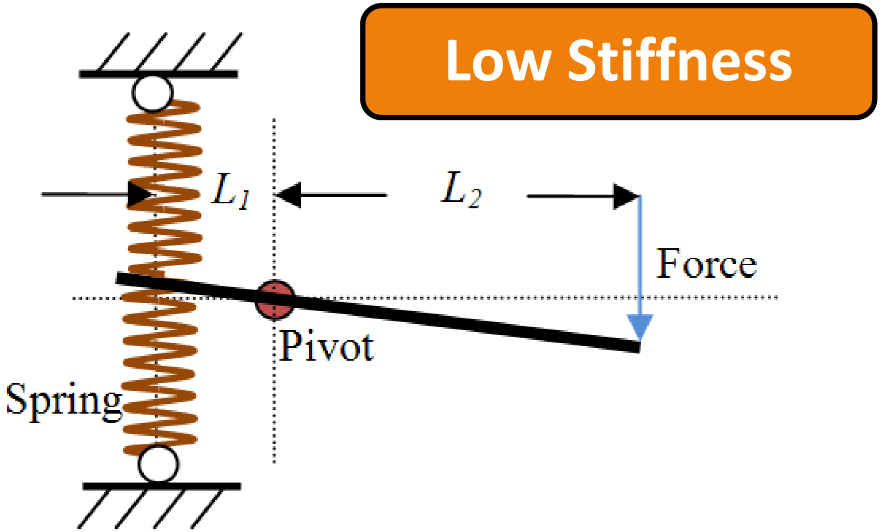


AwAS II
Jafari *et al.* , ICRA 2011,

AwAS: A. Jafari *et al*., IROS 2010

CompAct-VSA: Lever arm with variable pivot point principle



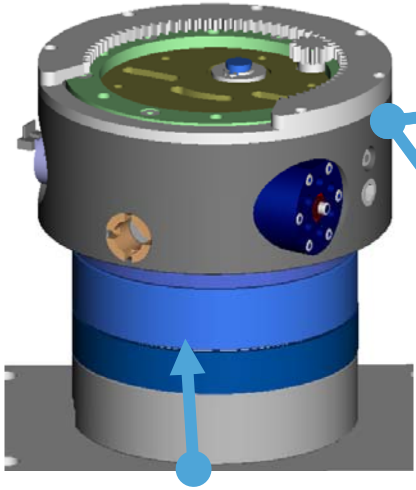


CompAct-VSA: Realization

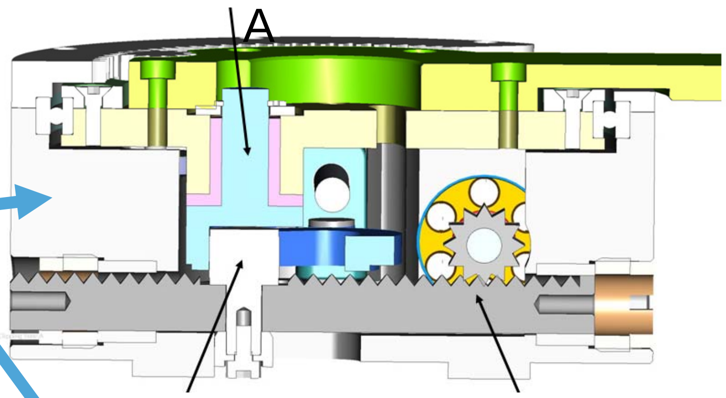
Variable Stiffness Module

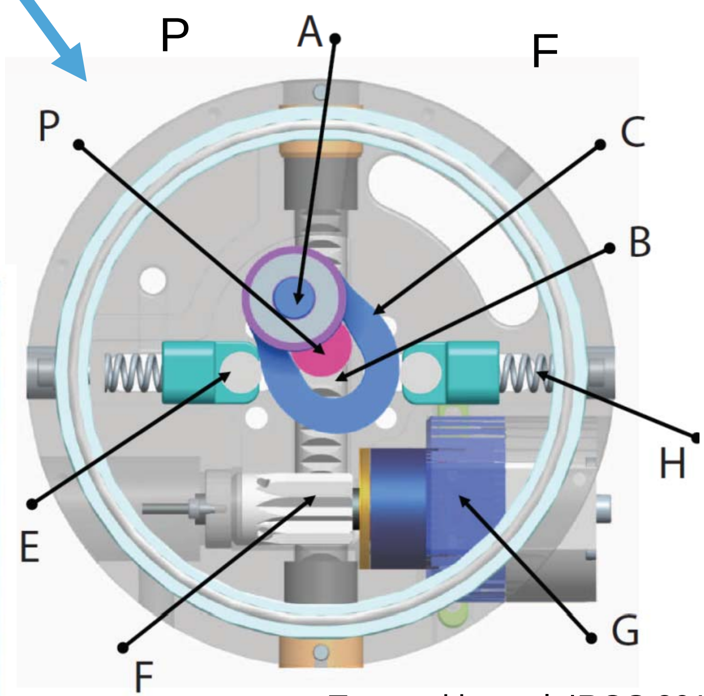
- A) Link/Cam Connection
- B) Joint Axis
- C) Cam Shaped Lever Arm
- E) Cam Roller
- F) Rack/Pinion
- G) Stiffness Motor
- H) Springs
- P) Pivot Point

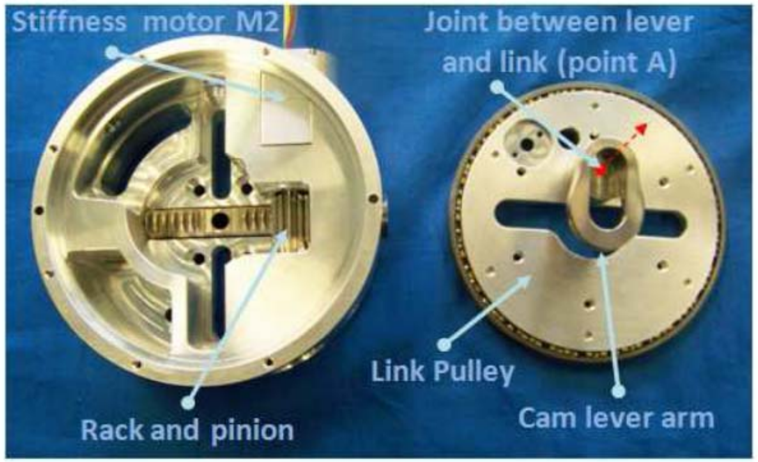
Variable stiffness module



Main joint actuator





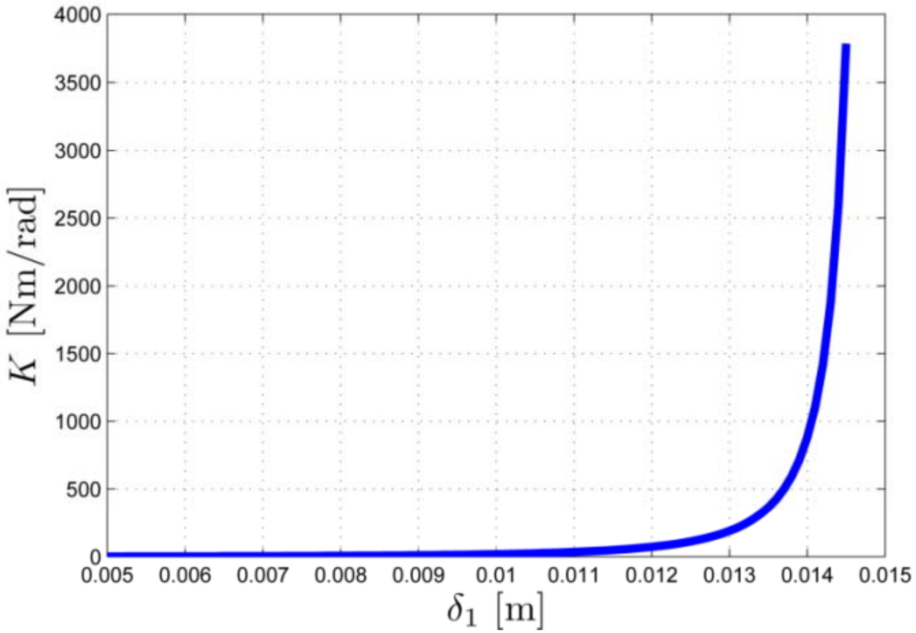


Tsagarakis et al. IROS 2011

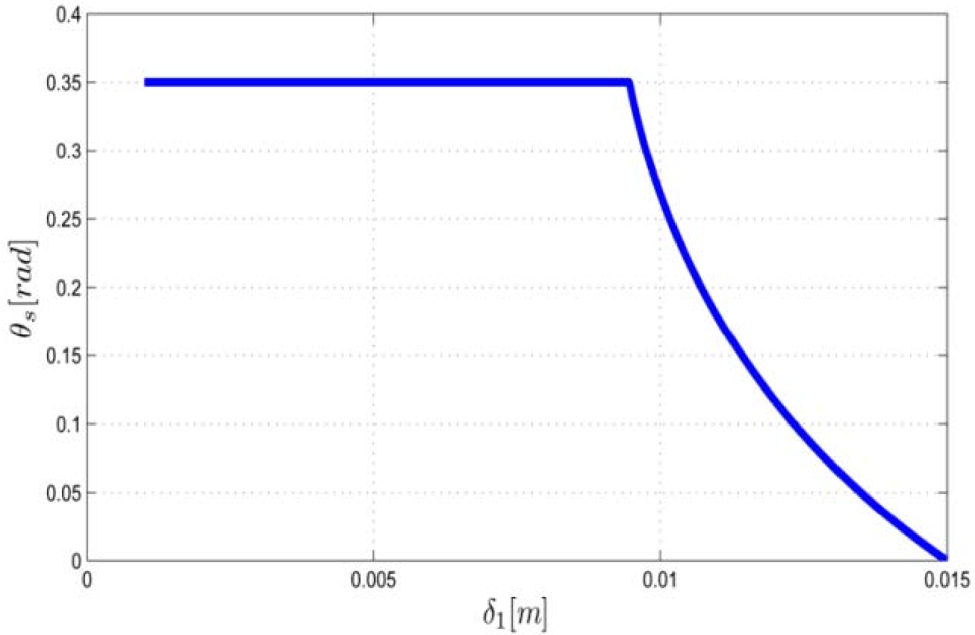
Stiffness & Passive deflection profiles

Stiffness

$$K = \frac{2k_s\delta_1^2\Delta^2}{(\Delta - \delta_1)^2}.$$



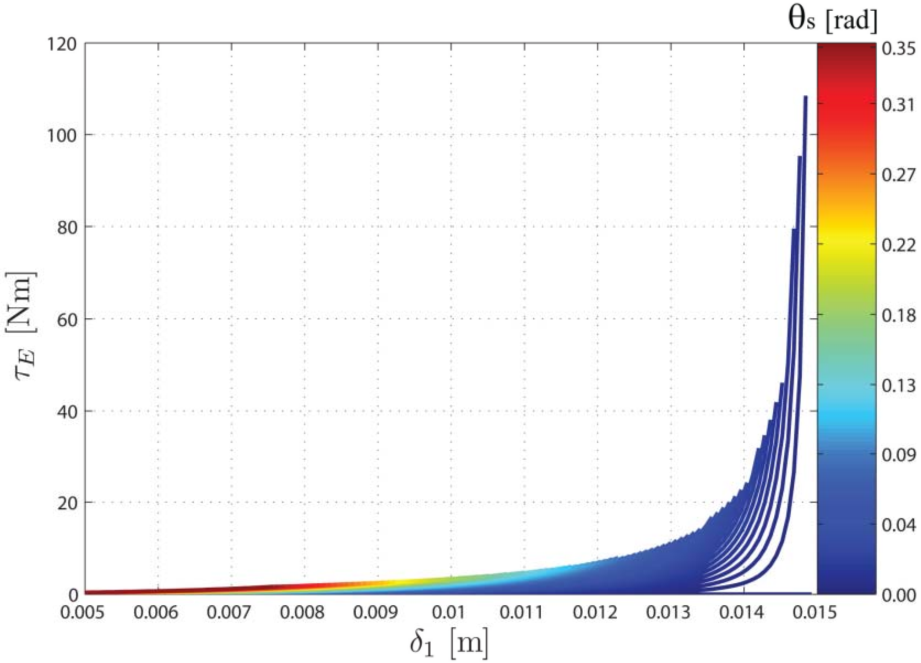
Passive deflection angle range



Elastic and pivot motor torques

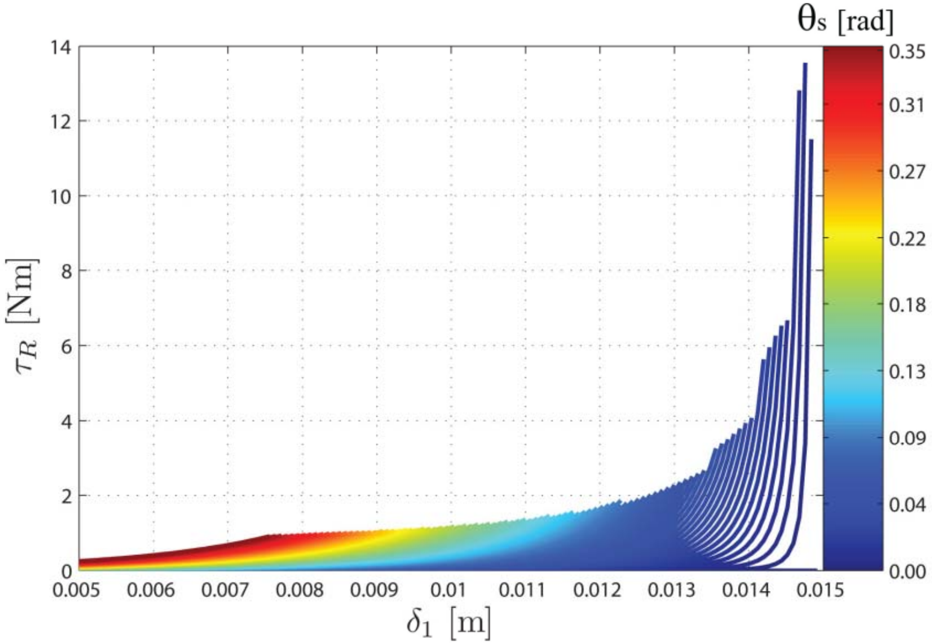
Elastic torque

$$\tau_E = \frac{2k_s\delta_1^2\Delta^2\theta_s}{(\Delta-\delta_1)^2}$$



Resistant torque
of the pivot motor

$$\tau_R = \frac{2k_s n^2\theta_2\theta_s^2\Delta^3}{(\Delta-n\theta_2)^3}.$$



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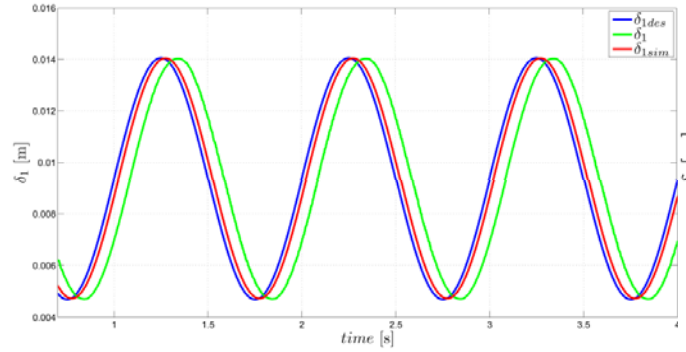
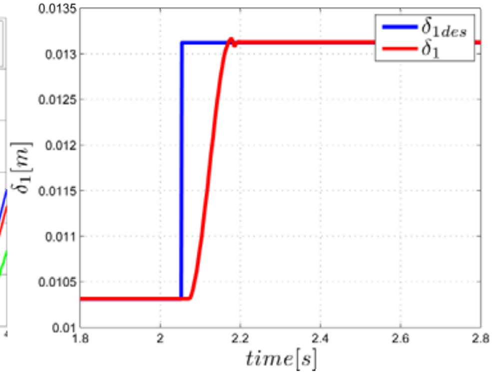
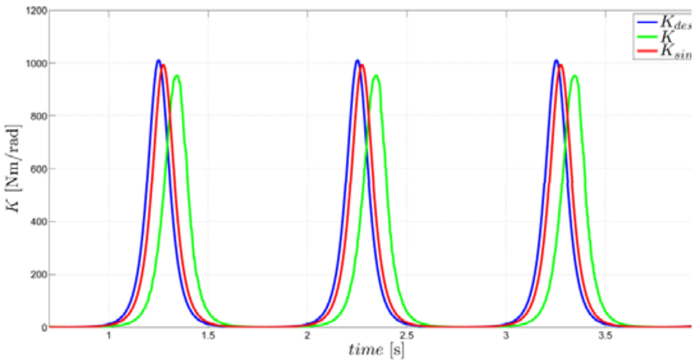
Stiffness response:Experimental results

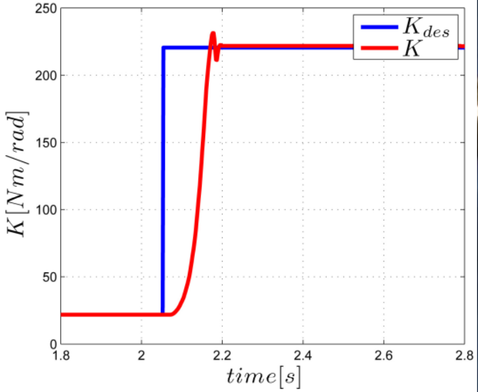
- Pivot Tracking

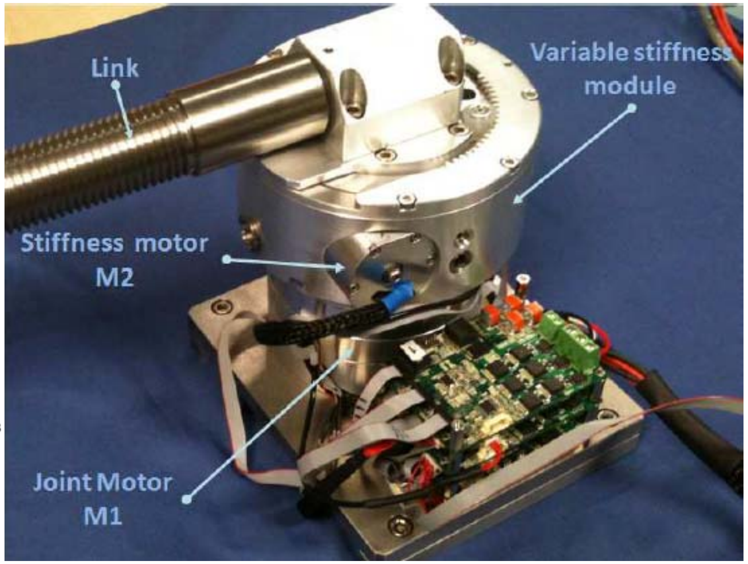




- Stiffness tracking







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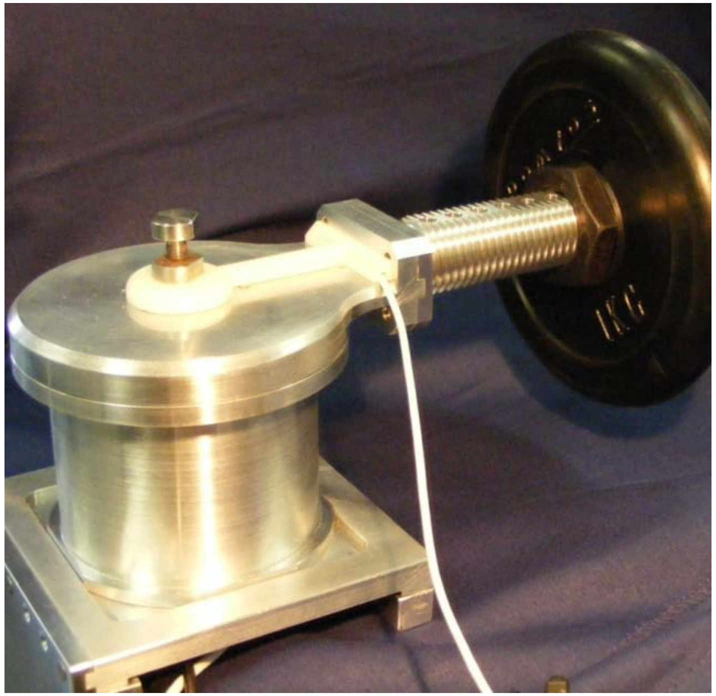
VPDA -Variable physical damping actuator

Motivation

- Facilitates control
  - Damps vibration
  - Reduces control effort
  - Inherently passive
- Manage energy of the spring



Principle & Features

- Semi-Active Solution
- Introduces “real” physical damping
- Piezoelectric actuation

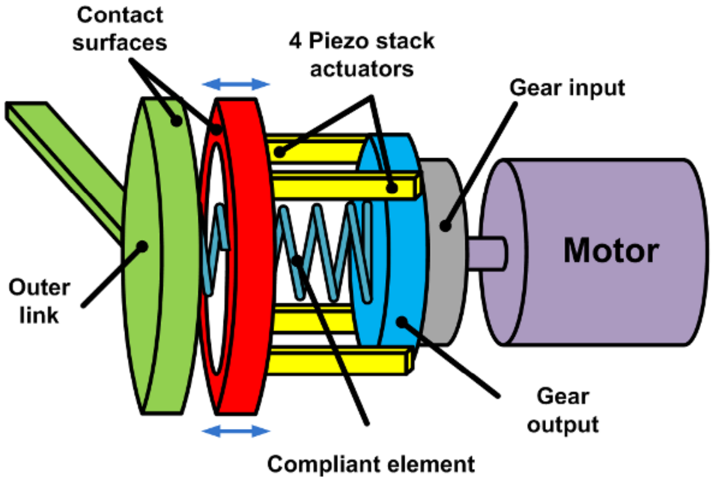
SEA + Variable physical damping actuator (VPDA)

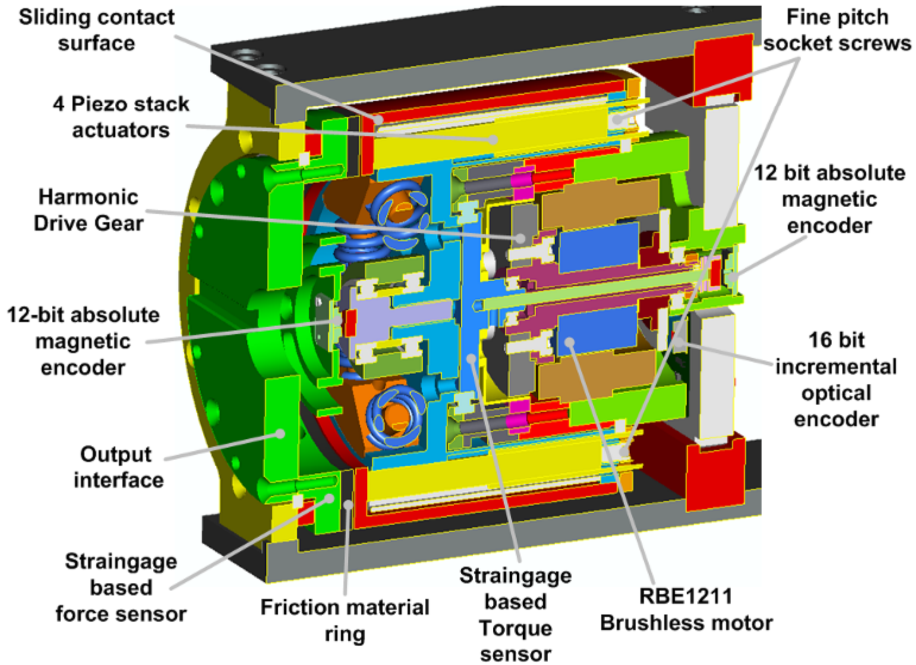
Principle
Semi-Active Solution
Introduces “real” physical damping
Piezoelectric actuation

VPDA + **SEA**

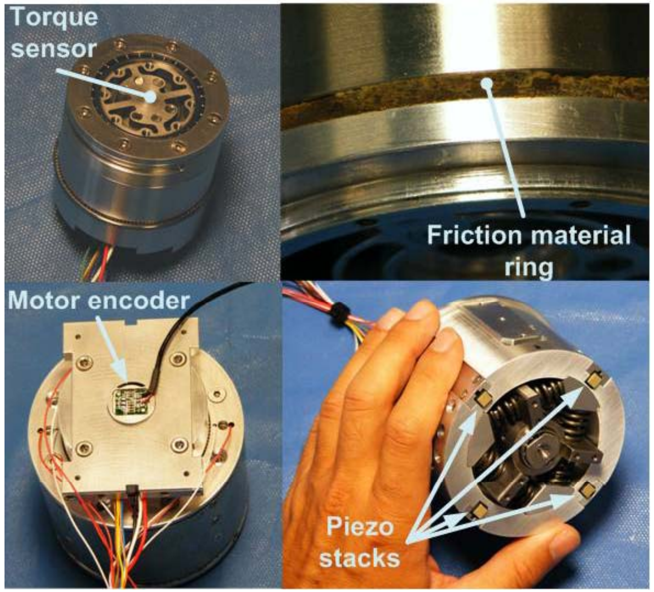
Laffranchi et al. ICRA 2010

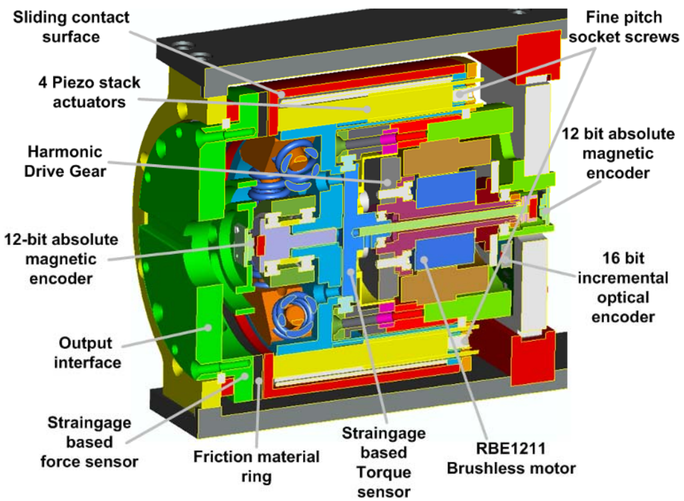
Tsagarakis et al. ICRA 2009





VPDA Prototype assembly

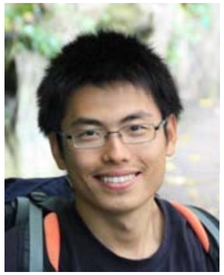




People involved

- **Locomotion/Balancing**: Zhibin Li, Luca Colasanto
- **Learning for locomotion**: Petar Kormushev, Barkan Ugurlu
- **Variable Impedance Actuators:** Matteo Laffranchi, Amir Jafari

Petar Kormushev



Zhibin Li

Matteo Laffranchi

Amir Jafari

Barkan Ugurlu

Luca Colasanto