# Safe Control of a Pneumatic Muscle Powered System

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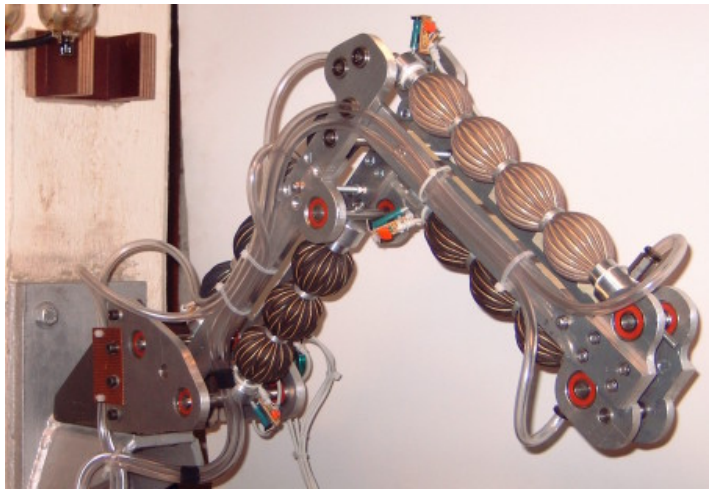
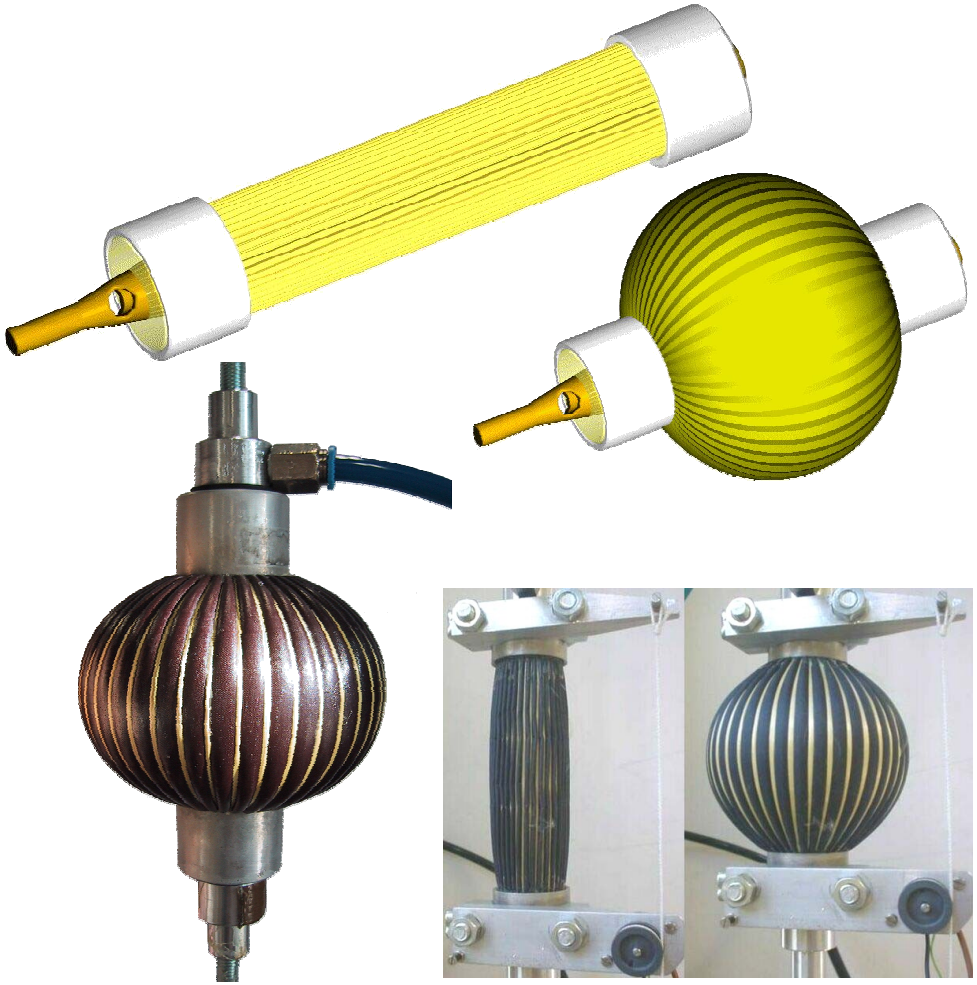
# Overview

- Actuators
- Safety
- Safe control: PSMC
- Conclusion

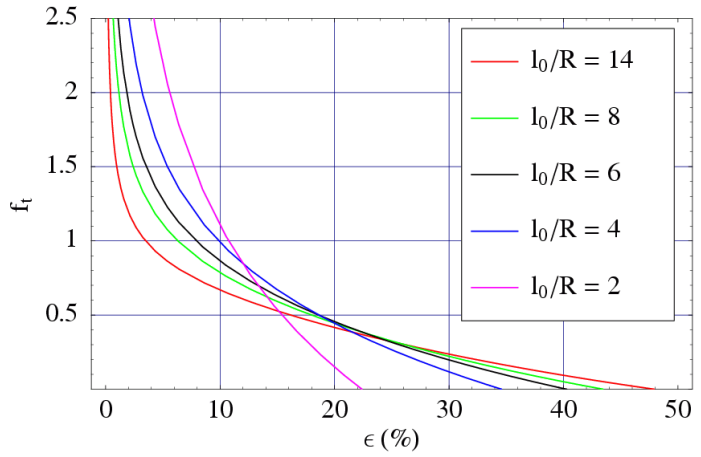


# Pleated Pneumatic Artificial Muscle



- Pleated membrane
- Low weight (< 150 g!)
- High force levels
- Scalable
- No stick-slip
- No threshold pressure
- Direct joint attachment
  - → No gear reduction, no backlash
- Inherent compliance

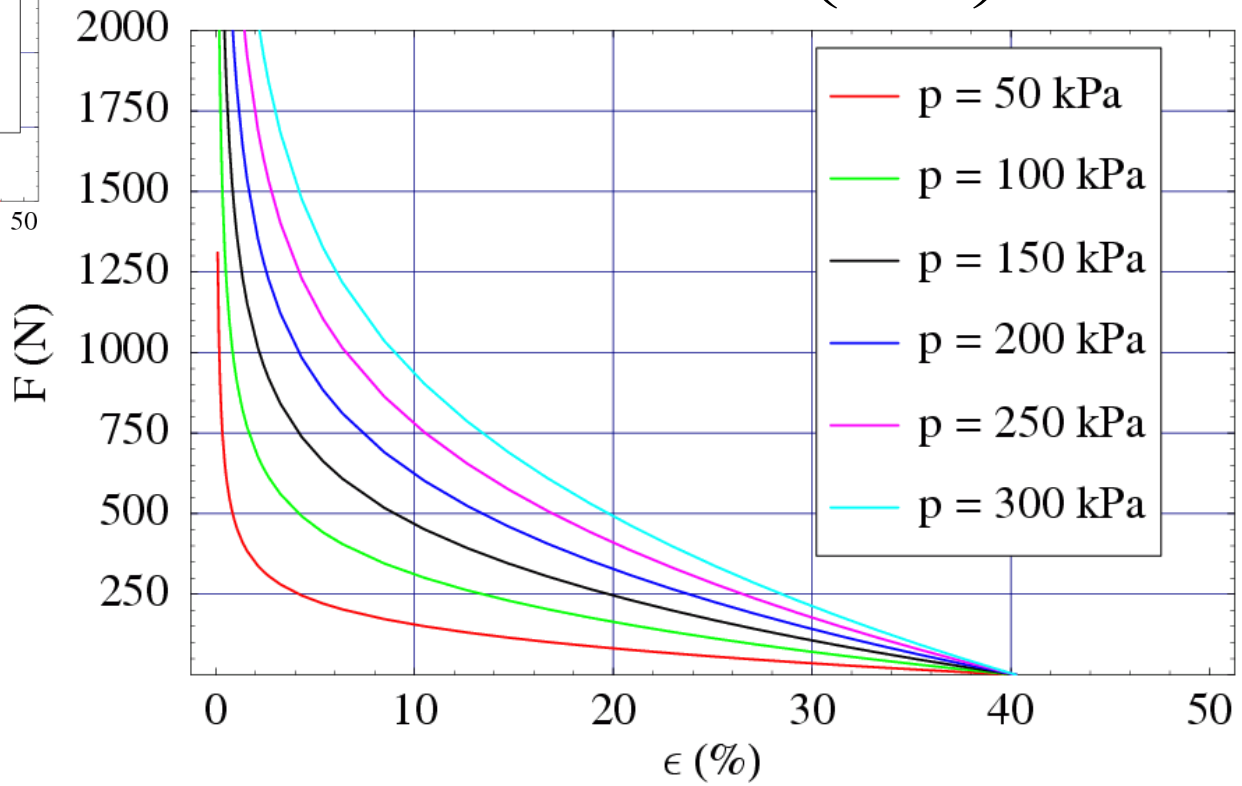
# PPAM – Force Characteristic




$$F = p \cdot l_0^2 \cdot f_{t0}\left(\varepsilon, \frac{l_0}{R}\right)$$

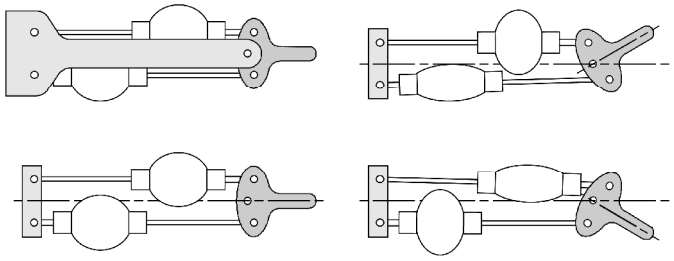
$$l_0 / R = 6$$

$$l_0 = 6\,cm$$



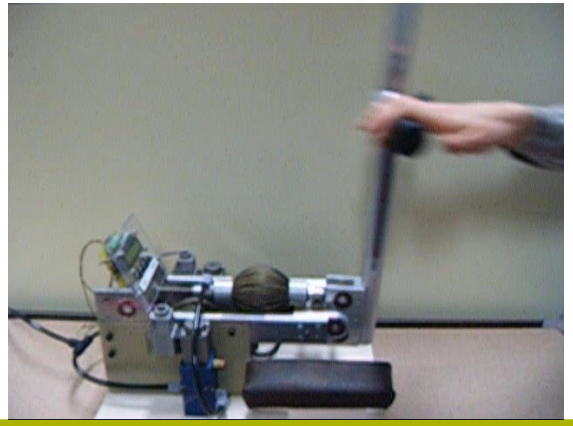
# Revolute Joint

PAMs are unidirectional → antagonistic setup



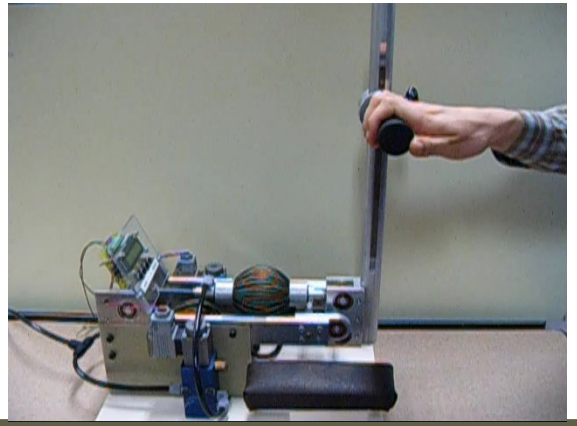
Pressures:

- Difference determines position
- Sum determines stiffness



More Compliant

More stiff



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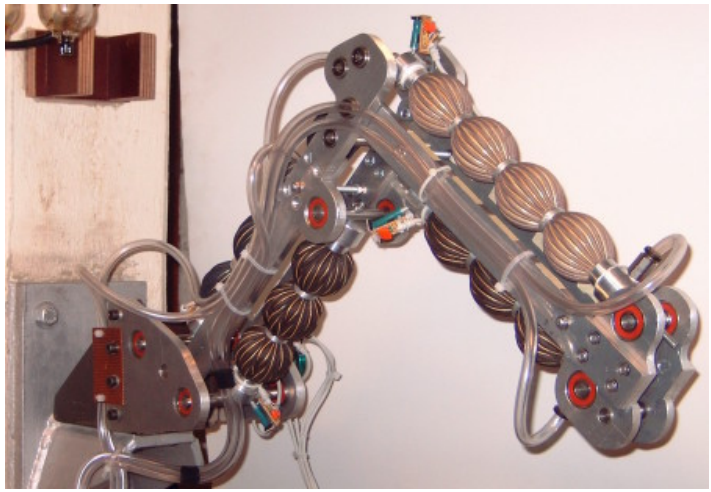
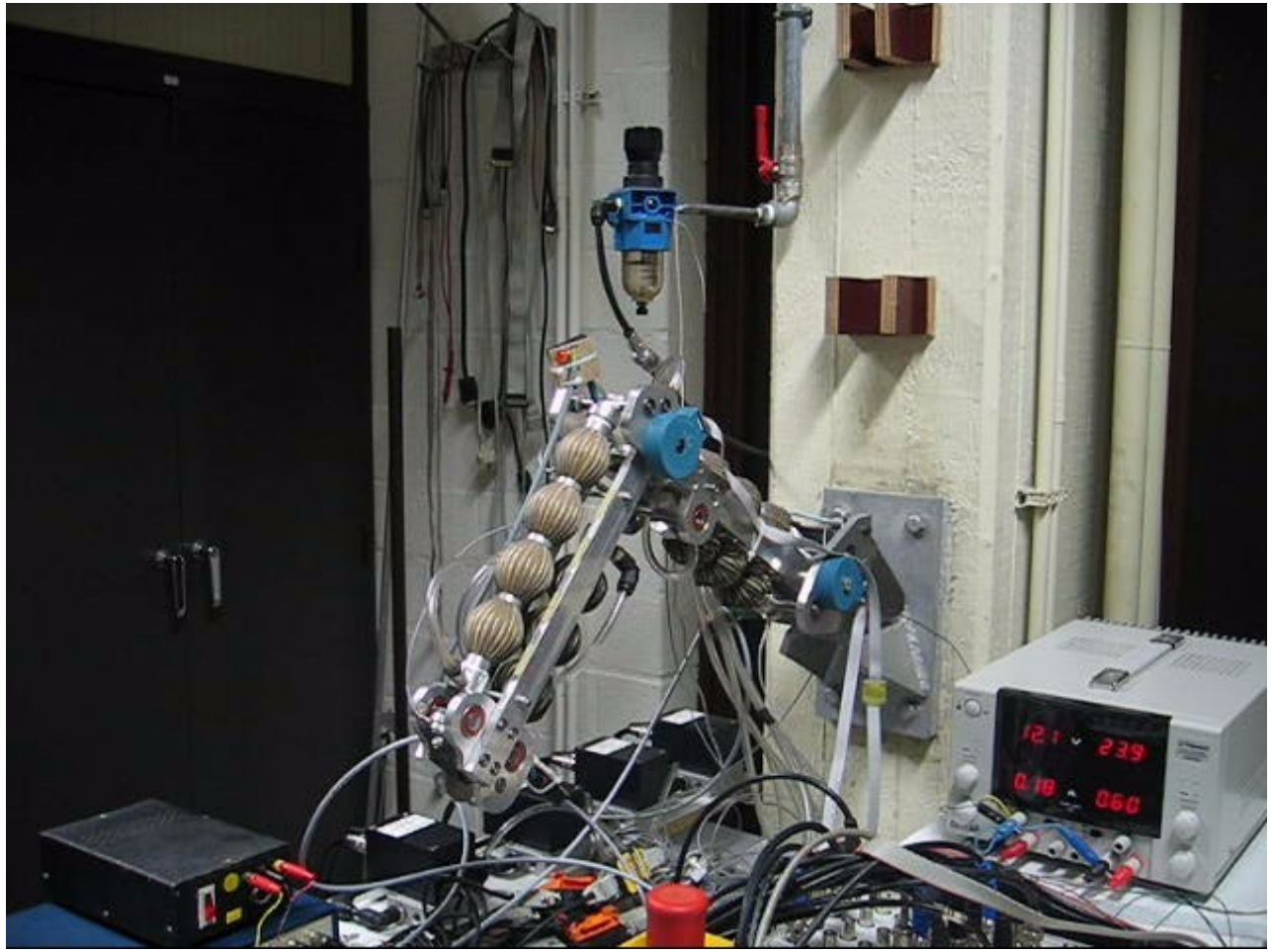
# Safety

## Safe Human-Robot interaction

- Safe hardware
- Safe control system



# Safety - Motivation



# Safety - HIC

$$\mathrm{HIC} = \max_{\Delta t} \left\{ \Delta t \left( \frac{1}{\Delta t} \int_{t_1}^{t_2} \|\ddot{\boldsymbol{r}}_H\| \, dt \right)^{2.5} \right\}$$

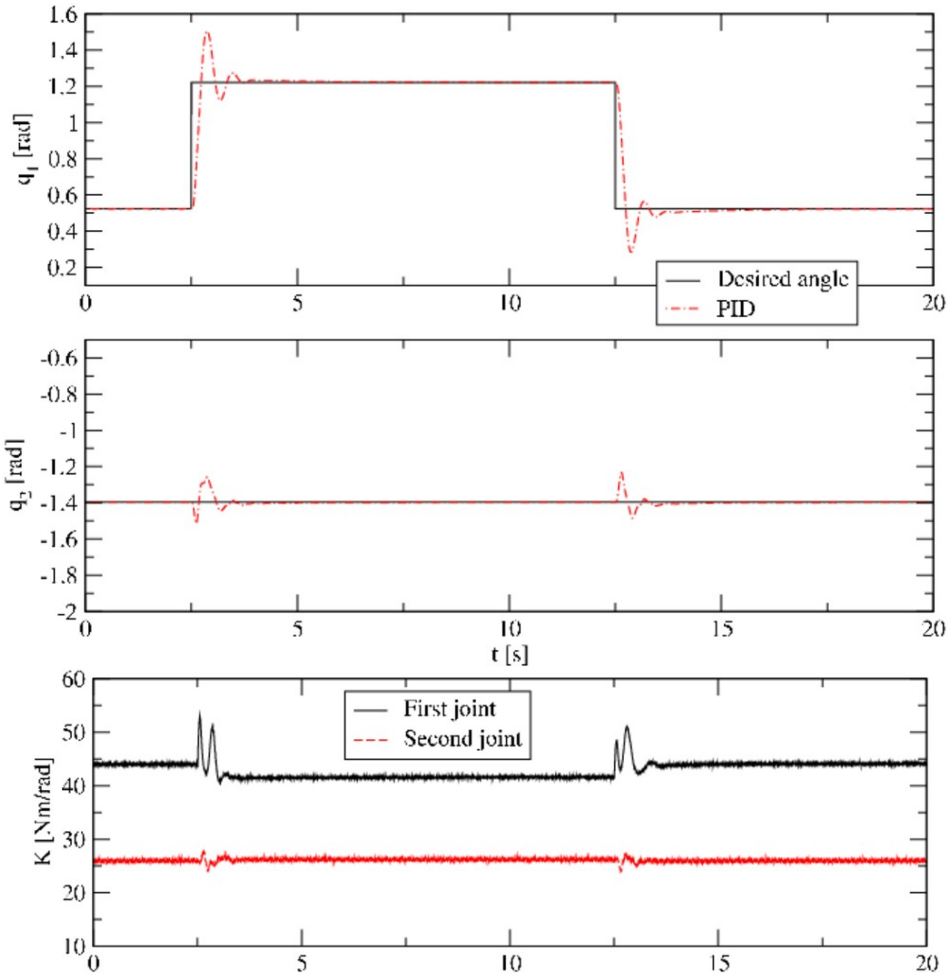
With:

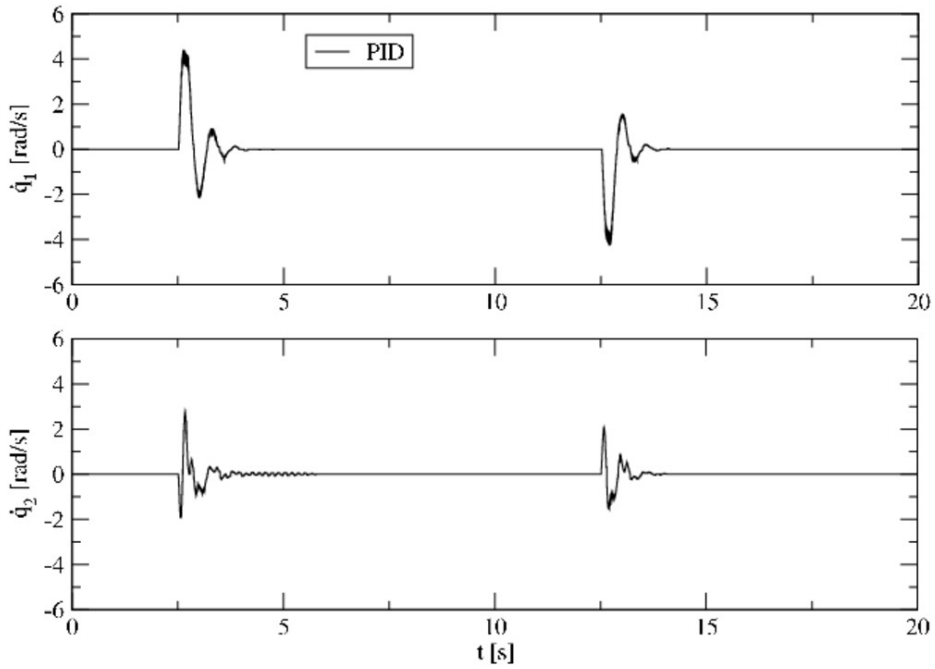
- $\Delta t = t_2 - t_1 \leq 36\, ms$
- $\|\ddot{\boldsymbol{r}}_H\|$ measured in *g*

Introduced in robotics in:

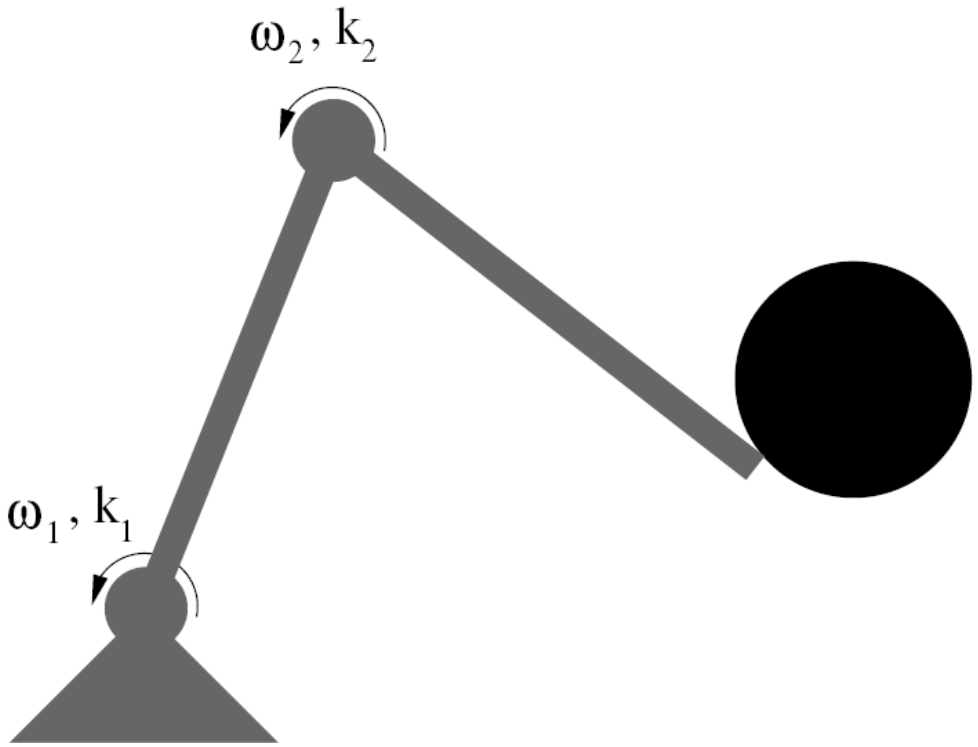
- Zinn, M., Roth, B., Khatib O., and Salisbury, J. K.,
A New Actuation Approach for Human Friendly Robot Design,
The International Journal of Robotics Research, 23(4-5):379-398, 2004
- Bicchi, A. and Tonietti, G., Fast and Soft Arm Tactics: Dealing with the Safety-Performance Trade-Off in Robot Arms Design and Control,
IEEE Robotics and Automation Magazine 11(2):22-33, 2004

# Safety – PID Step



# Safety - Simulations




Hunt-Crossley contact model: Haddadin, S., Albu-Schäffer, A., and Hirzinger, G., Safety Evaluation of Physical Human-Robot Interaction via Crash-Testing. RSS2007.

# Safety - Results

HIC: 4.81

$F_{max}$: 1524 N

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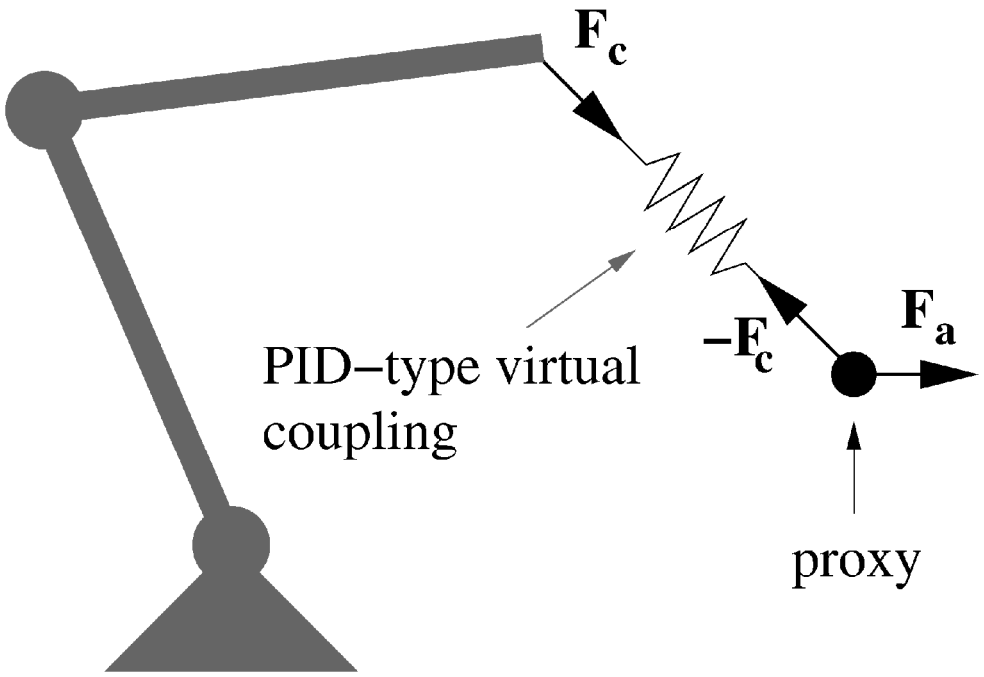
# Control - PID

## PID + Gravity compensation

- Low gains: safe, very bad performance
- Higher gains: unsafe, acceptable performance
- Even higher gains: unstability

# Proxy-Based Sliding Mode Control: Idea




$$\boldsymbol{\tau} = J^T \boldsymbol{F}_c$$

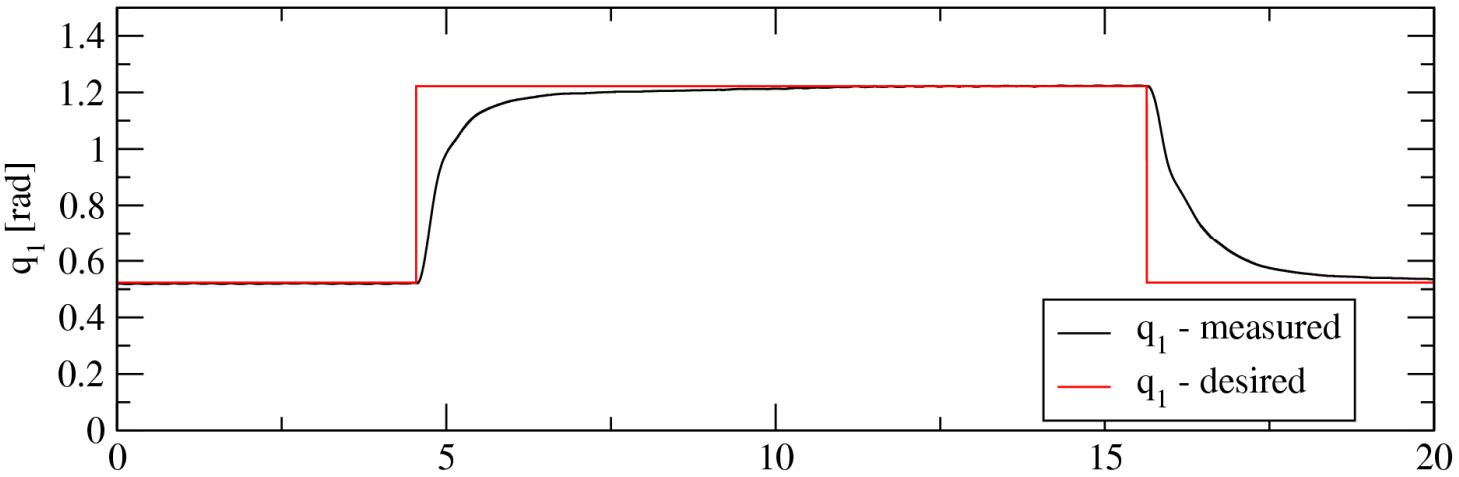
- No Chattering
- Safe response to large position errors

Ryo Kikuuwe and Hideo Fujimoto, "Proxy-based sliding mode control for accurate and safe position control", Proceedings of the 2006 IEEE International conference on Robotics and Automation, 2006, pp. 25-30.

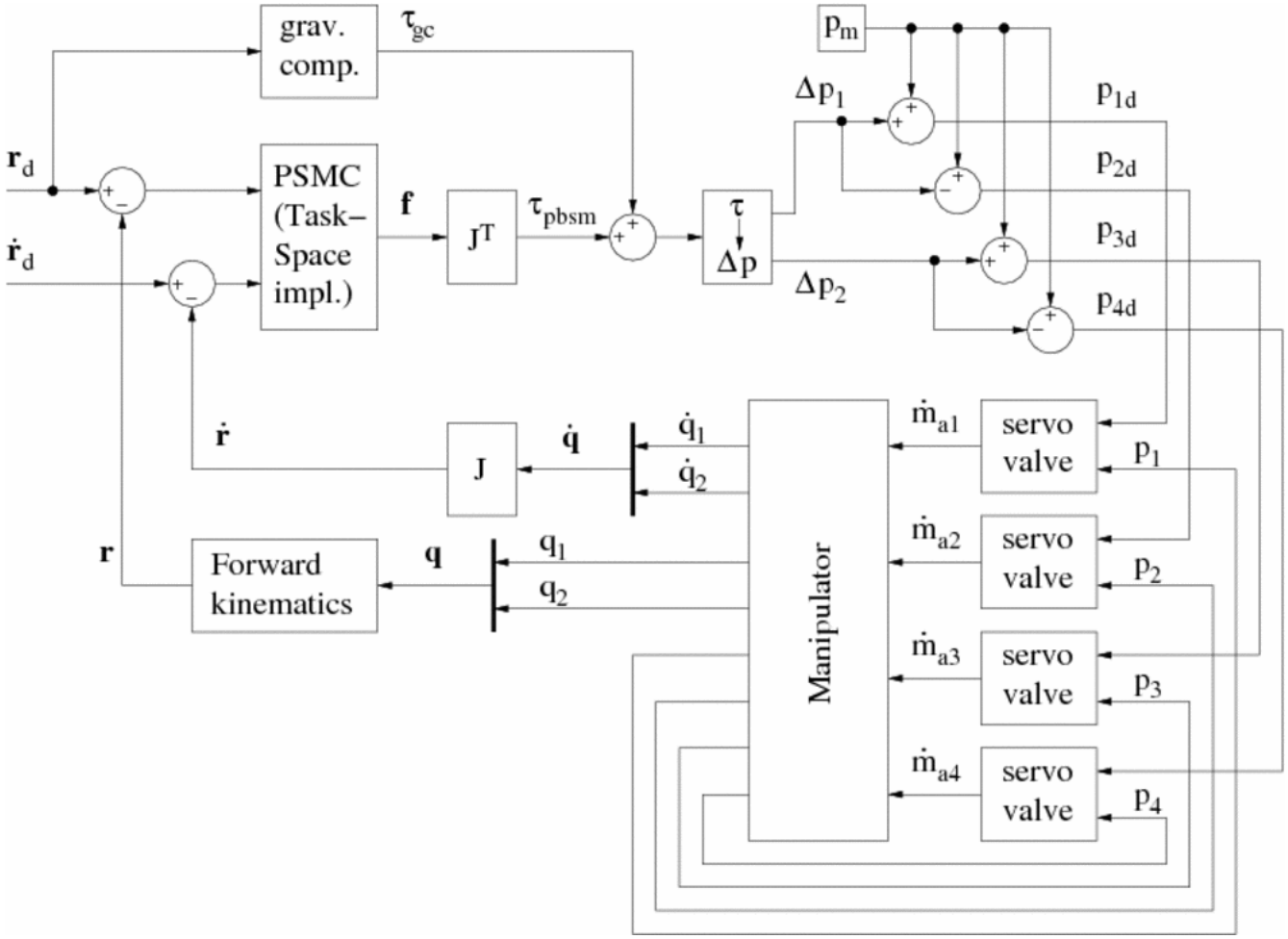
# Why?

$$\boldsymbol{s} = 0 = (\boldsymbol{r}_d - \boldsymbol{r}_p) + \lambda (\dot{\boldsymbol{r}}_d - \dot{\boldsymbol{r}}_p)$$

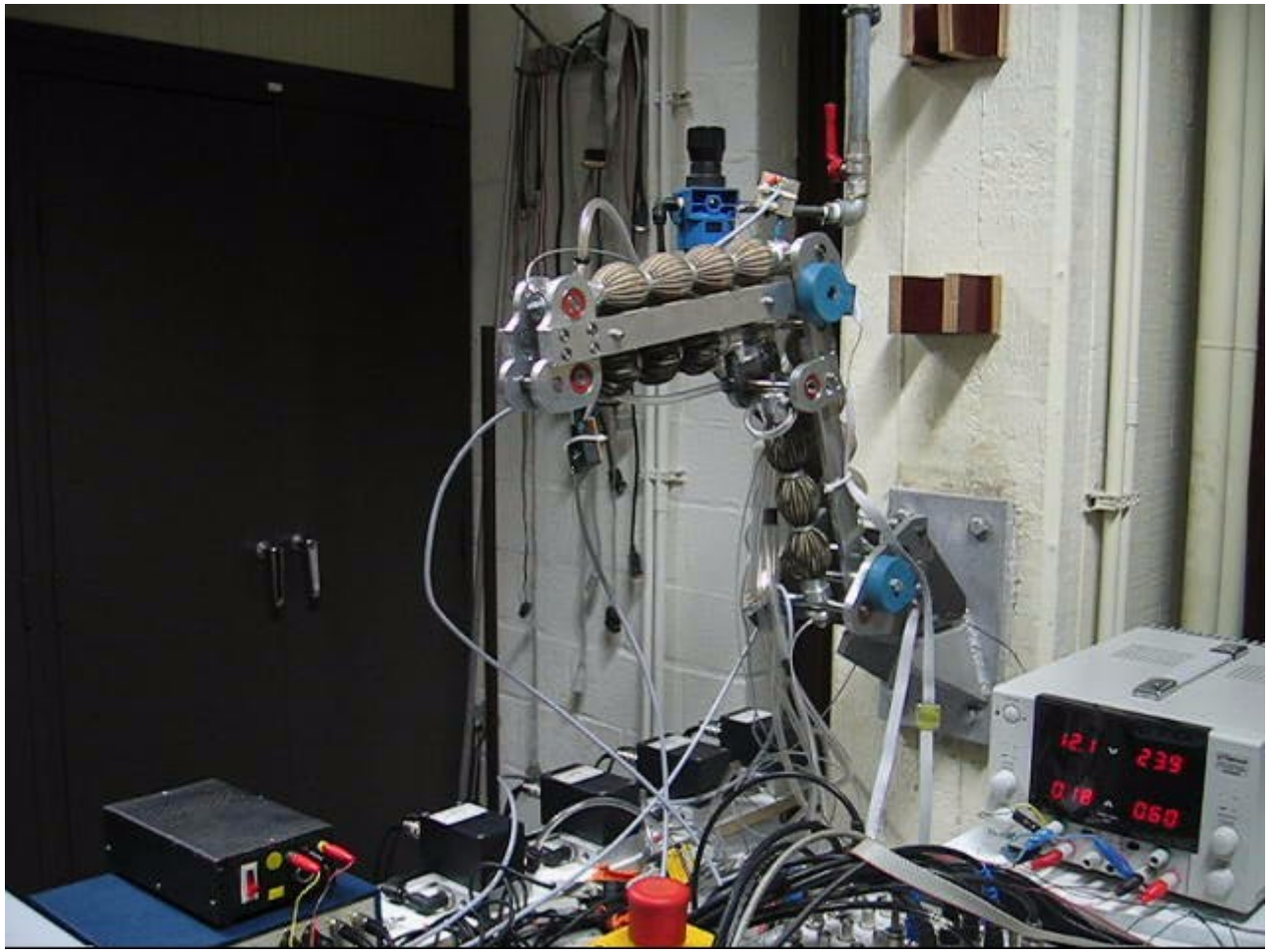
$$\Rightarrow \dot{\boldsymbol{r}}_p = \frac{1}{\lambda} (\boldsymbol{r}_d - \boldsymbol{r}_p) + \dot{\boldsymbol{r}}_d$$



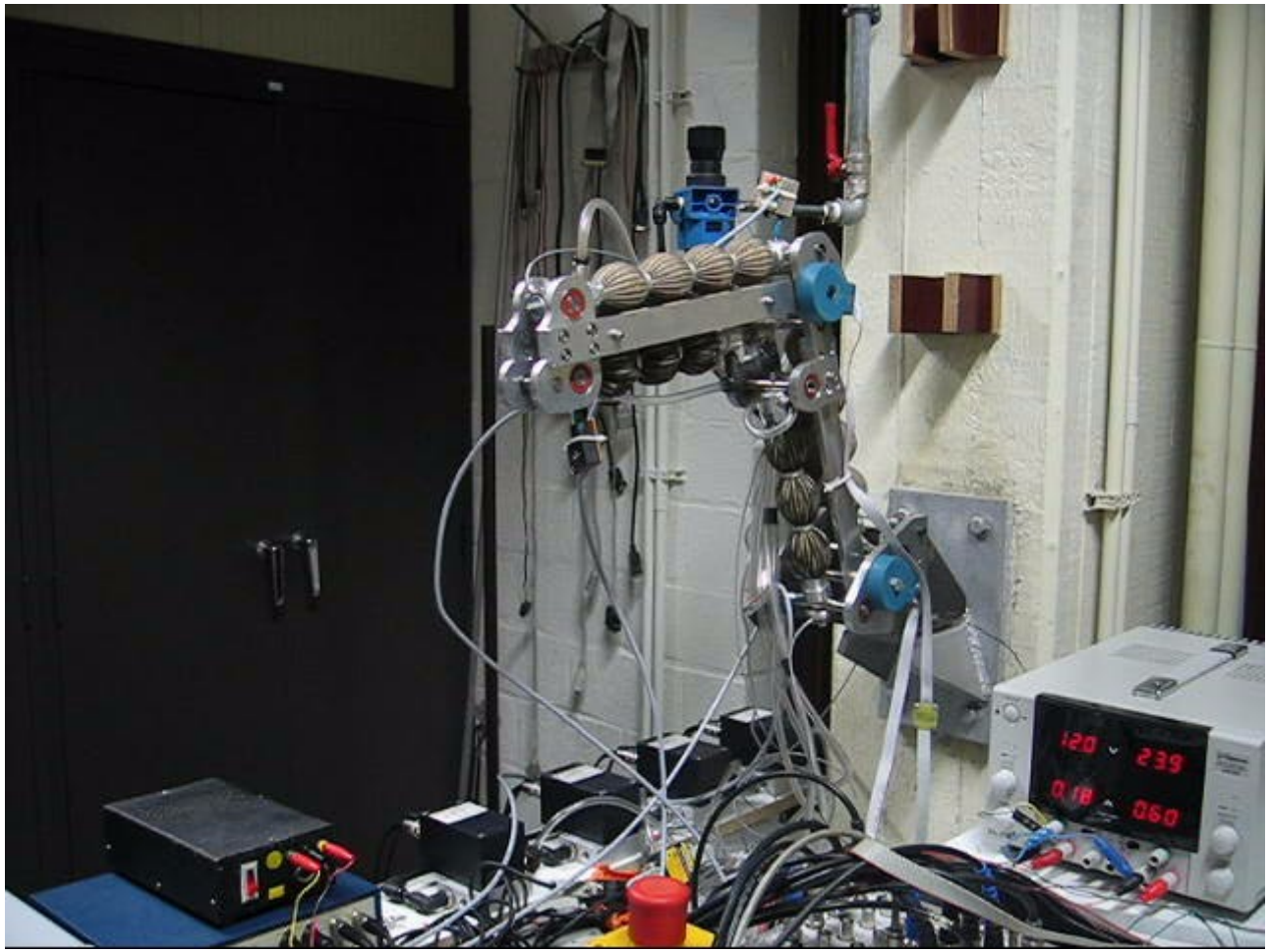
# PSMC


grav. comp.
$\tau_{gc}$
$p_m$
$\Delta p_1$
$p_{1d}$
$\mathbf{r}_d$
PSMC (Task–Space impl.)
$\mathbf{f}$
$J^T$
$\tau_{pbsm}$
$\tau$
$\Delta p$
$p_{2d}$
$\dot{\mathbf{r}}_d$
$\Delta p_2$
$p_{3d}$
$p_{4d}$
$\dot{\mathbf{r}}$
J
$\dot{\mathbf{q}}$
$\dot{q}_1$
$\dot{q}_2$
$\dot{m}_{a1}$
servo valve
$p_1$
$\dot{m}_{a2}$
servo valve
$p_2$
$\mathbf{r}$
Forward kinematics
$\mathbf{q}$
$q_1$
$q_2$
Manipulator
$\dot{m}_{a3}$
servo valve
$p_3$
$\dot{m}_{a4}$
servo valve
$p_4$

# Step response (1)



# Step response (2)



# Safety

PID:

HIC: 4.81

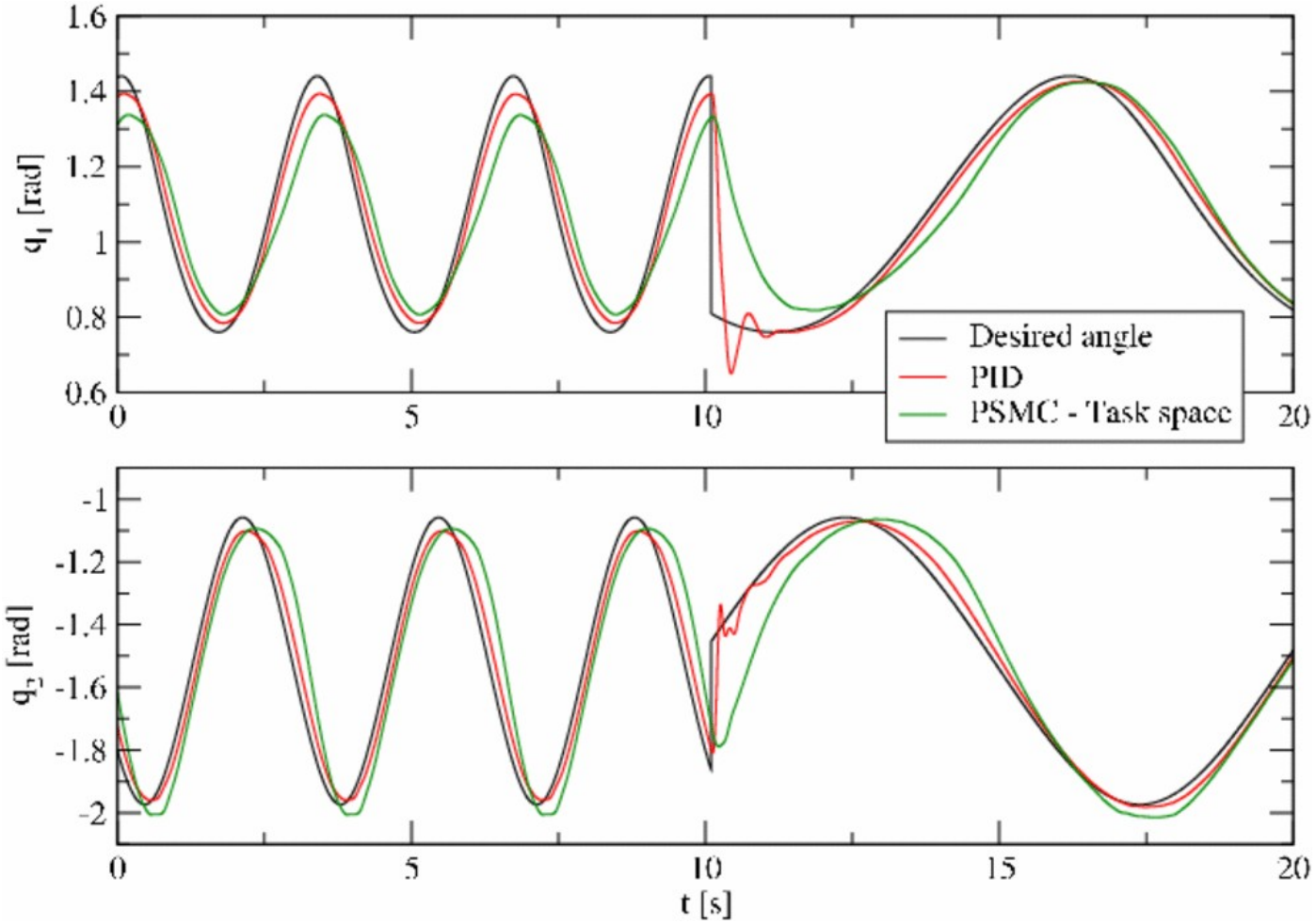
$F_{max}$: 1524 N

PSMC ($\lambda = 0.8$):

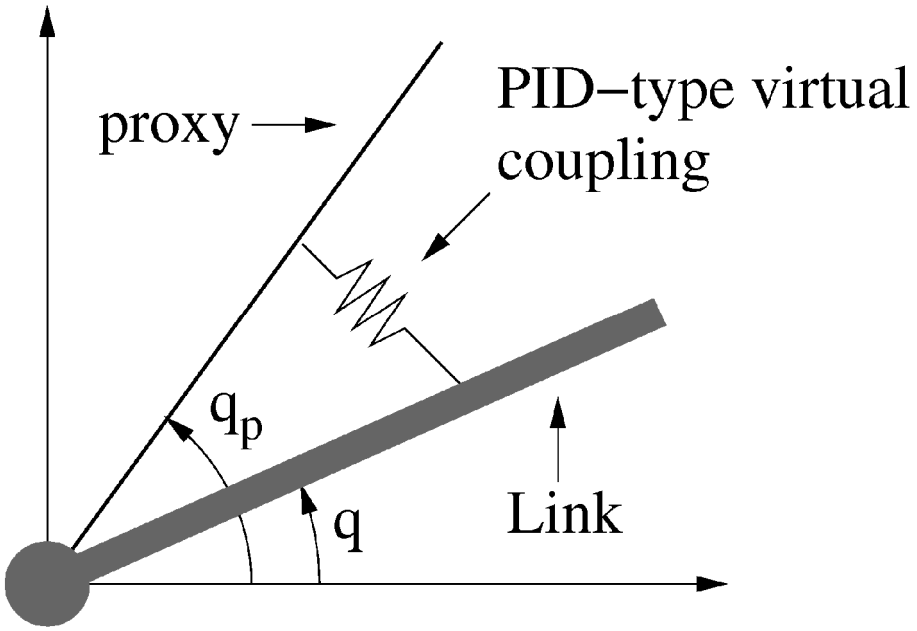
HIC: 0.05

$F_{max}$: 170 N

# Tracking Performance



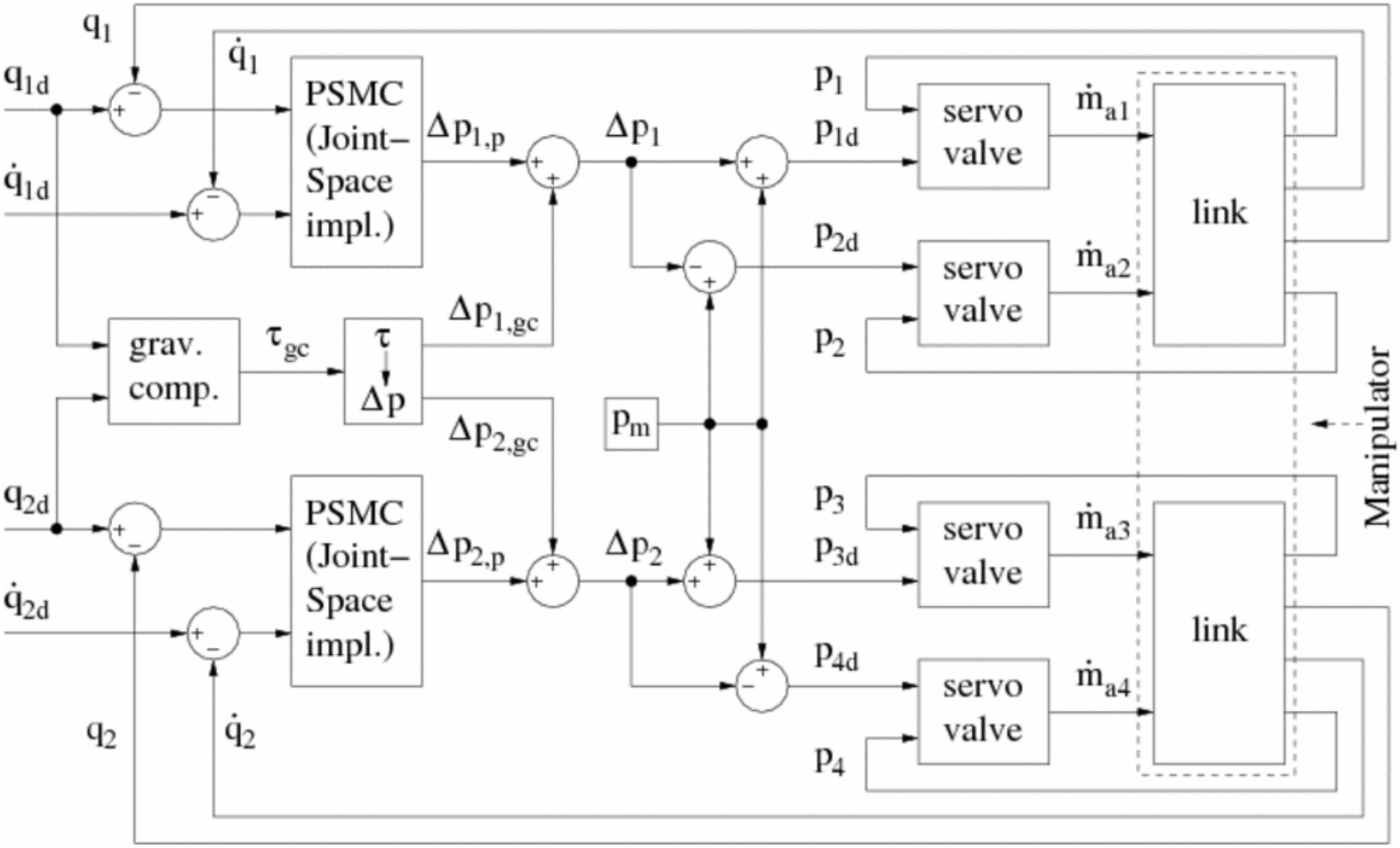
# Proxy-Based Sliding Mode Control: Joint-Based implementation



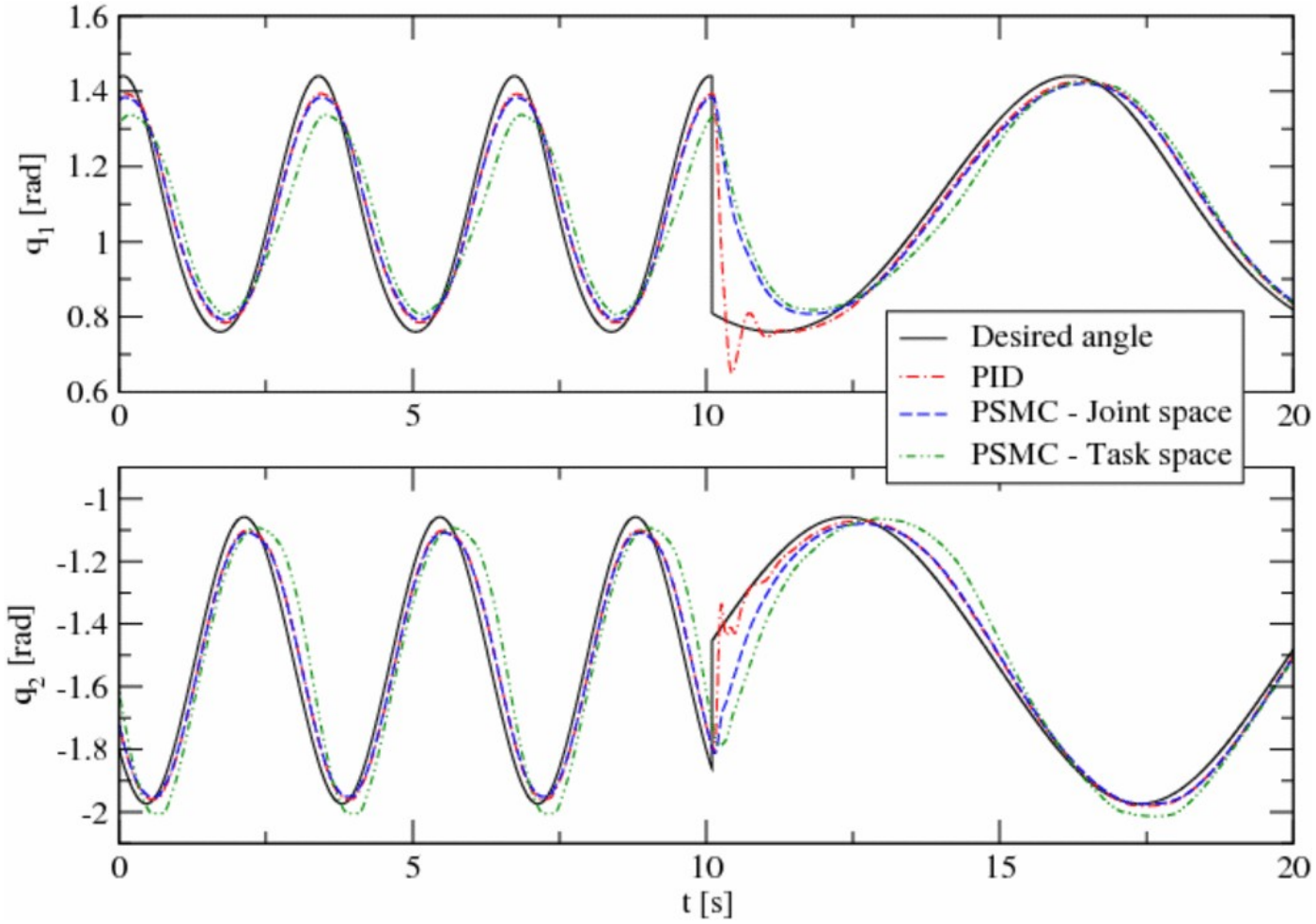

$$I\ddot{q}_p = \tau_a - \tau_c$$

$$\begin{aligned} \tau_a &= \tau_{lm}\,\mathrm{sgn}\left((q_d - q_p) + \lambda\left(\dot{q}_d - \dot{q}_p\right)\right) \\ \tau_c &= K_p\left(q_p - q\right) + K_i\int\left(q_p - q\right)dt + K_d\left(\dot{q}_p - \dot{q}\right) \end{aligned}$$

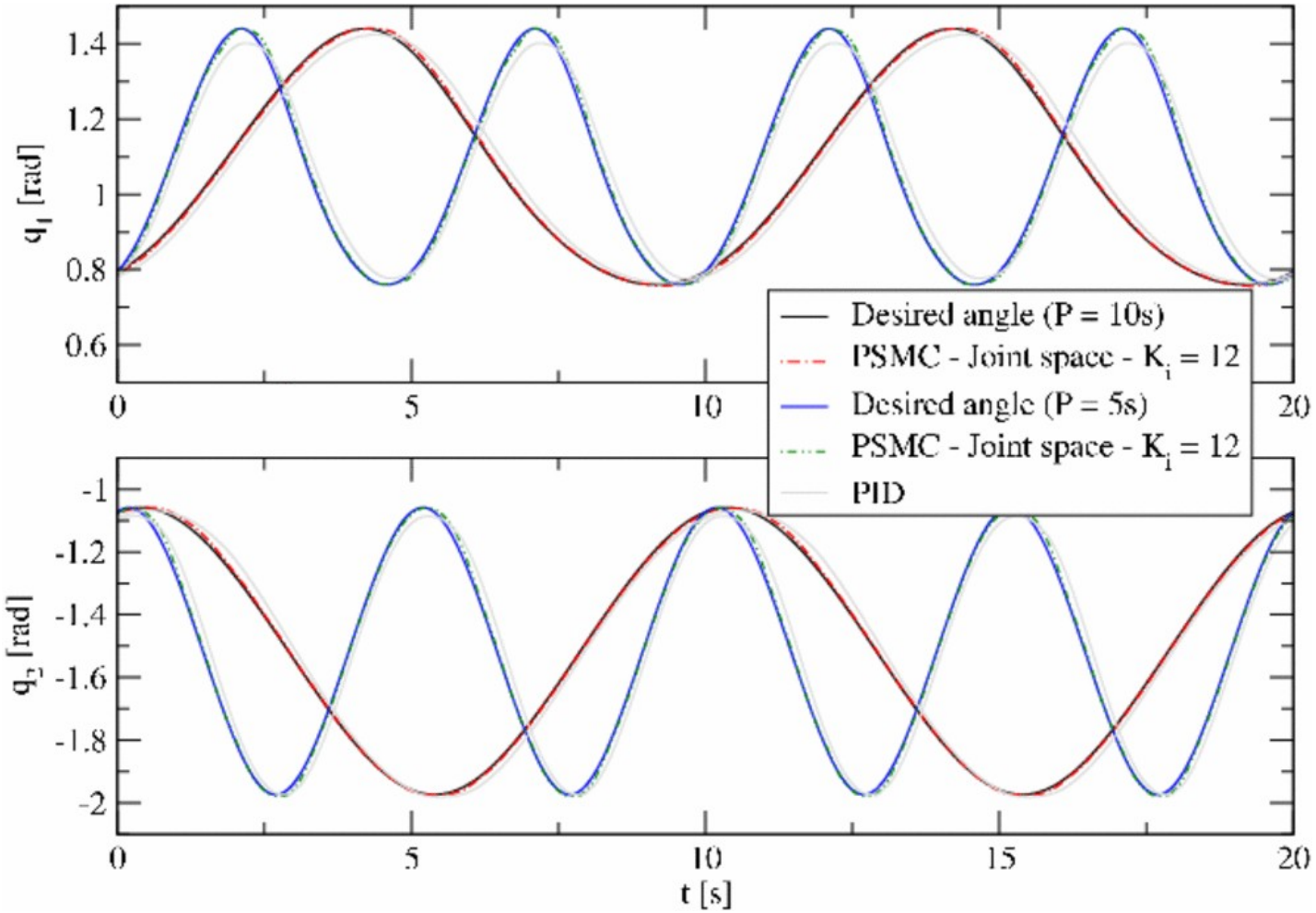
# PSMC – Joint Based Impl.



# Tracking Performance



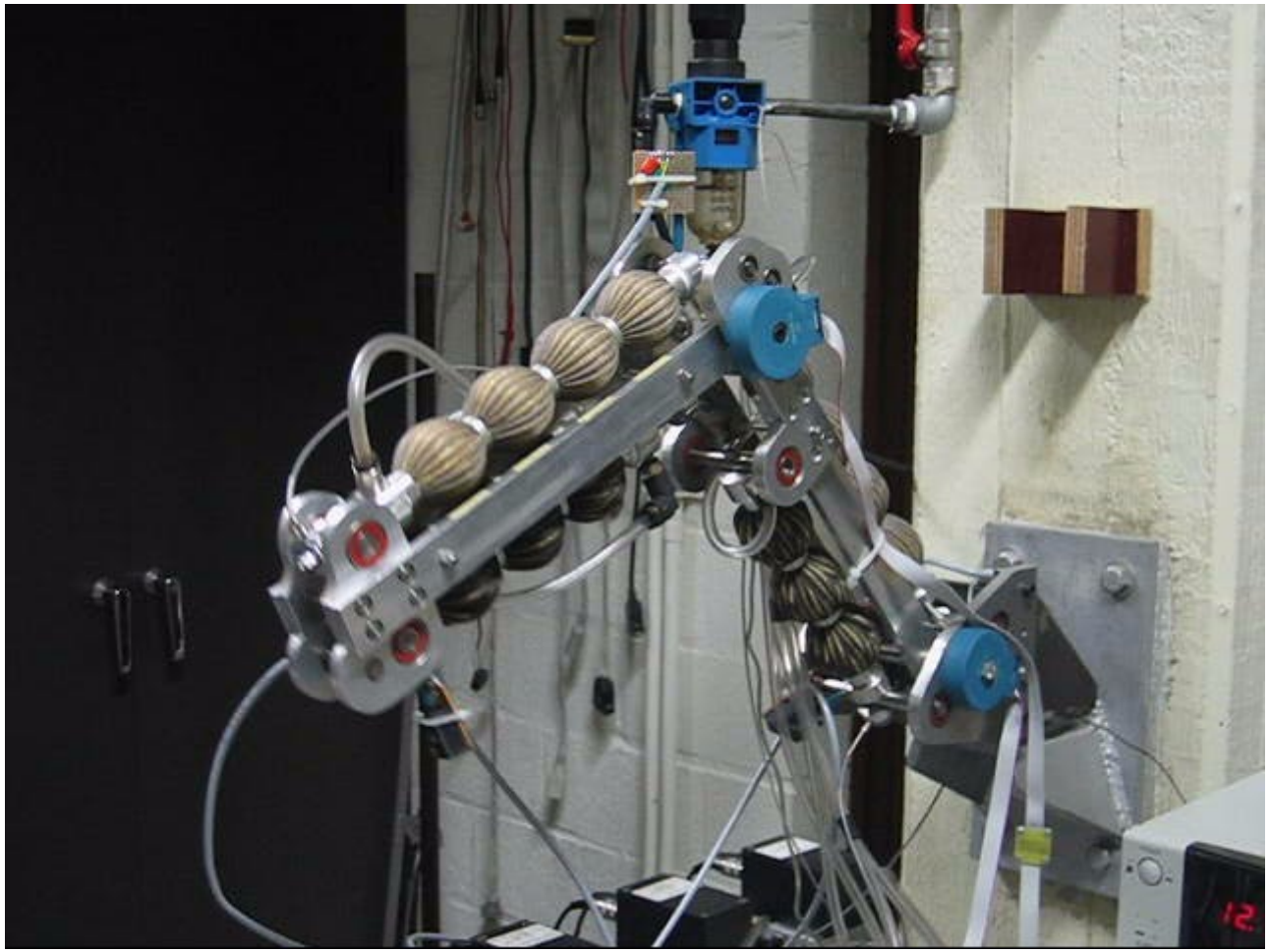
# Tracking Performance



# Safety

| | Step | | Switch between trajectories | |
|---|---|---|---|---|
| | HIC | $F_{\max}$ $[N]$ | HIC | $F_{\max}$ $[N]$ |
| PID | 4.81 | 1524 | 3.02 | 1004 |
| PSMC - Joint space - $\lambda = 0.4\,s$, $K_i = 2\,bar/rad \cdot s$ | 0.23 | 338 | 0.10 | 206 |
| PSMC - Joint space - $\lambda = 0.8\,s$, $K_i = 2\,bar/rad \cdot s$ | 0.05 | 167 | 0.02 | 100 |
| PSMC - Joint space - $\lambda = 1.5\,s$, $K_i = 2\,bar/rad \cdot s$ | 0.01 | 79 | 0.02 | 96 |
| PSMC - Joint space - $\lambda = 0.4\,s$, $K_i = 12\,bar/rad \cdot s$ | 0.48 | 481 | 0.14 | 251 |
| PSMC - Joint space - $\lambda = 0.8\,s$, $K_i = 12\,bar/rad \cdot s$ | 0.10 | 233 | 0.03 | 132 |
| PSMC - Joint space - $\lambda = 1.5\,s$, $K_i = 12\,bar/rad \cdot s$ | 0.02 | 110 | 0.04 | 129 |
| PSMC - Task space - $\lambda = 0.4\,s$, $K_i = 2\,bar/rad \cdot s$ | 0.29 | 375 | 0.03 | 117 |
| PSMC - Task space - $\lambda = 0.8\,s$, $K_i = 2\,bar/rad \cdot s$ | 0.05 | 170 | 0.01 | 81 |
| PSMC - Task space - $\lambda = 1.5\,s$, $K_i = 2\,bar/rad \cdot s$ | 0.01 | 82 | 0.01 | 80 |

# Compliance (1)



# Conclusion

- Hardware safety features alone are not enough
  - System unsafe when under PID control
- Control has to be designed with safety in mind
- PSMC improves safety and provides good tracking performance for pneumatic muscle systems