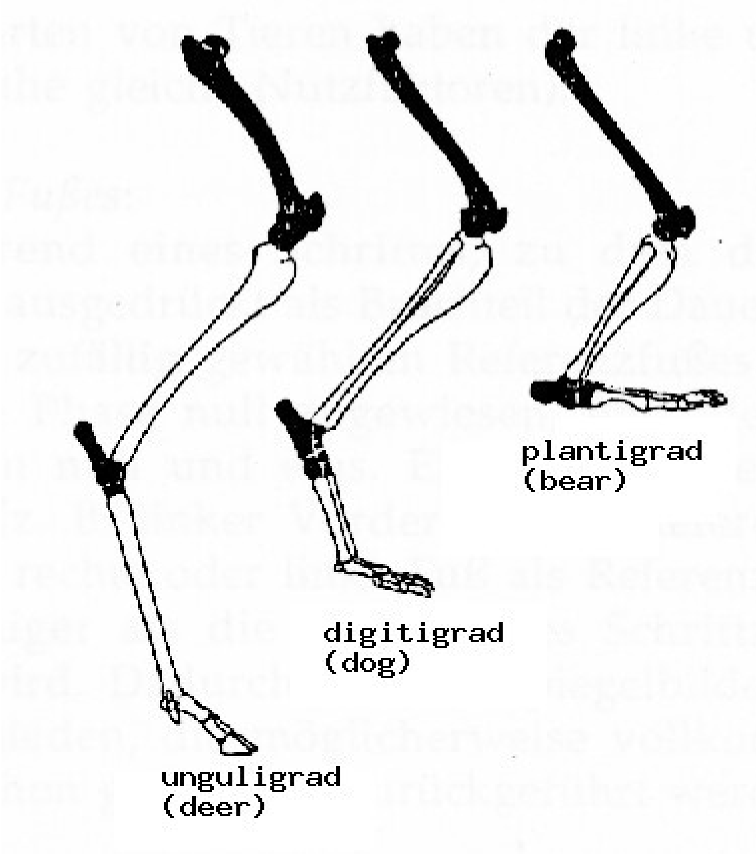
Model and Control of compliant joints driven by fluidic muscles

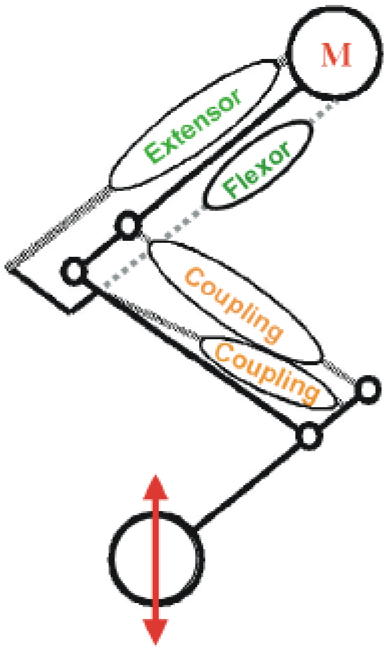
T. Kerscher[1], J.M. Zoellner[2], R. Dillmann[1,2],
A. Stella[3], and G. Caporaletti[3]
[1] Universität Karlsruhe
[2] Forschungszentrum Informatik
[3] EICAS Automazione S.p.A

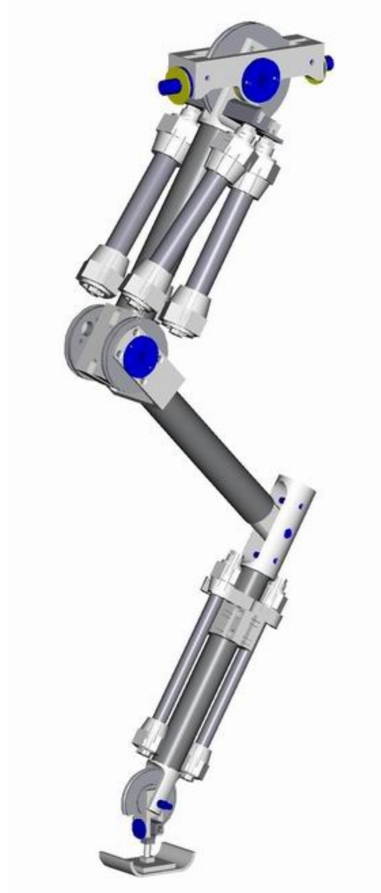
Locomotion in nature

- mammals are highly adapted to the environmental structure
- design and the functionality of the mammalian legs depends an the habitat and the locomotion strategy
- all mammalian legs share the same basic concept of a z-shaped construction

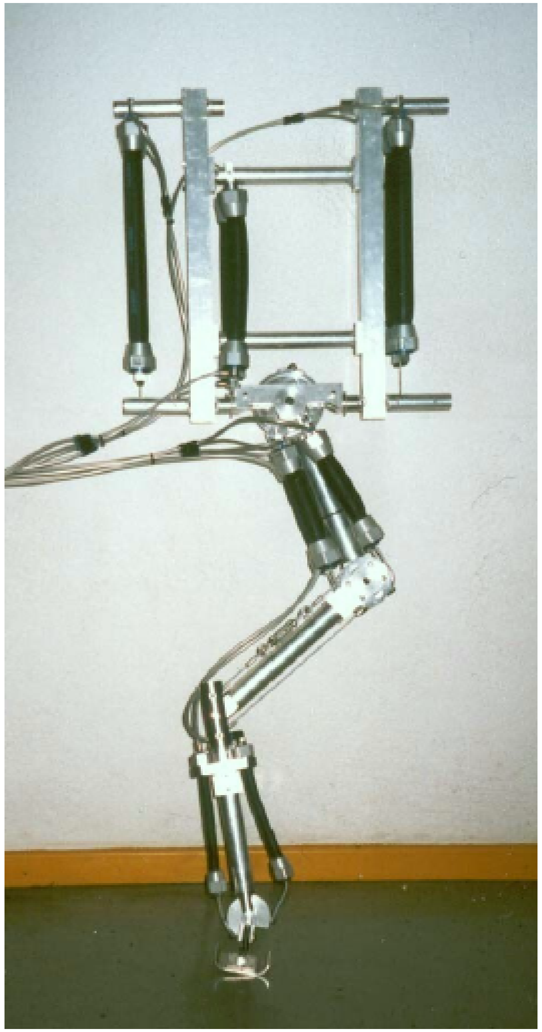
The idea of the PANTER leg







Design of the PANTER leg



- angular range
  α=55°, β=30°, γ=41°, δ=49°
- leg length l_{max} = 85 cm, l_{min} = 72 cm
- step width ~82 cm
- total weight 8.1 kg
  - weight of leg 4.6 kg
  - shoulder fastener 3.5 kg

	muscle length	muscle diameter	number muscles	joint radius	avg. torque
α	295 mm	20 mm	4	53 mm	50 Nm
β	120 mm	20 mm	4	38 mm	40 Nm
γ	210 mm	20 mm	2	40 mm	20 Mm
δ	140 mm	10 mm	2	40 mm	10 Nm

Biological muscle as actuator

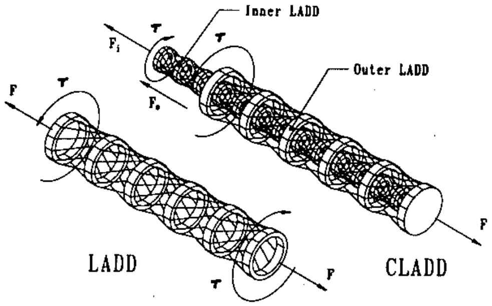
- Fast and also slow precise movement possible
- Tendons are integrated position and speed sensors
- Energy storage using the passive damping behaviour
- Adaptation to uneven terrain
- Only tractive force: two muscle work antagonistically

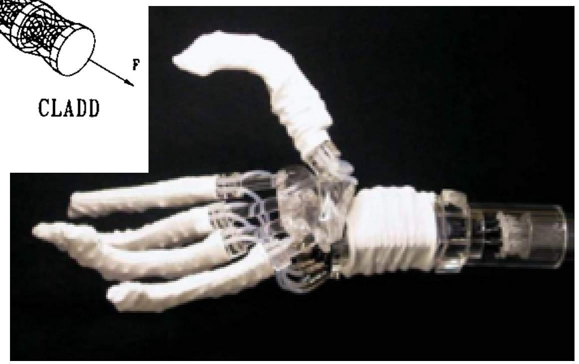
→ Properties that are very interesting for building legged robots

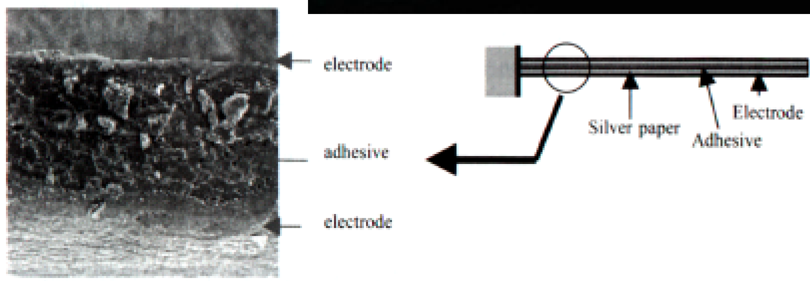
Different artificial muscles

- McKibben muscle is often used

- MAS-FESTO for industrial application

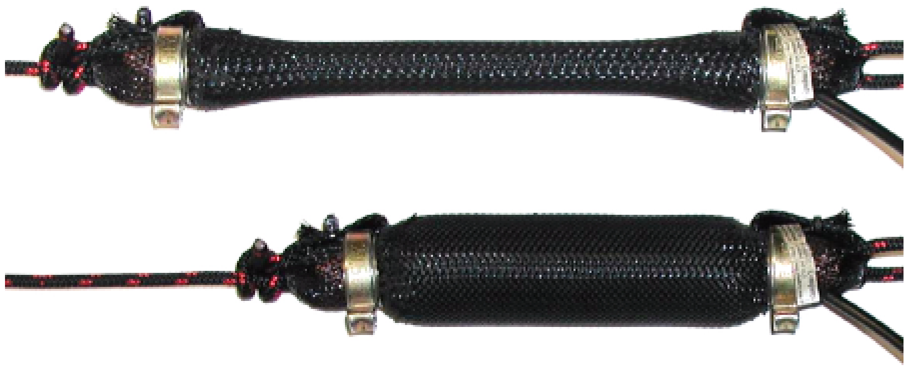






Fluidic Muscle – the McKibben Principle

Muscle from the Shadow-Company



Mechanical built-up

- Outer braided shell of non-elastic fibre
- Inner elastic Rubber tube

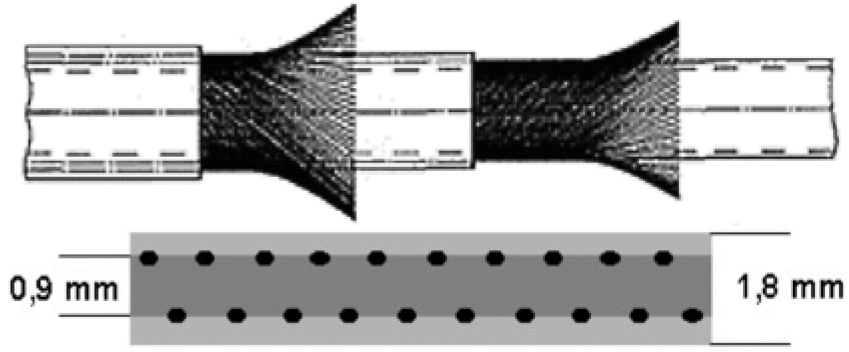
Fluidic-Muskel from FESTO

Properties

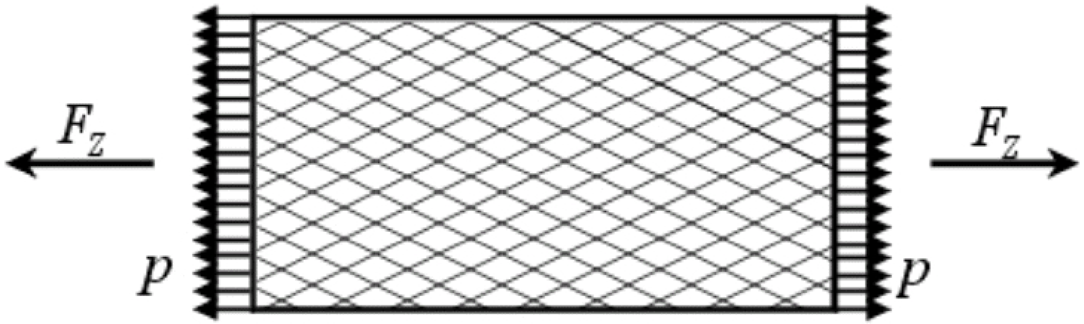
- Only tractive force
- Passive compliance
- Flexible joint
- Protection of the mechanics
- Analogy to nature
- Lightweight cheap actuator

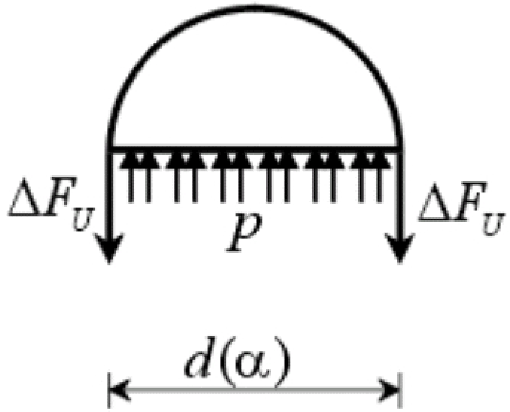
Fluidic Muscle – FESTO MAS-20

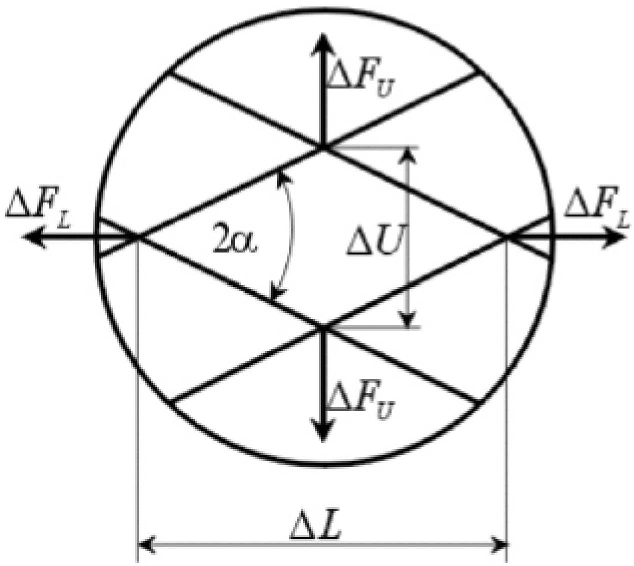
- The tube is composed of three rubber layer, between two layers lies a layer of non-elastic fibres
- working pressure: 0..6bar
- max. force ~1700 N
- Length contraction up to 28%



Fluidic Muscle – Working Principle



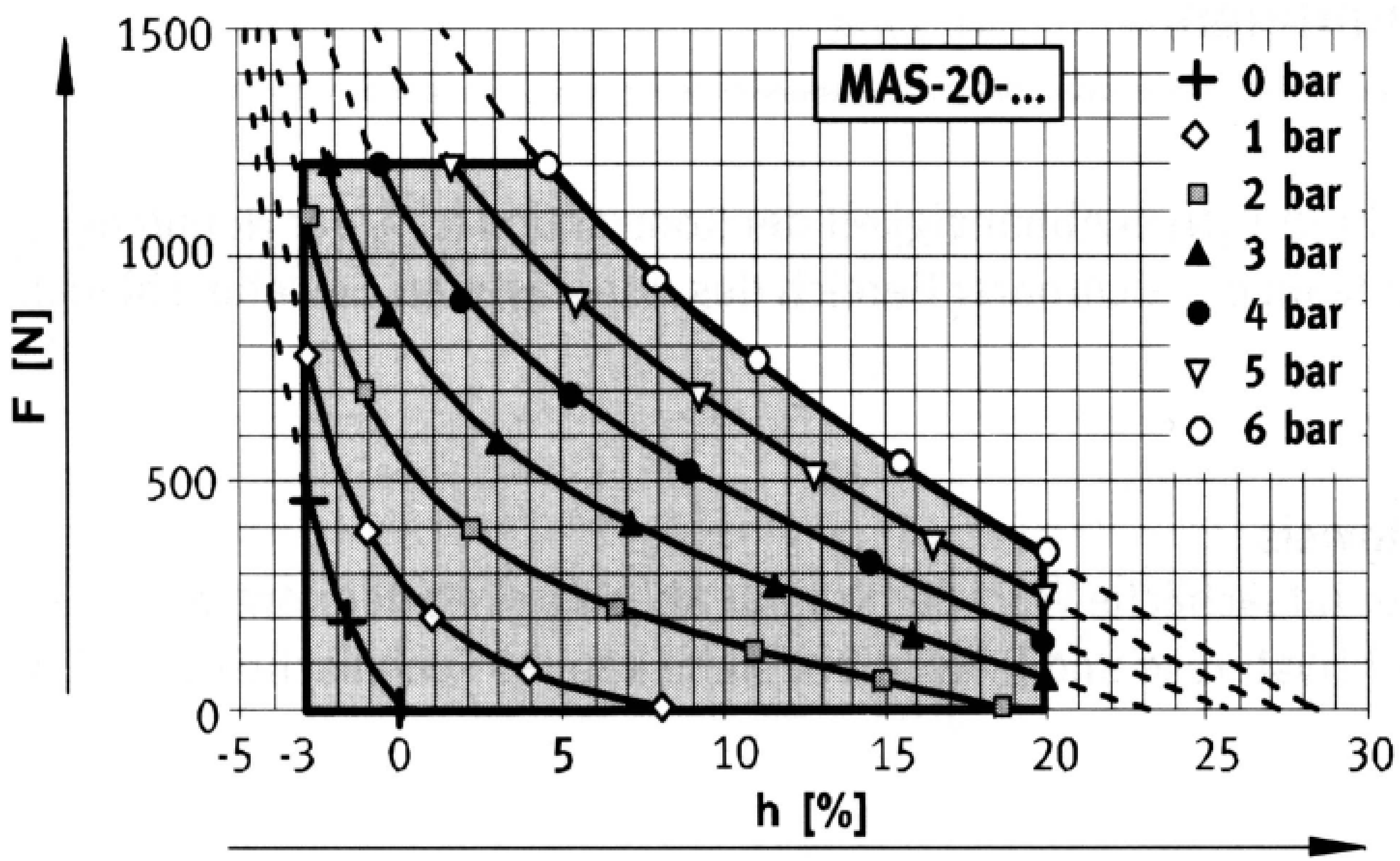




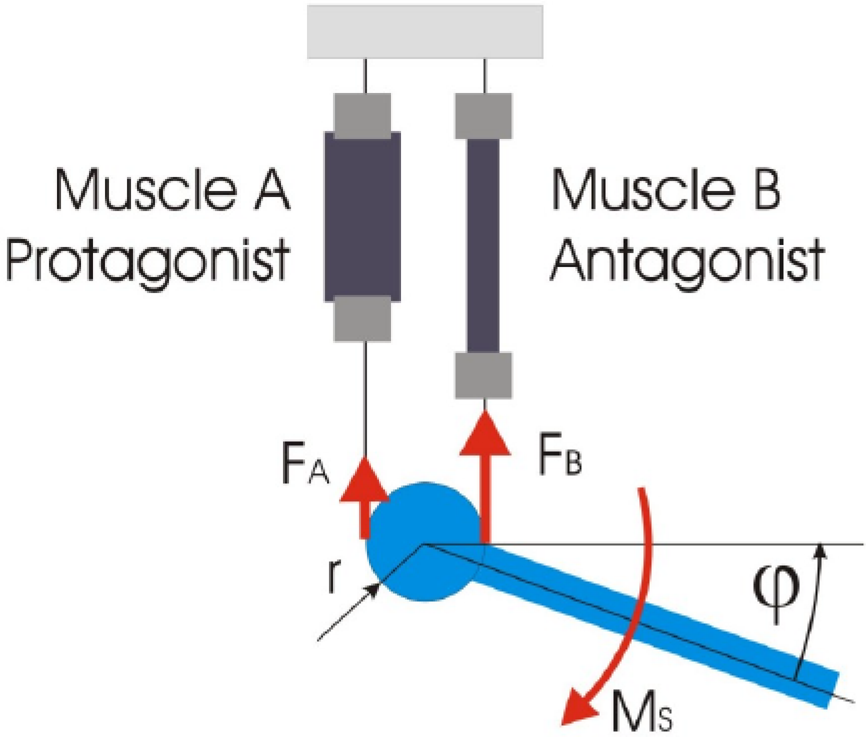
- Muscle pressure affects contraction
- develop axial tractive force
- at a fibre angle of about 55° there is no tractive force

Fluidic Muscle - Non-Linear Actuator

Correlation between force, pressure and contraction



Joints Driven Antagonistic by Fluidic Muscle I



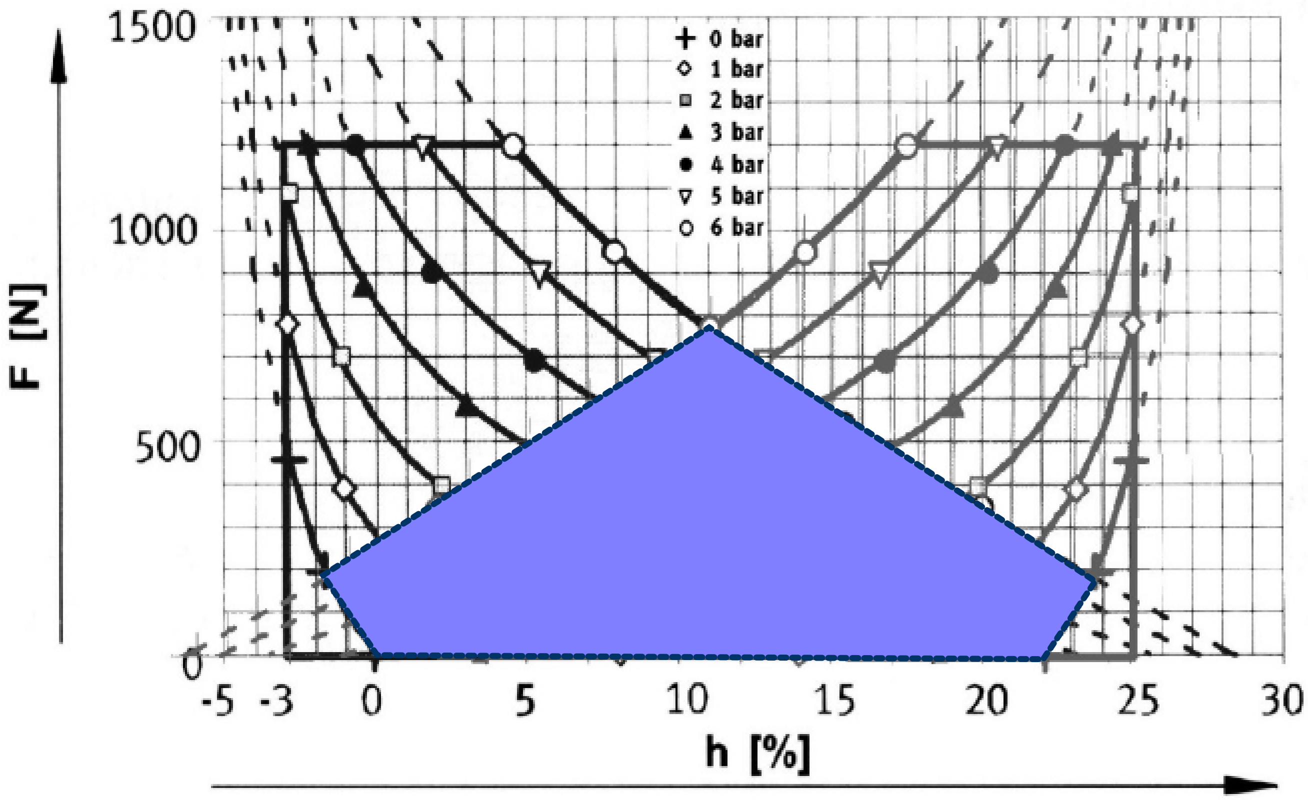
$$\left(F_A - F_B\right) \cdot r = M_S$$

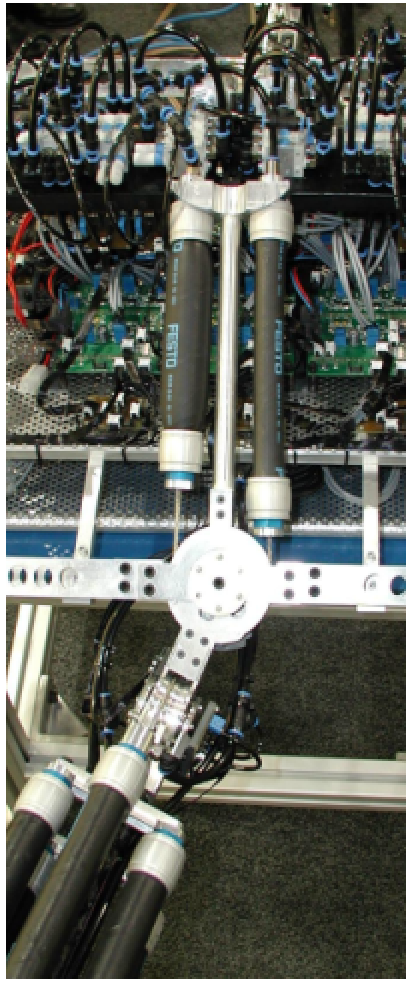
FA(B): force in muscle A(B)

r: joint radius

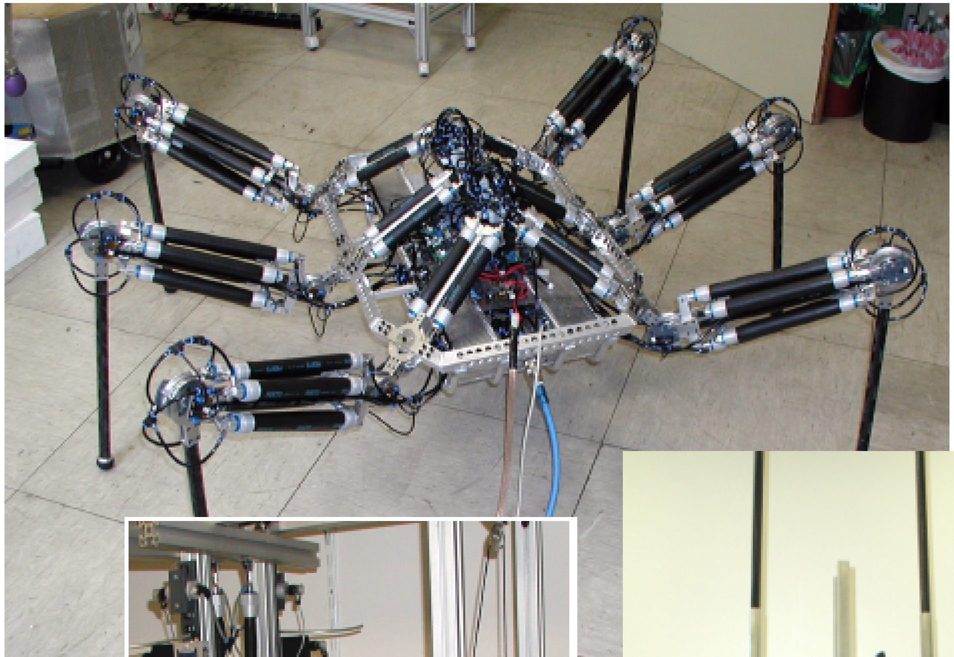
M_S: disturbance / outer torque

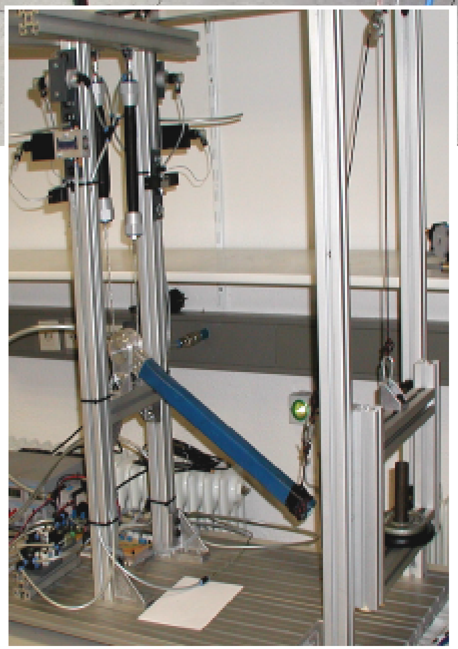
Joints Driven by Fluidic Muscle

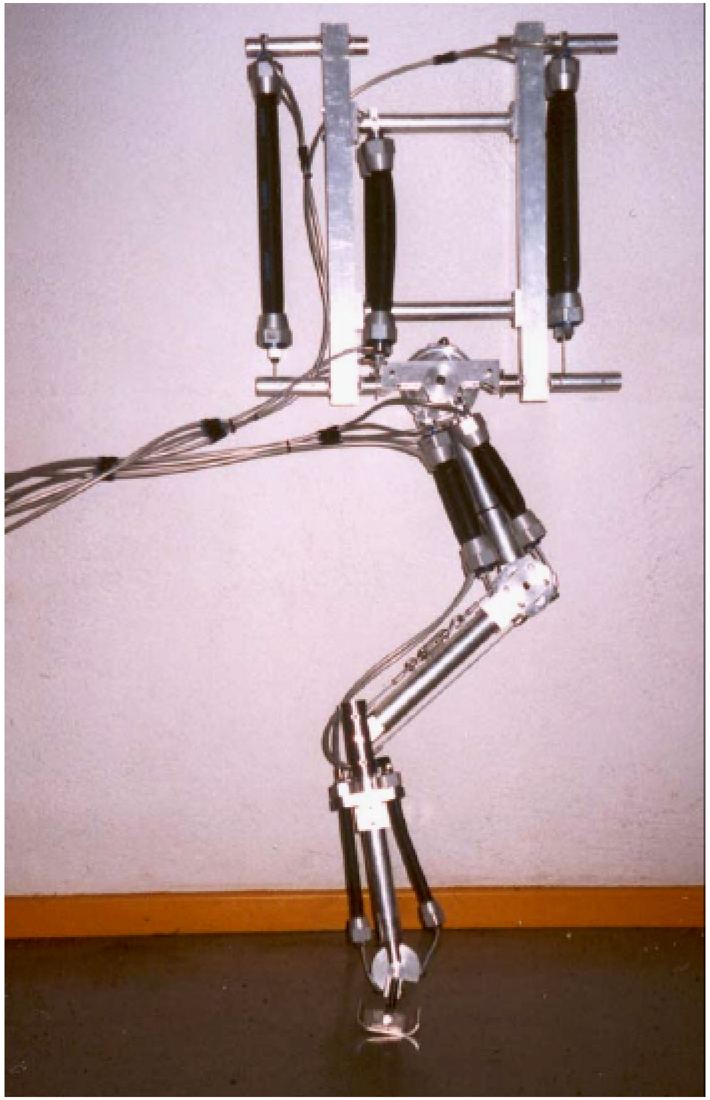




Robots with fluidic muscles built at FZI/UKA



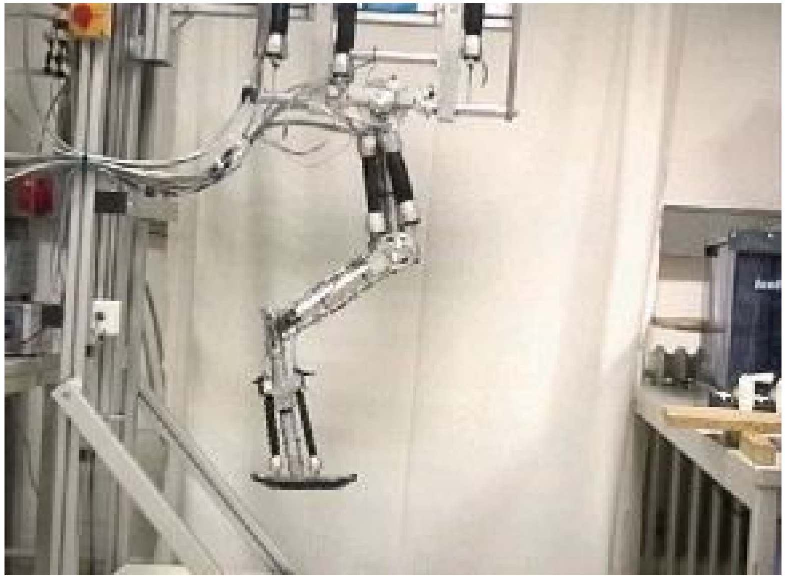




ACODUASIS IPS-2001-42068

Experiments with AirBug and PANTER

Walking with pneumatic muscle is possible



Problems:

☹ mechanical built up

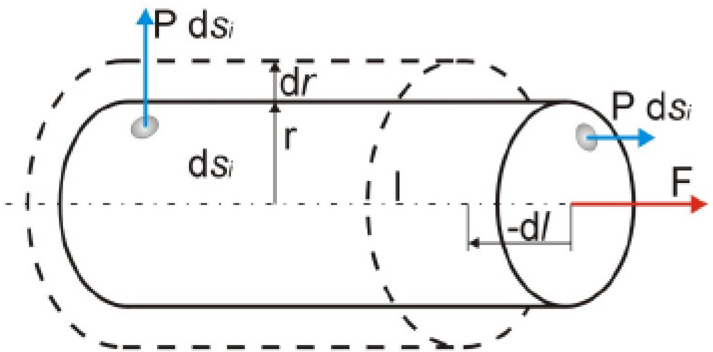
☹ Hardware

☹ Joint control

Usage of advance simulation software

- Help during modelling process
- Support during Control design

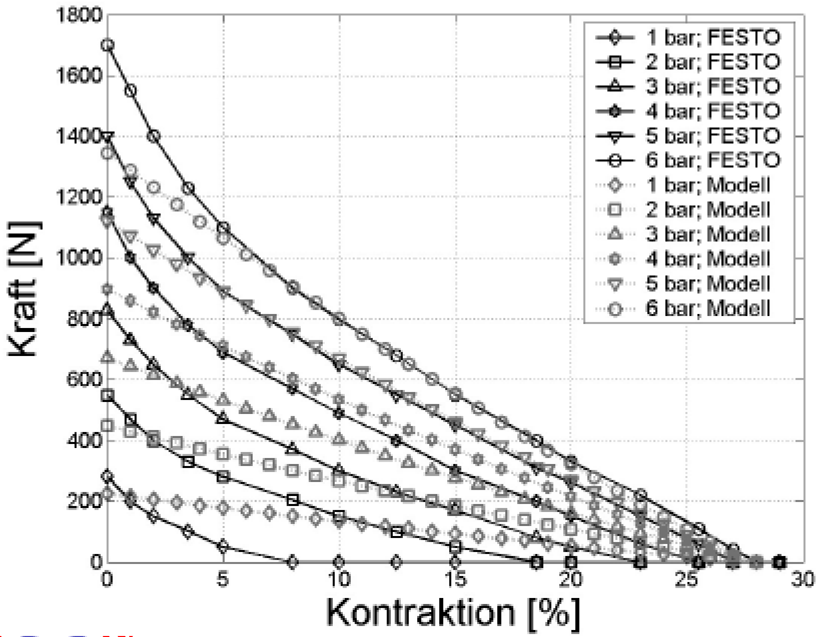
Static muscle model



$$F(\kappa, P) = (\pi \cdot r_0^2) \cdot P \cdot [a \cdot (1-\kappa)^2 - b]$$

$$\kappa = \frac{(l_0 - l)}{l_0}, \quad 0 < \kappa \le \kappa_{max}$$

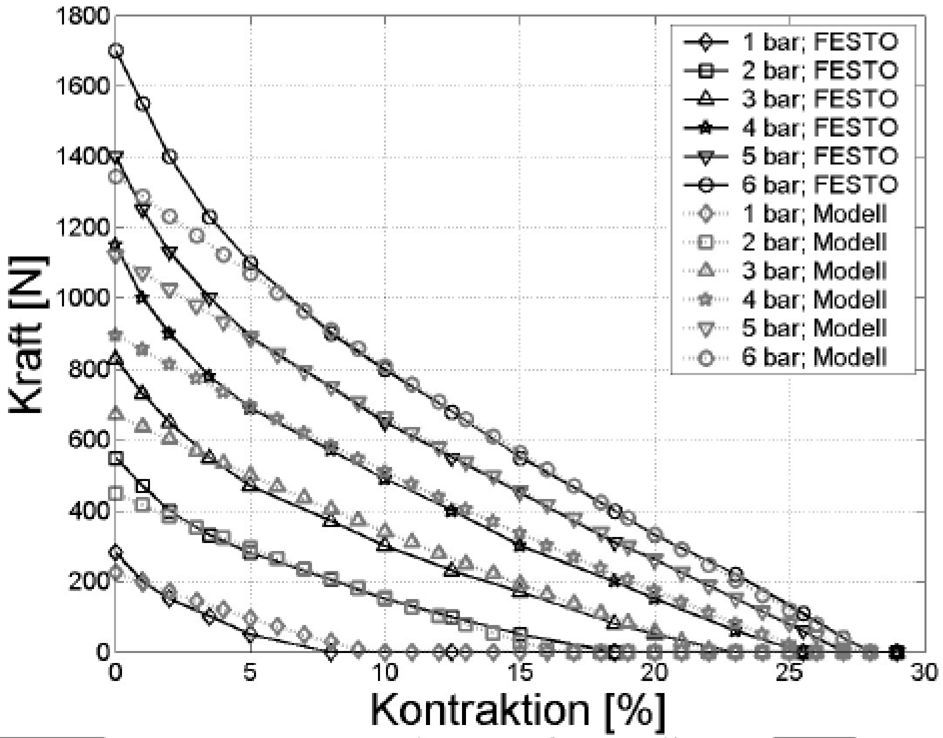
$$a = \frac{3}{\tan^2(\alpha_0)}, \quad b = \frac{1}{\sin^2(\alpha_0)}$$



$$F_{max} = (\pi \cdot r_0^2) \cdot P \cdot [a - b] \quad \mathit{für}\ \kappa = 0$$

$$\kappa_{max} = 1 - \sqrt{b/a} \quad \mathit{für}\ F = 0$$

Improvement of the muscle model



Use of a correction funktion e

- Better adaptation to the real muscle behaviour
- Modification of the model for small pressure
- Calculation of c_1 and c_2 with the help of the least-square-method

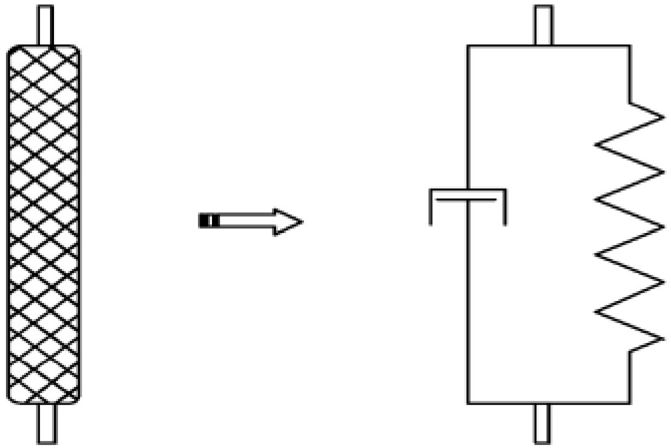
$$F(\kappa, P) = (\pi \cdot r_0^2) \cdot P \cdot [a \cdot (1 - \varepsilon \cdot \kappa)^2 - b]$$

$$mit \;\; \varepsilon = c_1 \cdot e^{-P} + c_2$$

Fluidic Muscle - Mathematical Description

Equation of force: $$F_{Mus}(\kappa, \dot{\kappa}, p) = F_{spring}(\kappa, p) + F_{damper}(\dot{\kappa}, p).$$

Mechanical equivalent circuit

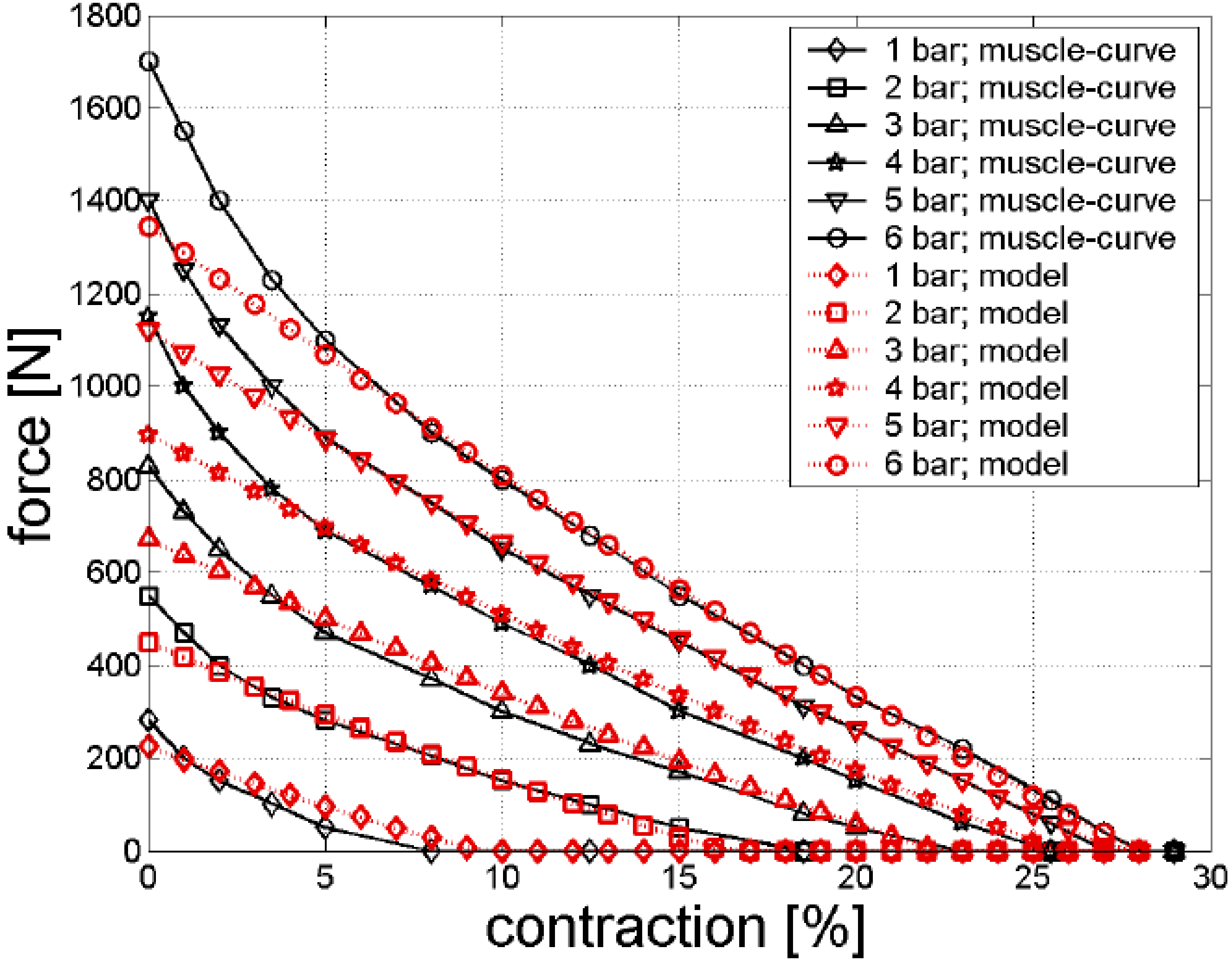


$$F_{damper}(\dot{\kappa}, p) = -C_D \cdot (p + P_n) \cdot \dot{\kappa}$$

$$F_{spring}(p, \kappa) = \mu \cdot (\pi \cdot r_0^2) \cdot p \cdot (a \cdot (1 - (a_\varepsilon \cdot e^{-p} + b_\varepsilon) \cdot \kappa)^2 - b)$$

$$+ \sigma(-\kappa) \cdot (-f_0) \cdot \kappa$$

Comparison between real muscle-curve and muscle model



Fine model – equation for the muscle pressure

State equation for ideal gas

$$p \cdot V = const. \quad \longrightarrow \quad p_{Mus} = p_N \cdot \frac{V_{Luft}}{V_{Mus}}$$

Pressure change by deviation

$$\boxed{\dot{p}_{Mus} = p_N \cdot \left(\frac{\dot{V}_{Luft}}{V_{Mus}} - V_{Luft} \cdot \frac{\dot{V}_{Mus}}{V_{Mus}^2} \right)}$$

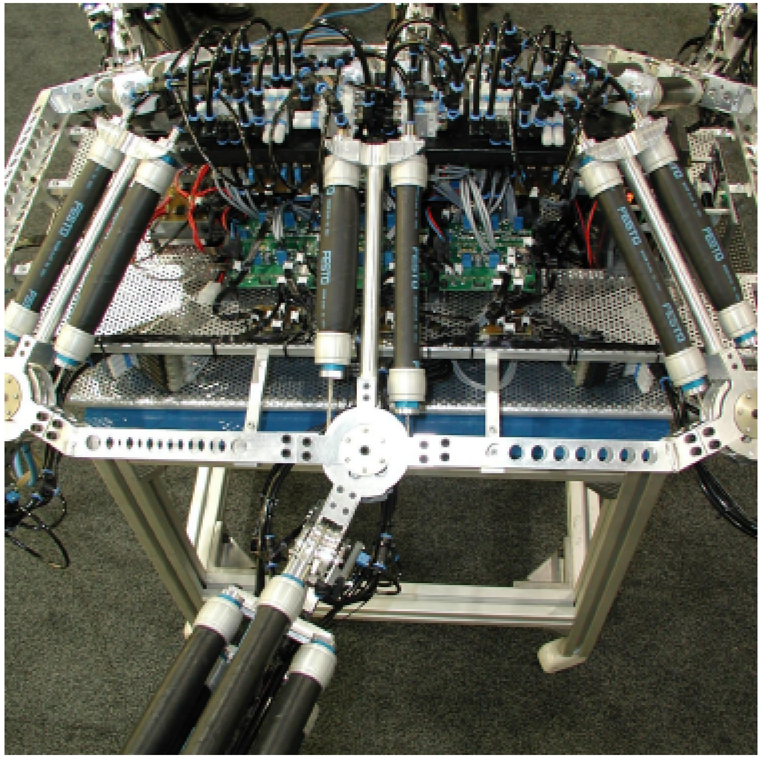
Airflow with the help of the bernoulli-equation

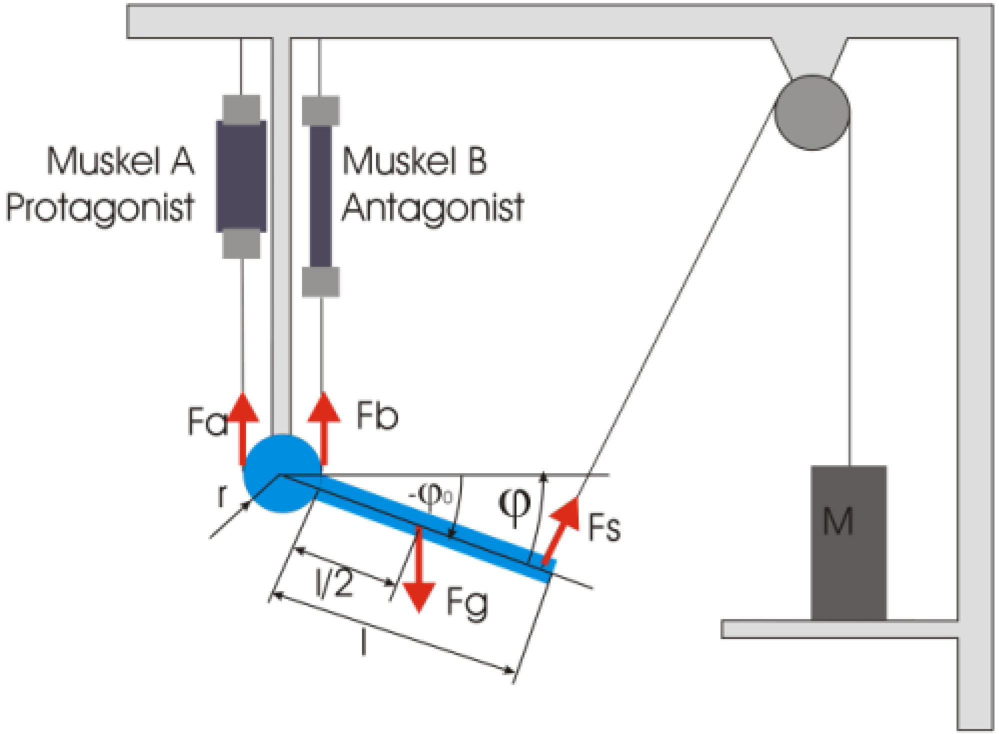
$$\boxed{p + \frac{1}{2}\rho v^2 = p_0 = const} \quad \longrightarrow \quad \boxed{\dot{V}_{Luft} = C_a \cdot A_{min} \cdot \sqrt{(p_0 - p)}.}$$

Differential equation for the pressure change

$$\dot{p}_{Mus} = p_N \cdot \frac{C_a \cdot A_V \cdot \sqrt{(p_0 - p)}}{V_{Mus}(\kappa)} - p_{Mus} \cdot \frac{\dot{V}_{Mus}(\kappa, \dot{\kappa})}{V_{Mus}(\kappa)}.$$

Fine model – equation of motion

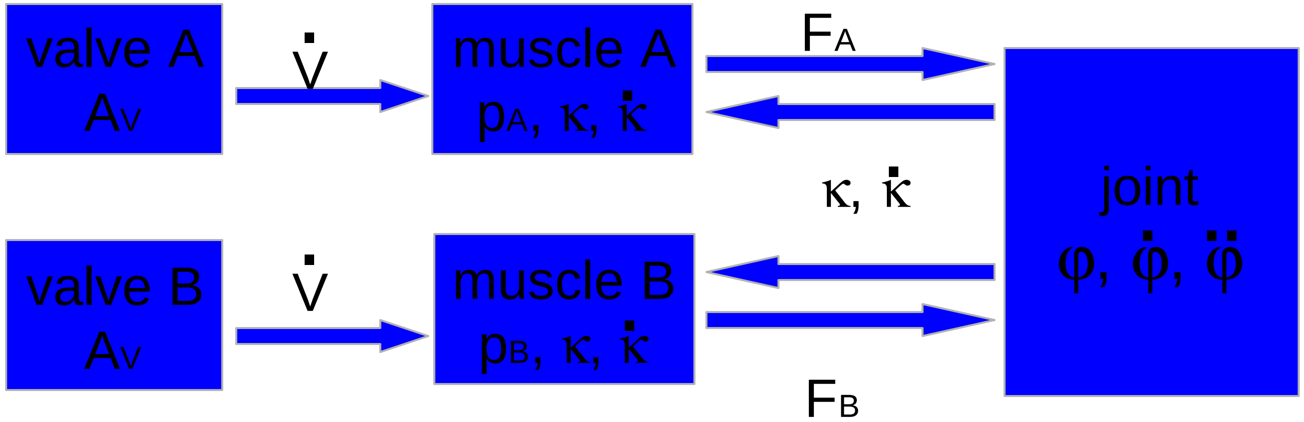




Equation of motion

$$J\ddot{\varphi} = -rF_{MusA}(\kappa_A,\dot{\kappa}_A,p_A) + rF_{MusB}(\kappa_B,\dot{\kappa}_B,p_B) - \frac{l}{2}\cos(\varphi-\varphi_0)F_g + lF_s$$

Fine model - Definition of the state variables



State variable $\underline{x}$:

- pressure muscle A
- pressure muscle B
- joint angle φ
- angular speed $\dot{\varphi}$

input variable $\underline{u}$:

- opening area A_V of valve A
- opening area A_V of valve B

Non-linear differential equation

$$\dot{\underline{x}} = \underline{f}(\underline{x}, \underline{u}, t),$$
$$\underline{y} = \underline{g}(\underline{x}, \underline{u}, t)$$

working point linearization

$$\dot{x}_{AP_i} + \Delta\dot{x}_i(t) \approx f_i(x_{AP1}, \ldots, x_{APn}, u_{AP1}, \ldots, u_{APp}) + \sum_{j=1}^{n} \frac{df}{dx_j}\Big|_{AP} \Delta x_j(t) + \sum_{k=1}^{p} \frac{df}{du_k}\Big|_{AP} \Delta u_k(t).$$

linear-differential equation

$$\begin{aligned} \underline{\dot{x}} &= \underline{A} \cdot \underline{x}(t) + \underline{B} \cdot \underline{u}(t), \ \underline{x}(0) = \underline{x}_0 \\ \underline{y} &= \underline{C} \cdot \underline{x}(t) + \underline{D} \cdot \underline{u}(t) \end{aligned}$$

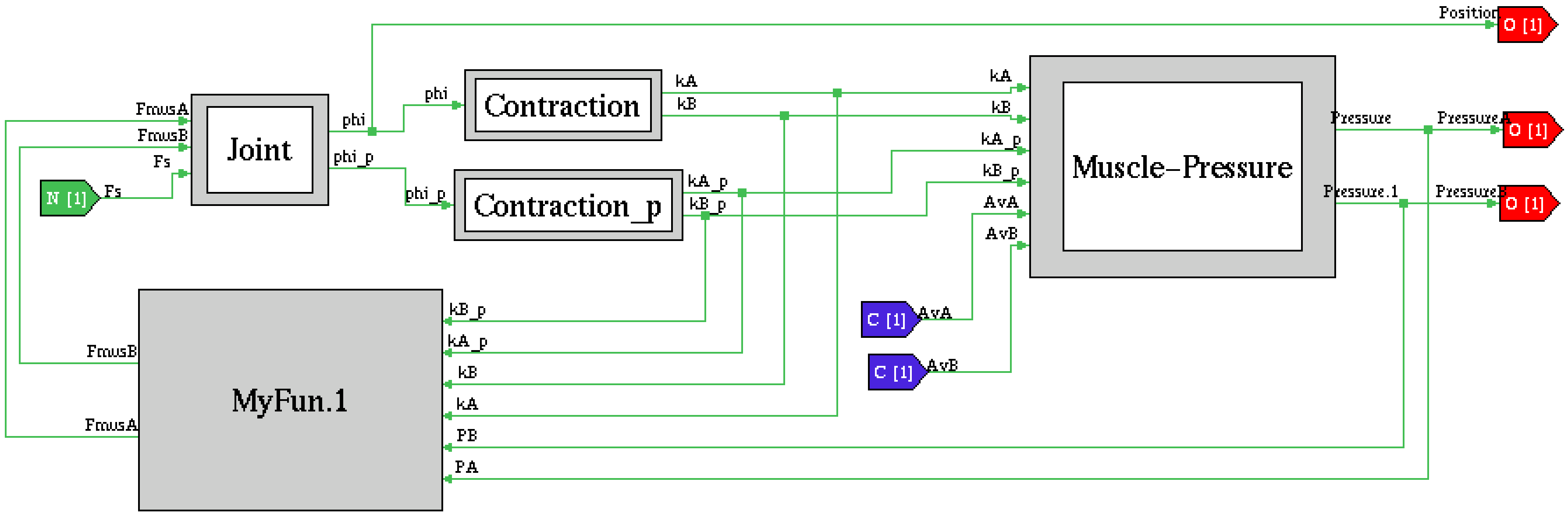
$$\underline{\dot{x}} = \begin{pmatrix} 0 & 0 & 0 & \mu_{A2} \\ 0 & 0 & 0 & \mu_{B2} \\ 0 & 0 & 0 & 1 \\ \mu_1 & \mu_2 & \mu_3 & \mu_4 \end{pmatrix} \cdot \underline{x} + \begin{pmatrix} \mu_{A1} & 0 \\ 0 & \mu_{B1} \\ 0 & 0 \\ 0 & 0 \end{pmatrix} \cdot \underline{u} \cdot \qquad \underline{y} = \begin{pmatrix} 0 & 0 & 1 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{pmatrix} \cdot \underline{x}$$

$$\mu_1 = -\frac{r \cdot c_1}{J}, \ \mu_2 = \frac{r \cdot c_1}{J}, \ \mu_3 = \frac{2 \cdot c_2 \cdot r^2}{J \cdot l_0} + sin(\varphi_0)\frac{l}{2 \cdot J} \cdot F_g \text{ und } \mu_4 = -\frac{2 \cdot r^2 \cdot c_D}{l_0 \cdot J}$$

$$\mu_{A1} = \mu_{B1} = \frac{p_N \cdot l_0 \cdot C_\delta \cdot \sqrt{(p_C - x_{AP1})}}{a(l_0) \cdot r \cdot \varphi_{A0} + b(l_0) \cdot l_0} \qquad \mu_{A2} = \mu_{B2} = \frac{x_{AP1} \cdot a(l_0) \cdot r}{a(l_0) \cdot r \cdot \varphi_{A0} + b(l_0) \cdot l_0}$$

Modeling in EICASLAB

SIMBuilder window for the plant



Joint Control - Necessary Preconditions

Target: Walking in rough terrain

walking → cyclic motion

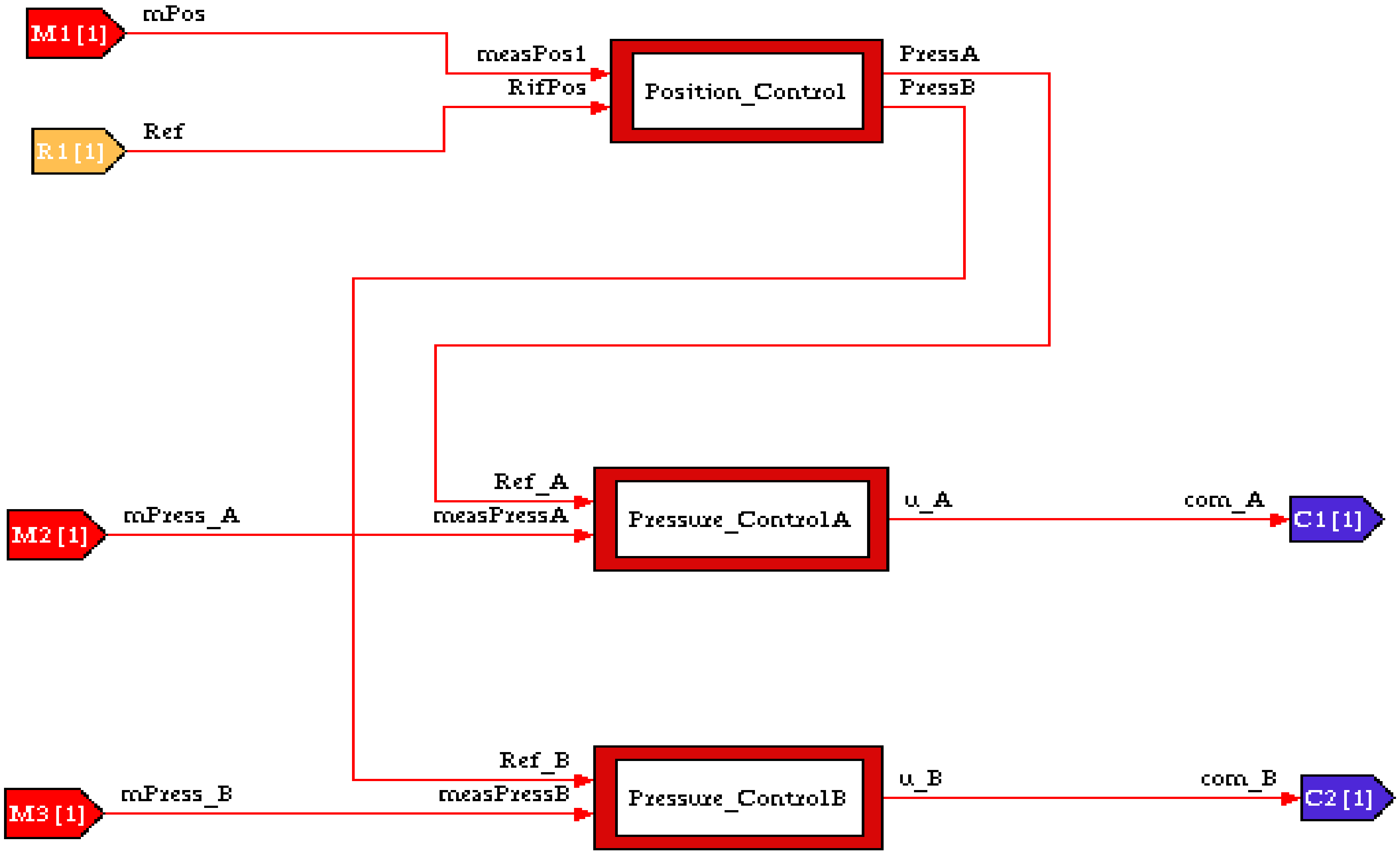
Power phase:

- leg has contact with the ground
- holds and pulls the robot
- interacting forces between the legs
- large change of account possible

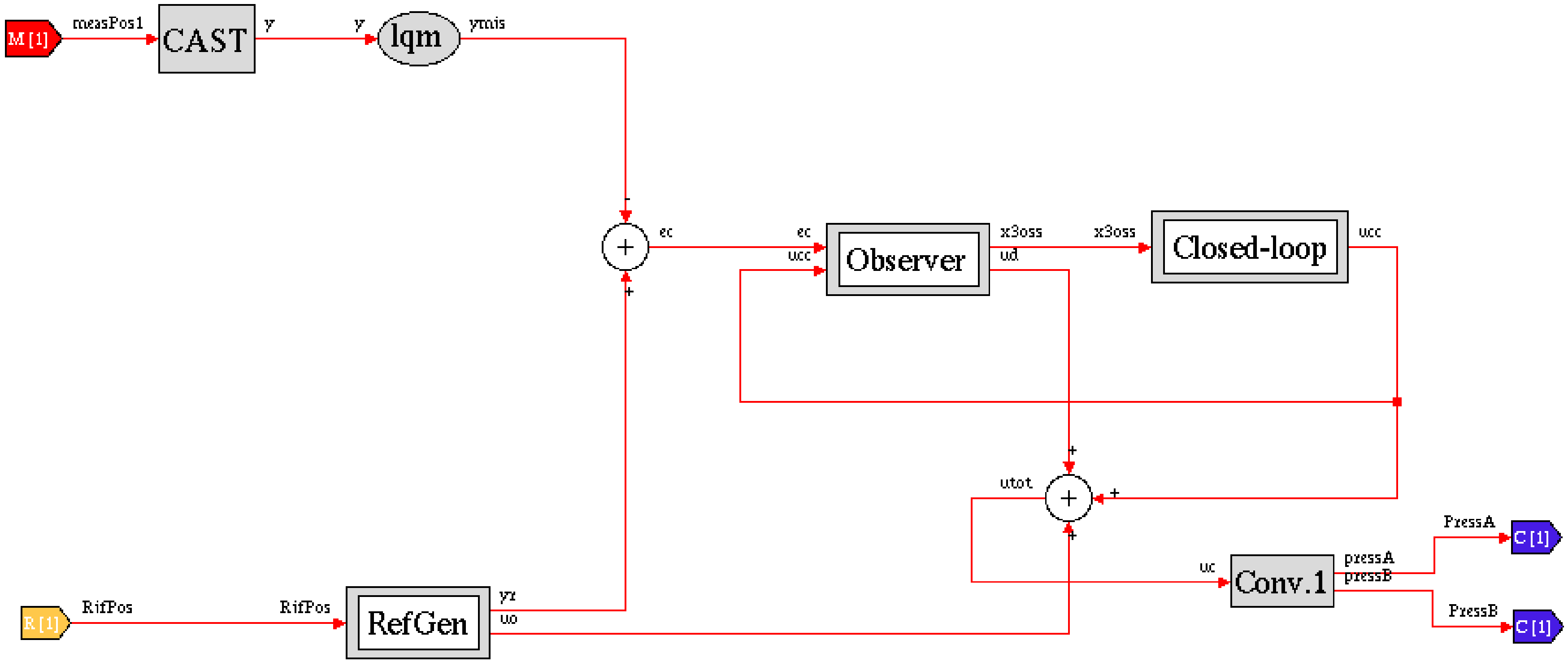
Return phase:

- leg has no contact to the ground (non-interacting)
- fast motion (from last point of past power phase to first point of the next power phase)

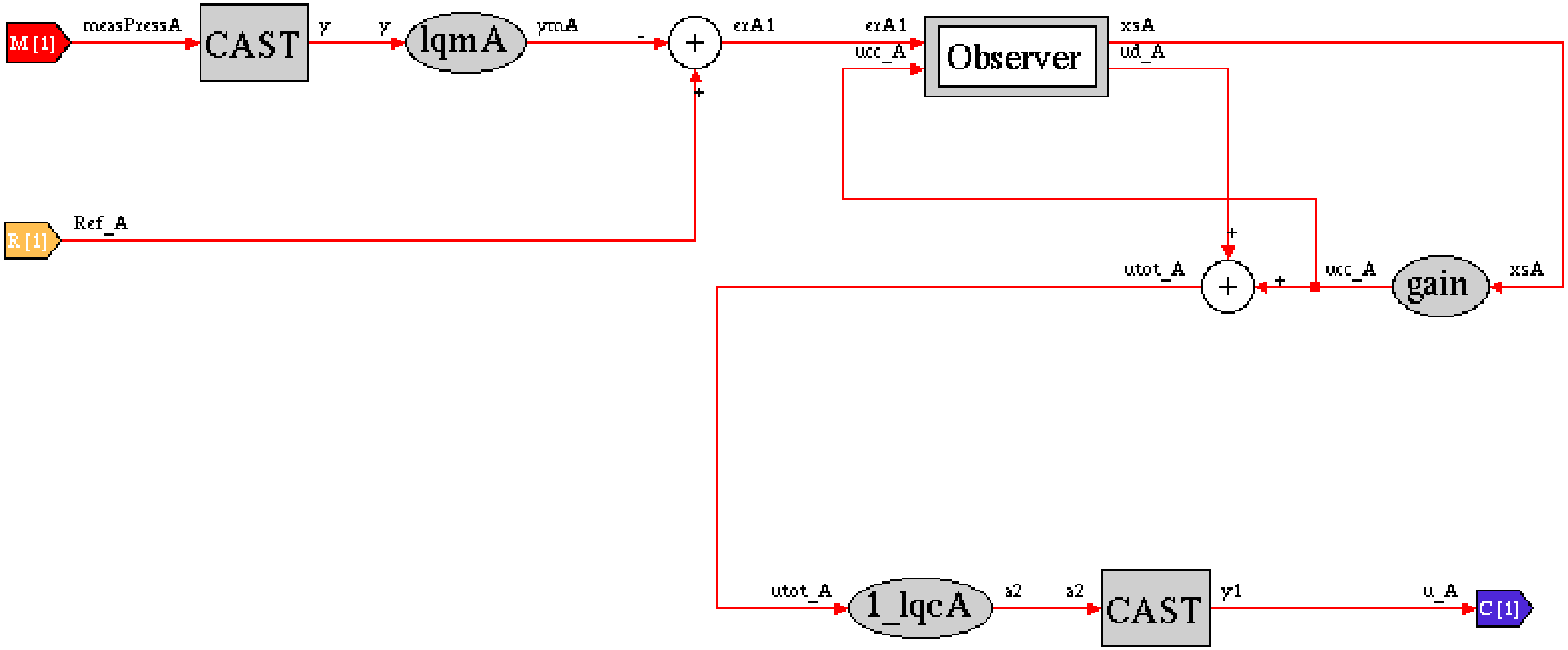
Control design with EICASLAB



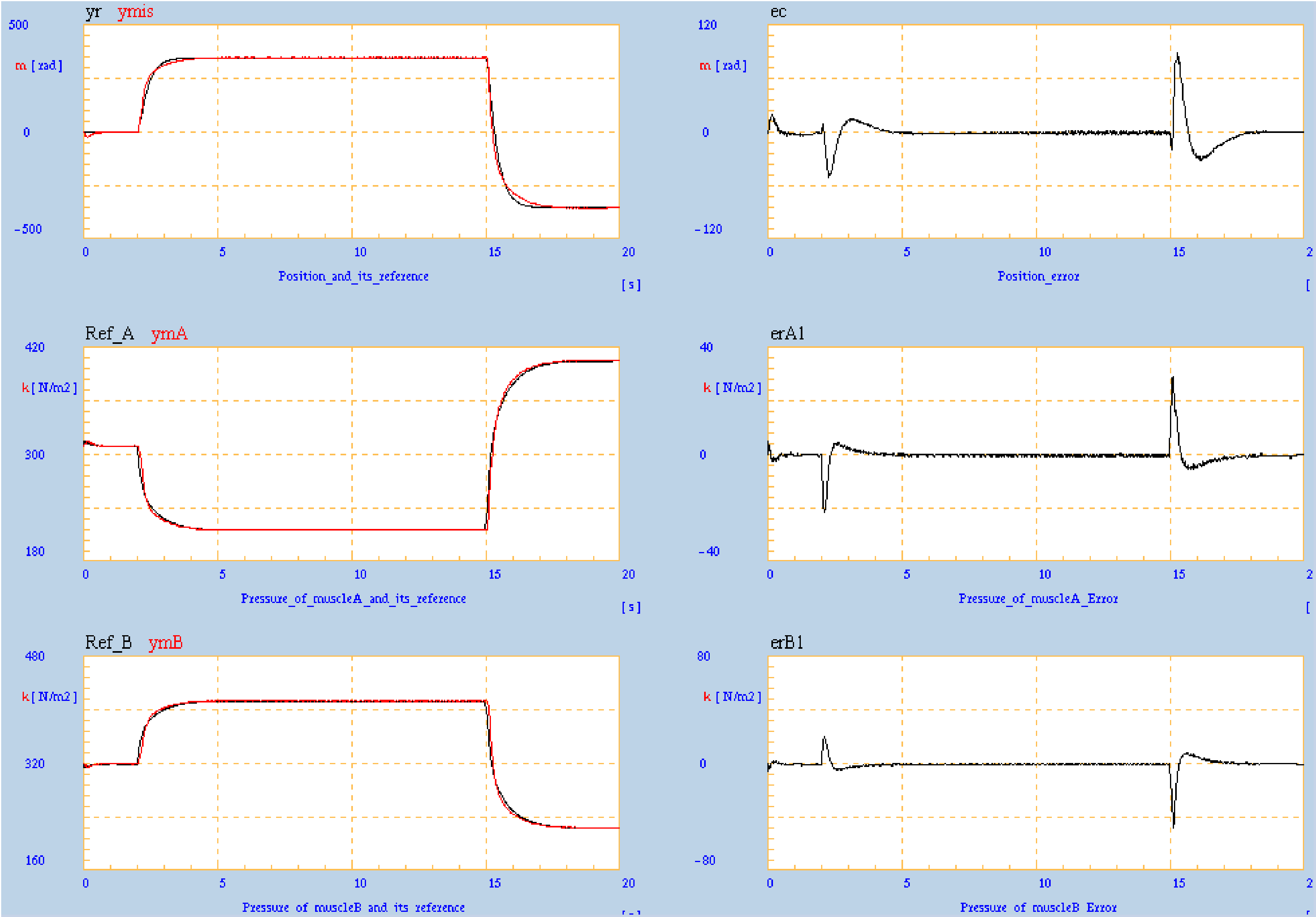
Position control in EICASLAB



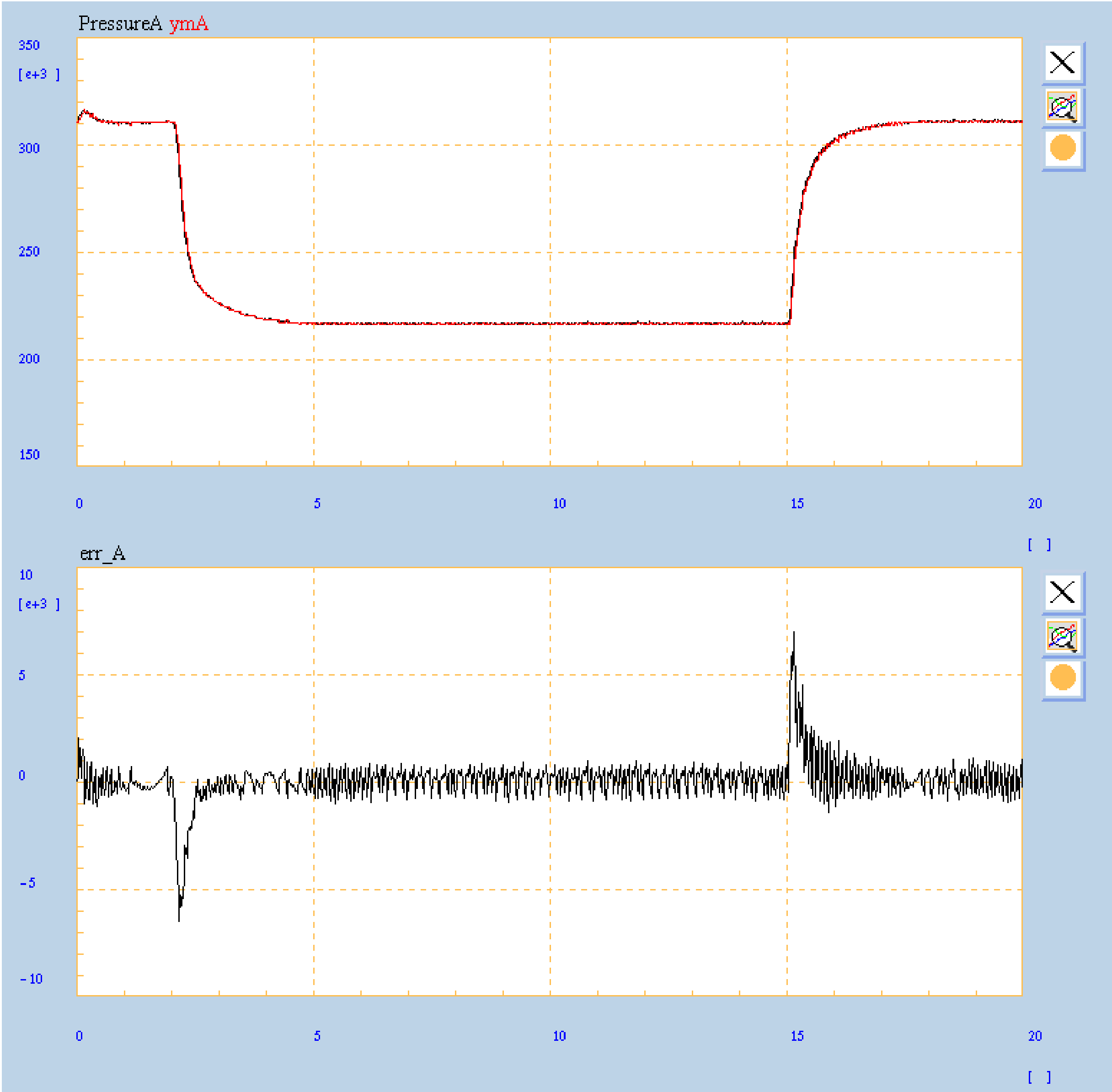
Pressure control in EICASLAB



Simulation results in EICASLAB-SIM



Simulation results in EICASLAB-SIM



Conclusion and outlook

- Better dynamic model of the muscle
- Control algorithm for a joint driven by two fluidic muscle
- Improvement of the joint controller
- Taking advance of the automatic control methodology

- Development of the whole mammal-like machine to study dynamic stable walking and running behaviour
- Development of a controller for the whole legs (AirBug/PANTER)
- Control algorithm for a joint driven by two fluidic muscle

Very good joint controller!?