Model and Control of compliant joints driven by fluidic muscles

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Abstract.

The content of this paper describes the model and control of an elastic joint driven by fluidic muscles including the nonlinear behavior of the fluidic muscle, the valves and the joint dynamics. Such elastic joints have a lot advantages like passive compliance, low power to weight relation. The control of the joint is developed with the help of a professional software tool named EICASLAB which has been realized within the ACODUASIS Project founded by the European Commission in the frame of the Innovation Program aiming at transferring to the robotics sector the EICAS methodology

Keywords: Pneumatic muscle, flexible manipulator, walking machine, modeling, automatic control.

1 Introduction

The FZI at the University of Karlsruhe started 2000 to use fluidic muscle as actuators for robotic system [6]. This is motivated by the fact of building biologically inspired robots. In order to take advantage from nature not only the mechatronical parts, but also the actuators should be imitated. It is obviously that artificial muscles as actuator are the nearest models of the biological actuator. By using artificial muscles in robotics one can use the analogy of the biological motor for locomotion or manipulation. There are a lot of advantages like the passive damping and good power-weight ratio. Because of this about ten years ago a lot research groups started to study artificial muscles. The most common used muscles are fluidic muscles like the well known McKibben muscle. But there are still only few robots actuated with such muscles and the interest in control theory for such systems is decreasing. The major problem is that the control of these actuators is much more complicated than the control of electrical motors, (e.g. the need for two antagonistic muscles for each joint). Due to the compressed air it is hardly possible to build autonomous robots. A different problem is that nearly every robotic control algorithm was designed for electrical motor as actuator using classical control methods and the mechanical set-ups are also designed for electrical motors. Another problem is the strongly nonlinear properties of the muscles.
In all cases of use of fluidic muscles as actuator control is a big issue because of the elastic behaviour of these muscles [2, 3, 4]. Nevertheless in future 'soft' actuators are needed for robots which interact with humans or in human environments.

At the moment fluidic muscles have been used at the University of Karlsruhe for walking research with the sixed legged robot AirBug [6] and the test-leg for the four legged mammal like robot PANTER (Fig. 1) [7]. Right now, only joint-controller are used for walking instead of controller for the whole legs.

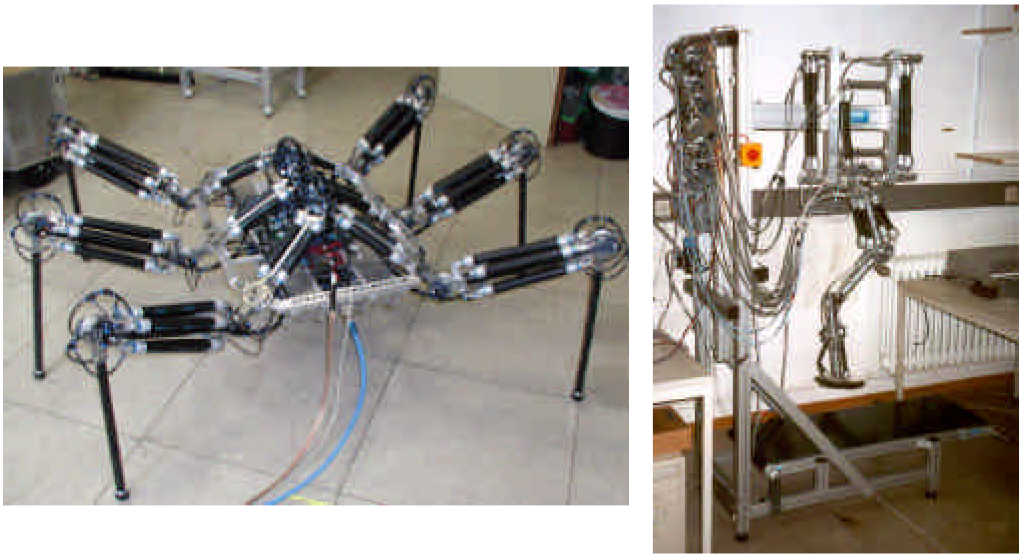

Fig. 1. (left) Six legged robot AirBug driven by fluidic muscles, (right) Test-Leg for the quadruped running PANTER-robot

Different assumption can be defined for leg-joints for walking-machines due to the fact, that walking is a cyclic motion. There are two different walking-phases the power phase and the return phase. During power phase the leg holds and pulls the robot. There may be interacting forces between the legs with ground contact and large disturbance torques. During the return phase the leg to perform a fast motion from the last point of the past power phase to the first point of the next power phase.
The desired walking behaviour makes great demands on joint-controllers for walking machines. Due to this the software tool EICASLAB [1] was used to find and test joint-controller. With the help of EICASLAB it is possible to use automated algorithm and code generation. For the set up of the controller and for modelling the control problem in simulation it is necessary to have an accurate model of the joint which should be controlled.

2 Fine model of a joint driven by fluidic muscles

The fine model of a general test-rig for elastic joints (see Fig. 2) is introduced, so that the found controller can be easily adapted to an elastic actuated robot joint.
To find the equation of motion for the joint the Euler-equation is used:

$$J \cdot \ddot{\varphi} = -r \cdot F_{MusA}(\kappa_A, \dot{\kappa}, p_A) + r \cdot F_{MusB}(\kappa_B, \dot{\kappa}, p_B) - \cos(\varphi - \varphi_0) \cdot \frac{1}{2} \cdot F_g + f_s \cdot l \qquad (1)$$

with joint inertia J, muscle forces $F_{MusA,B}$, muscle pressures $p_{A,B}$, muscle contractions $\kappa_{A,B}$, gravitation force F_g, angle between inertial position and horizontal plan φ_0, length of the joint

l and disturbance force F_s (assumed that it is always orthogonal to the joint). φ should be equal zero for the joint position where both muscle have the same contraction length.

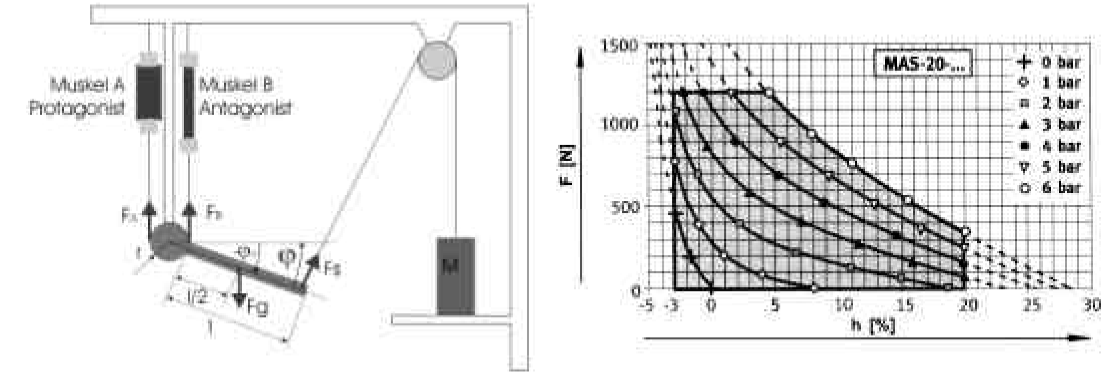

Fig. 2. (left) Schematic joint driven by pneumatic msucles. (right) Static correlation between force, pressure and contraction [5].

There is a linear correlation between the joint angle and the contraction of the muscle if the tendons between muscle and joint are tensed, so the contraction can be calculated with the help of the joint-angle:

$$\kappa_A(\varphi) = \frac{r}{l_{A0}}(\varphi_{A0} - \varphi), \quad \kappa_B(\varphi) = \frac{r}{l_{B0}}(\varphi - \varphi_{B0}) \tag{2}$$

$\varphi_{A0,B0}$ are the joint angles where the muscle have there initial length l_0.

2.1 Equation for force and pressure of the muscle

The fluidic muscle can be modelled as a spring and a parallel damper. The force of the muscle F_{Mus} is correlated with the relative muscle pressure p, the contraction k and the derivative of the contraction $\dot{k}$ of the muscle (see Fig. 2).

$$F_{Mus}(\kappa, \dot{\kappa}, p) = F_{spring}(\kappa, p) + F_{damper}(\dot{\kappa}, p). \tag{3}$$

with

$$\begin{aligned} F_{damper}(\dot{\kappa}, p) &= -C_D \cdot (p + P_n) \cdot \dot{\kappa} \\ F_{spring}(p, \kappa) &= \mu \cdot (\pi \cdot r_0^2) \cdot p \cdot (a \cdot (1 - (a_\varepsilon \cdot e^{-p} + b_\varepsilon) \cdot \kappa)^2 - b) + \sigma(-\kappa) \cdot (-f_0) \cdot \kappa \end{aligned} \tag{4}$$

The different parameters of the equations are the damping coefficient C_D, absolute ambient pressure P_N, correction value μ, muscle radius r_0, geometric muscle parameter a, b, muscle force correction parameter a_ε, b_ε and the correction parameter f_0 for $p = 0$.

The pressure in the muscle can be calculated by the following equations:

$$P_{Mus} = P_N \cdot \frac{V_{air}}{V_{Mus}} \quad \Rightarrow \quad \dot{P}_{Mus} = P_N \cdot \left(\frac{\dot{V}_{air}}{V_{Mus}} - V_{air} \cdot \frac{\dot{V}_{Mus}}{V_{Mus}^{\ 2}} \right) \tag{5}$$

$\dot{V}_{air}$ can be found with the help of the Bernoulli-equation:

$$\dot{V}_{air} = f_V \cdot C_a \cdot A_V \cdot \sqrt{(P_0 - P)}. \quad (6)$$

Two cases must be distinguished:

- Filling: $f_V = 1$, $P_0 =$ absolute pressure of the gas storage, $P = P_{Mus}$.
- Emptying: $f_V = -1$, $P_0 = P_{Mus}$, $P = P_N$.

C_a is an aerodynamic correction factor. The area of the valve A_V is proportional to the airflow to the muscle. The Muscle volume V_{Mus} is correlated with the contraction of the muscle and the initial muscle length l_0. It can be approximated by:

$$V_{Mus}(\kappa) = a(l_0)\cdot\kappa + b(l_0) \quad \Rightarrow \quad \dot{V}_{Mus}(\dot{\kappa}) = a(l_0)\cdot\dot{\kappa} \quad (7)$$

The amount of air volume in the muscle under normal pressure can be calculated by:

$$V_{air} = V_{Mus}(\kappa)\cdot\frac{P_{Mus}}{P_N} \quad (8)$$

The differential equation resulting for the muscle-pressure is:

$$\dot{P}_{Mus} = P_N \frac{f_V \cdot C_a \cdot A_V \cdot \sqrt{(P_0 - P)}}{V_{Mus}} - P_{Mus}\cdot\frac{\dot{V}_{Mus}(\dot{\kappa})}{V_{Mus}(\kappa)}. \quad (9)$$

2.2 Model for High-speed switching valve

The switching valves used to control the muscle pressure have three possible states:

1. closed: no airflow;
2. opened for filling: max. opening area for airflow into the muscle;
3. opened for emptying: max. opening area for airflow out of the muscle.

The valves operate with pulse width modulation (PWM). For a given input u the valve activation can be calculated:

$$A_V = \mathrm{sign}(u)\cdot \mathrm{rect}\left(t, \frac{|u|}{u_{max}}\right). \quad (10)$$

u_{max} is the biggest possible input and

$$\mathrm{rect}(t,e) = \begin{cases} \dot{V}_{max} & \text{for } k\cdot T_{PWM} \le t < (k+e)\cdot T_{PWM} \\ 0 & \text{for } (k+e)\cdot T_{PWM} \le t < (k+1)\cdot T_{PWM} \end{cases} \quad (11)$$

with $0 \le e \le 1$, the pulswidth T_{PWM}, $k = \mathrm{floor}\left(\frac{t}{T_{PWM}}\right)$.

2.3 State equation

For the description of the whole dynamics the state equation for nonlinear systems is used. State variables are: $x_1 = p_A$, $x_2 = p_B$, $x_3 = \varphi$ and $x_4 = \dot{\varphi}$. The input variables are $u_1 = A_{VA}$ (opening area valve A) and $u_2 = A_{VB}$ (opening area valve B). The following state equation (shown only for the case of filling the muscle) ($\overline{\varphi}_0 = \varphi_{A0} = \varphi_{B0}$) is found:

$$\underline{\dot{x}} = \begin{pmatrix} P_N \dfrac{f_V \cdot C_a \cdot u_1 \cdot \sqrt{(P_C - x_1)}}{V_{MusA}\left(\dfrac{r}{l_0}\cdot(\overline{\varphi}_0 - x_3)\right)} - x_1 \cdot \dfrac{\dot{V}_{MusA}\left(-\dfrac{r}{l_0}\cdot x_4\right)}{V_{MusA}\left(\dfrac{r}{l_0}\cdot(\overline{\varphi}_0 - x_3)\right)} \\ P_N \dfrac{f_V \cdot C_a \cdot u_2 \cdot \sqrt{(P_C - x_2)}}{V_{MusB}\left(\dfrac{r}{l_0}\cdot(x_3 - \overline{\varphi}_0)\right)} - x_2 \cdot \dfrac{\dot{V}_{MusB}\left(\dfrac{r}{l_0}\cdot x_4\right)}{V_{MusB}\left(\dfrac{r}{l_0}\cdot(x_3 - \overline{\varphi}_0)\right)} \\ x_4 \\ \dfrac{1}{J}\cdot\left(-r\cdot F_{MusA}\left(\dfrac{r}{l_0}\cdot(\overline{\varphi}_0 - x_3), -\dfrac{r}{l_0}\cdot x_4, x_1\right) + r\cdot F_{MusB}\left(\dfrac{r}{l_0}\cdot(x_3 - \overline{\varphi}_0), \dfrac{r}{l_0}\cdot x_4, x_2\right) - \cos(x_3 - \varphi_0)\cdot\dfrac{l}{2}\cdot F_g\right) \end{pmatrix}$$

$$\underline{y} = \begin{pmatrix} x_3 & x_1 & x_2 \end{pmatrix}^T \qquad (12)$$

3. Simplified model of a joint driven by fluidic muscles

For the design of different controllers a linearization of the nonlinear-system was necessary. For this the working point $\underline{x}_{AP} = (3\text{bar}, 3\text{bar}, 0, 0)^T$ and the constant input variable $\underline{u} = (0,0)^T$ are used. One can also use the following simplified model for the muscle-force to receive a more linear behaviour:

$$F_{Mus}(p,\kappa) = c_1 \cdot p + c_2 \cdot \kappa + c_3 - c_d \cdot \dot{\kappa}. \qquad (13)$$

The parameters $c_1 = 193$, $c_2 = -50$ and $c_3 = 229$ were estimated with the help of the least-square-method. In the damping part of the muscle-force equation C_D was multiplied with the working point pressure 3 bar so we got $c_D = 6.9$.

The main linearization is done by a Taylor series at the working point. Finally the following linear state equation is found:

$$\underline{\dot{x}} = \begin{pmatrix} 0 & 0 & 0 & \mu_{A2} \\ 0 & 0 & 0 & \mu_{B2} \\ 0 & 0 & 0 & 1 \\ \mu_1 & \mu_2 & \mu_3 & \mu_4 \end{pmatrix} \cdot \underline{x} + \begin{pmatrix} \mu_{A1} & 0 \\ 0 & \mu_{B1} \\ 0 & 0 \\ 0 & 0 \end{pmatrix} \cdot \underline{u}. \qquad (14)$$

$$\underline{y} = \begin{pmatrix} 0 & 0 & 1 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{pmatrix} \cdot \underline{x} \qquad (15)$$

with $\mu_{A1} = \dfrac{P_N \cdot l_0 \cdot f_V \cdot C_a \cdot \sqrt{(P_C - x_{AP1})}}{a(l_0)\cdot r \cdot \overline{\varphi}_0 + b(l_0)\cdot l_0}$, $\mu_{B1} = \dfrac{P_N \cdot l_0 \cdot f_V \cdot C_a \cdot \sqrt{(P_C - x_{AP2})}}{b(l_0)\cdot l_0 - a(l_0)\cdot r \cdot \overline{\varphi}_0}$

$\mu_{A2} = \dfrac{x_{AP1}\cdot a(l_0)\cdot r}{a(l_0)\cdot r \cdot \overline{\varphi}_0 + b(l_0)\cdot l_0}$, $\mu_{B2} = -\dfrac{x_{AP2}\cdot a(l_0)\cdot r}{b(l_0)\cdot l_0 - a(l_0)\cdot r \cdot \overline{\varphi}_0}$

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

4. Modelling and control of the elastic joint using the EICAS-Lab software tool

The control design is carried out according to the EICAS methodology that allows guaranteeing the required performance in presence of disturbances and uncertainty in the plant.

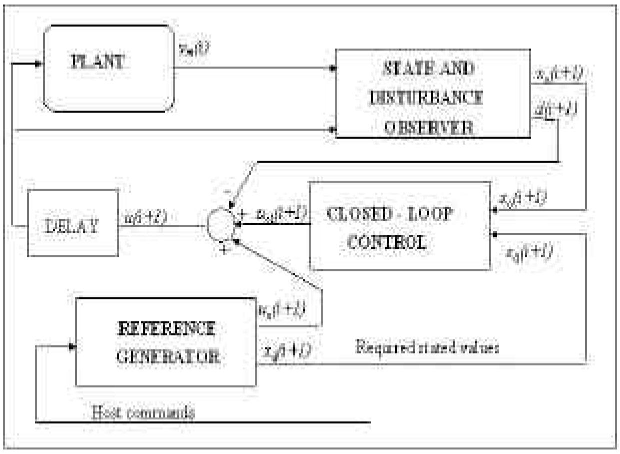

Fig. 3**.** Plant control design of the joint control using EICAS methodology

A feedback control is designed on the basis of the *"simplified model*", without considering the plant-model uncertainty. In order to get the best control performance, the plant control is typically designed according to the scheme of Fig. 3 including:

- the estimation of future equivalent additive disturbances acting on the plant inputs so that their effect can be directly compensated. This action is computed by means of the "state and disturbance observer", together with the estimation of the state values,
- an open loop control action, which is computed by means of the "reference generator", together with the required state values,
- the feedback state control, computed by the "closed-loop control".

Then the total command is composed of three contributes: the open loop command, the compensation of disturbances and the closed-loop command.

The plant control architecture related to PANTER test case is shown in Fig. 4, realised by means of EICASLAB.

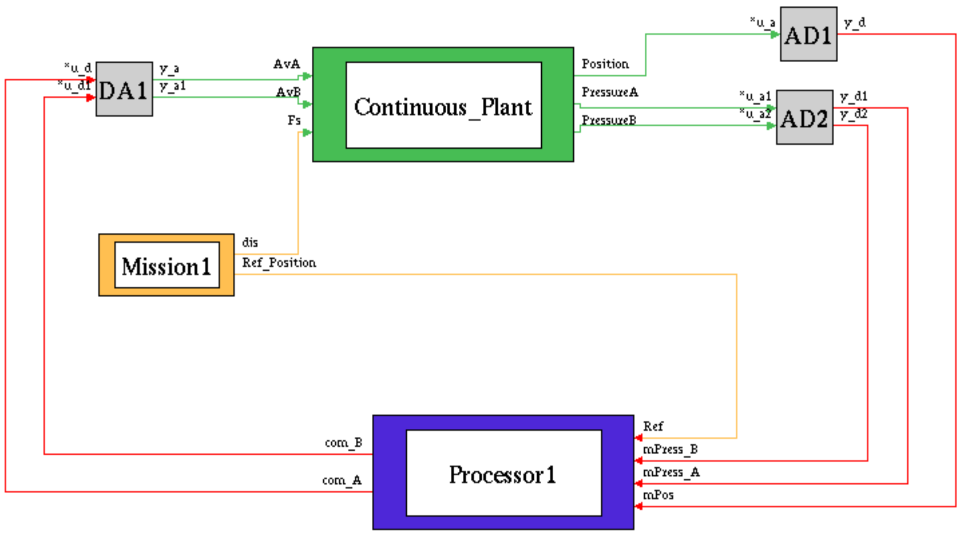

Fig. 4. Control design in EICASLAB for a compliant joint

The control realised for the compliant joint is a hierarchical control (see Fig. 5) composed of :

- one *position control*,
- two *pressure controls*.

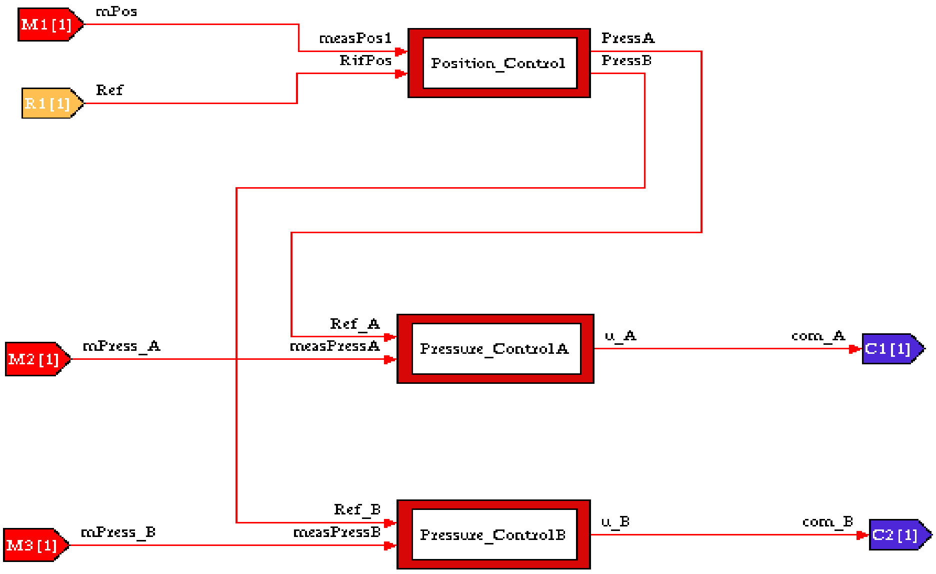

Fig. 5. Hierarchical Control for a compliant joint in EICASLAB

The *position control* has as input the measured position and the reference one and provides as output the reference pressures for the *pressure controls*, that compute the commands for the muscles.

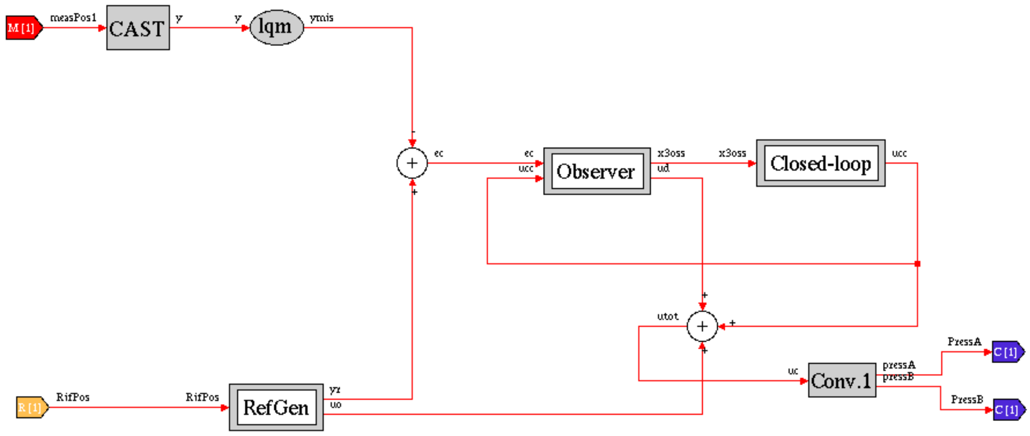

Fig. 6. Position Control for a compliant joint in EICASLAB

The position control and the pressure control structures are shown respectively in Fig. 6 and in Fig. 7.

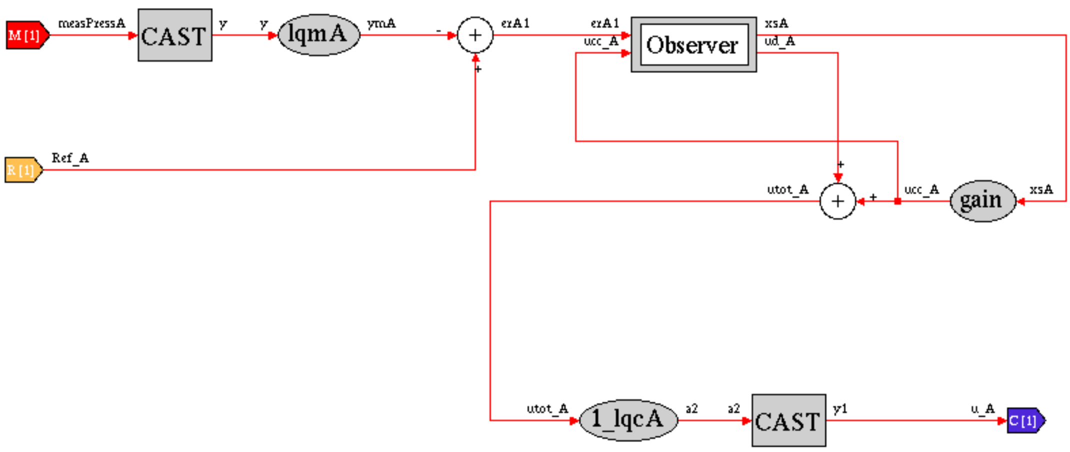

Fig. 7. Pressure Control for a compliant joint in EICASLAB

The control is tuned and its performance assessed by means of the EICASLAB simulator, where the fine model is used to simulate the plant. In this way the control immediately works well, without requiring set up in field. The simulation results are shown in Fig. 8.

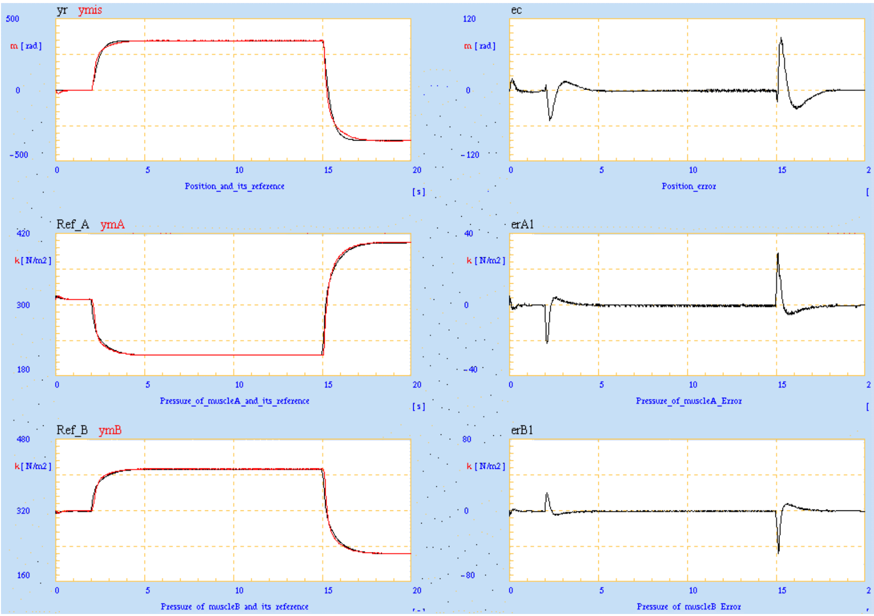

Fig. 8. Simulation results of the joint control using EICASLAB SIM

5 Conclusion and outlook

This paper presents the model and control of a joint driven by fluidic muscles. This control was implemented and simulated with the professional software tool named EICASLAB. For the implementation on the real robot PANTER the controller will be adapted for the microcontroller boards used to control the robot. This can be done also with the help of the EICASLAB software by using the automatic code generation function of the tool.

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References

1. G. Caporaletti, The ACODUASIS project – a professional software tool supporting the control design in robotics, In Proc. of the 6th International Conference on Climbing and Walking Robots (CLAWAR), 2003
2. S. Davis, D. Caldwell The bio-mimetic design of a robot primate using pneumatic muscle actuators, In Proc. of the 4th International Conference on Climbing and Walking Robots (CLAWAR), 2001
3. C.P. Chou, B. Hannaford Static and Dynamic Characteristics of McKibben Pneumatic Artificial Muscles, International Conference on Robotics and Automation, 1994, Vol. 1, 281-286

4. B. Tondu, P. Lopez Modeling and Control of McKibben Artificial Muscle Robot Actuators, IEEE Control Systems Magazine, April 2000, Vol. 20, 15-38
5. Produktkatalog 2001 -- Antriebe "http://www.festo.com"
6. K. Berns, V. Kepplin, R. Müller, M. Schmalenbach: Six-legged Robot Actuated by Fluidic Muscles. In Proc. of the 3th International Conference on Climbing and Walking Robots (CLAWAR), 2000
7. J. Albiez, T. Kerscher, F. Grimminger, U. Hochholdinger, R. Dillmann, K. Berns: PANTER - prototype for a fast-running quadruped robot with pneumatic muscles. In Proceedings of the 6th International Conference on Climbing and Walking Robots, 617-624, 2003.
8. F. Donati, M. Vallauri: Guaranteed control of almost- linear plants. IEEE Transactions on Automatic Control, vol. 29- AC, 1984, pp. 34-41
9. Website of the ACODUASIS-project funded by the European Community: http://www.fzi.de/acoduasis , June 2005.