Modeling and Control of a Seven Axes Hybrid Electric/Pneumatic Robot Arm

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Passively compliant drive concepts are often used in bio-inspired robot designs. Especially fluidic artificial muscles share many characteristics with their natural counterparts. Industrial manipulators can benefit from the increased robustness and safety (in contrast to rigid drives) especially in cooperative human/robot environments. We compare different model-based control concepts for a single rotational joint actuated by two fluidic muscles in combination with proportional valves. While the complete valve and muscle models are already included in this setup, the mechanical model becomes more complex when we extend the control to a full seven axes articulated robot arm with both, electrically and pneumatically actuated joints. In this case the Projection Equation in subsystem description is used for the multibody model, allowing a straight-forward realtime application to different robot kinematics. Remaining model errors and disturbances are handled by observer algorithms. We present measurement results and compare them to simulation outputs. Besides the position control, possible approaches for sensorless external force estimation are discussed. They take advantage of the compliance of the robot and are again based on the actuator and multibody models.

1 Pneumatic modeling and pressure control

The considered robot (see Figure 1) is mainly actuated by so-called pneumatic artificial muscles (PAM) [1] – fibre reenforced rubber tubes, which contract when filled with air. The static pulling muscle force F can be modeled by $F = a(h)\,p + b(h)$ [2], where p is the internal pressure, h the muscle contraction and $a(h)$ and $b(h)$ are polynomials used to approximate the nonlinear relation between the contraction and the force.

A pneumatic rotational joint is actuated by two antagonistically arranged PAMs 1 and 2. The contractions, $h_{1/2} = h_0 \pm r/l\,(q - q_0)\,100\,\%$, are both uniquely defined by the joint angle q and construction parameters (acting radius r, muscle length l, angle q_0, where both muscles have the same contraction h_0). The generated torque $Q = r\,(F_1 - F_2)$ is affine in the pressures and can be written as $Q = A(q)\,0.5\,(p_1 + p_2) + B(q)\,(p_1 - p_2) + C(q)$ with some functions A, B and C, which can be calculated from the single muscle characteristics or identified pointwise on the real system.

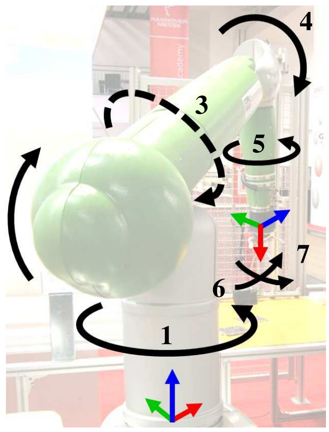

Fig. 1 The considered robot. Joints 1, 2, 4, 6 and 7 are actuated pneumatically. Joints 3 and 5 are driven by off the shelve brushless DC motors.

Figure 2 shows the comparison between the measured (thick line) and the nominal muscle model (thin line). A locally (only around $Q_1 = 0$) calibrated model (light line) has been added for reference. The validation maneuver used in this figure is a slow left/right movement, which means that the actual torque is always close to zero. Beside the differences in the models, a common hysteresis loop is visible in all three curves. This is not yet accounted for in our model and will be subject to further research.

The underlying control loop for the muscle pressures is flatness based (see, for example [3]) with the pressure dynamics $\dot{p}\,V + p\,\dot{V} = \dot{m}\,R_\mathrm{S}\,T$. The current muscle volume V depends only on the contraction and can therefore also be calculated from the joint angle. The absolute temperature T is assumed to be constant. R_S is the specific gas constant of air and $\dot{m}$ – the mass flow into or out of the muscle – our control variable, which can be adjusted by changing the voltage of the used proportional valves. To stabilize the error dynamics of the flat system a P feeback term is used.

2 Mechnical modeling and position control

Different control strategies were first evaluated on a single joint test rig with the simple equation of motion $J\,\ddot{q} - m\,g\,s\cos(q - q_0) + d\,\dot{q} = Q$ (moment of inertia J, mass m, gravitational constant g, center of gravity s, viscous friction constant d). As expected, the controller behavior clearly improved when model based feed forward and observer parts were added.

Therefore, a multibody dynamics model $\mathbf{M}(\mathbf{q})\,\ddot{\mathbf{q}} + \mathbf{h}(\mathbf{q}, \dot{\mathbf{q}}) = \mathbf{Q}$ for the complete robot was derived, based on the Projection Equation in subsytem formulation [4]. A rotating arm was used as the main subsystem with basically the same parameter set as

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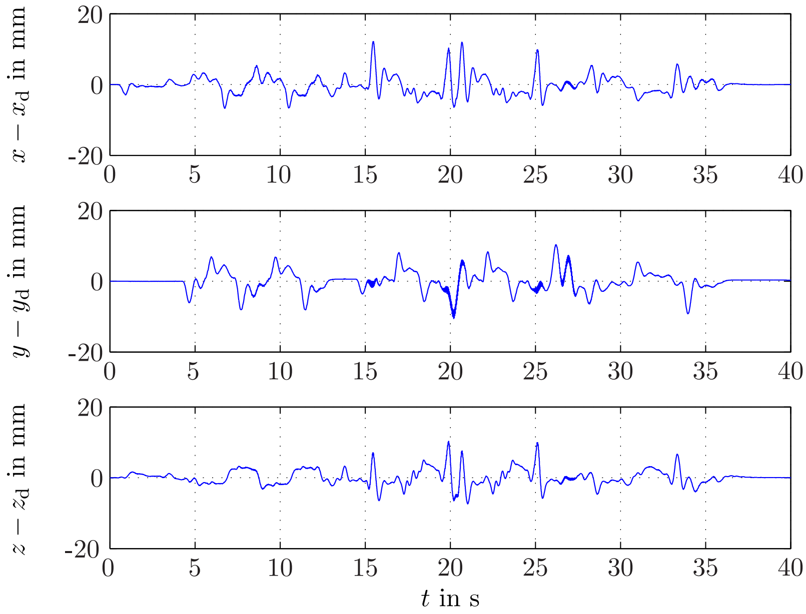

Fig. 3 Tracking errors in the three spacial directions for the considered test trajectory (see text for details).

used for the test rig model. The model has been implemented in a modular way and can be used for simulation of the forward dynamics as well as for calculating the inverse dynamics for real time control. All the controller algorithms are executed on a standard industrial PLC at a sample time of 0.5 ms. The subsystem parameters as well as the kinematical chain are configured in an XML file to allow an easy adaptation to different robots.

To compensate for model errors and parameter uncertainties, a disturbance torque observer with design parameter $K_{\mathrm{O},i}$,

$$\hat{Q}_{\mathrm{dis},i} = K_{\mathrm{O},i} \int \left(\left[\mathbf{M}(\mathbf{q})\,\hat{\ddot{\mathbf{q}}} + \mathbf{h}(\mathbf{q},\hat{\dot{\mathbf{q}}}) - \mathbf{Q} \right]_i - \hat{Q}_{\mathrm{dis},i} \right),$$

was used for each joint i. The vector $\mathbf{Q}$ contains the nominal torques calculated from the pressure and position sensor data while $\hat{\mathbf{Q}}_{\mathrm{dis}}$ are the observed disturbance torques. The estimates for the joint velocities, $\hat{\dot{\mathbf{q}}}$, and accelerations, $\hat{\ddot{\mathbf{q}}}$, are derived from the 17 Bit absolute optical encoders.

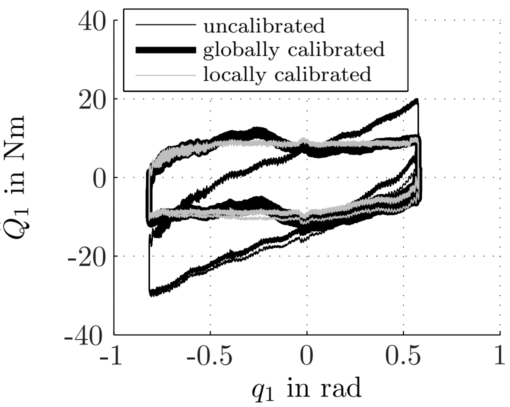

Fig. 2 Evaluation of different joint actuation models (see text for details).

3 Experiments and measurement results

To evaluate the controller performance, a test trajectory based on the ISO norm 9283 (a combination of circles, smoothened rectangles and lines in space) was chosen for the x, y and z coordinates of the tool center point ($v_{\max} = 0.5\,\mathrm{m/s}$). The three main joints (1, 2 and 4) were used in this first evaluation. The resulting tracking errors are displayed in Figure 3. They are in line with the expected values from the single joint test rig experiments. The errors are about 20 times higher than the ones reached on the output side of a six axes standard industrial robot (Stäubli RX130L) in our lab.

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References

[1] F. Daerden and D. Lefeber Pneumatic artificial muscles: Actuators for robotics and automation, in: European journal of mechanical and environmental engineering **47**, 11–21 (2002).

[2] M. Kastner, H. Gattringer, H. Bremer, M. Ramsauer, and P. Ferrara, Interaction of a flexible robot with its environment, in: ICINCO (1)'10, (2010), pp. 230–233.

[3] D. Schindele and H. Aschemann, Backstepping control of a high-speed linear axis driven by pneumatic muscles, in: Proceedings of the 17th World Congress The International Federation of Automatic Control, (2008).

[4] H. Bremer, Elastic Multibody Dynamics: A Direct Ritz Approach (Springer-Verlag GmbH, 2008).