This document serves as supplementary to the paper titled 'Decoupled and Closed-loop Control of Position and Stiffness for Articulated Soft Robots driven by a Class of Electromechanical Variable Stiffness Actuators'.

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I. Experimental results for a three-degree-of-freedom articulated soft robot

To validate the control approach on a multi-DoF setup, we mounted an additional link to the robotic setup, thus adding a degree of freedom to the previous robot such that the total number of degrees of freedom is equal to three, as shown in Fig. 1.

Again, the position and stiffness were commanded to follow the sinusoidal references. The trajectories are described as $q_{i,d} = \epsilon_{q_i} + A_{q_i} \sin \omega_{q_i} t$ and $\sigma_{i,d} = \epsilon_{\sigma_i} + A_{\sigma_i} \sin \omega_{\sigma_i} t$, for $i \in \{1, 2, 3\}$, where $\epsilon_{q_1} = 0.15$, $\epsilon_{q_2} = -0.3$, $\epsilon_{q_3} = 0.6$, $A_{q_1} = 0.1$, $A_{q_2} = 0.15$, $A_{q_3} = 0.15$, $\omega_{q_1} = \pi/15$, $\omega_{q_2} = \pi/7$, $\omega_{q_3} = \pi/7$, $\epsilon_{\sigma_1} = 11$, $\epsilon_{\sigma_2} = 10$, $\epsilon_{\sigma_3} = 7$, $A_{\sigma_1} = 1$, $A_{\sigma_2} = 1$, $A_{\sigma_3} = 2$, $\omega_{\sigma_1} = \pi/10$, $\omega_{\sigma_2} = \pi/8$, and $\omega_{\sigma_3} = \pi/8$.

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Intentionally, stiffness of the first two joints is set to a higher value such that these actuator are capable of supporting the robot structure. The corresponding control gains are $K_q \Lambda = \text{diag}_i \{4.9\}$, $K_q + \Lambda = \text{diag}_i \{0.7\}$, $K_\sigma = \text{diag}_i \{10\}$, $K_i = \text{diag}_i \{20\}$, $K_\pi = \text{diag}_i \{10\}$ and $\Delta = \text{diag}_i \{105\}$.

Figure 2 reports that the resulting positions and stiffness of all three joints converge to the desired trajectories, while the estimated parameters converge to the constant values. The figure also presents the commanded and achieved motor positions, as well as the corresponding tracking errors, which demonstrate smoothness of the input signals.

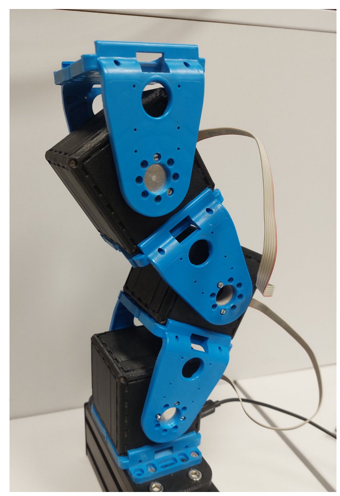

Fig. 1. A three degrees-of-freedom hardware setup used for the validation.

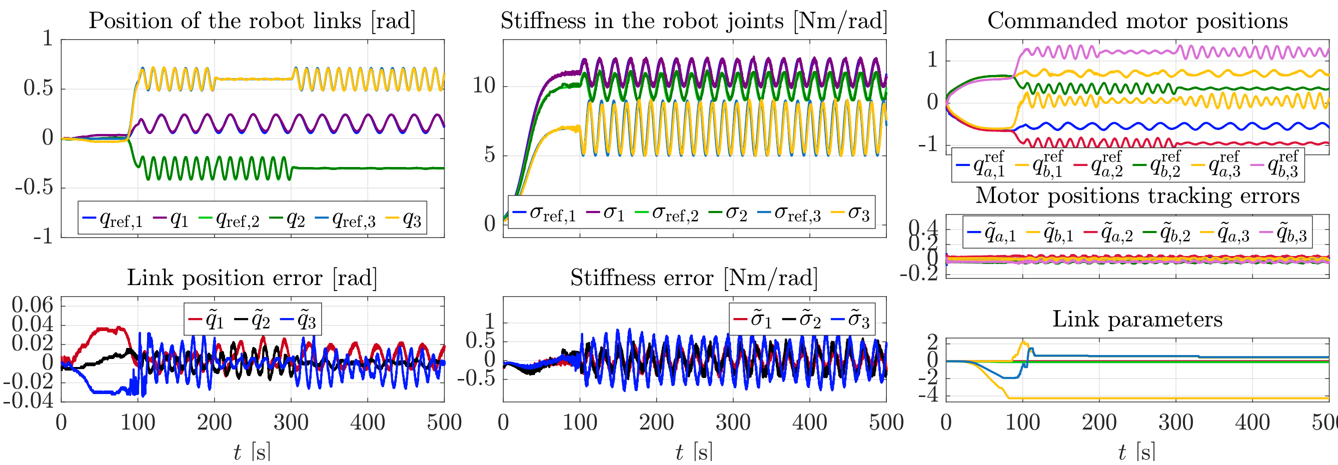

Fig. 2. The experiment on a three-DOF electromechanical articulated soft robot by using nonlinear adaptive control. All joint positions and joint stiffnesses are tracked accurately, while the parameters converge to constant values and the commanded motor positions have smooth behavior. The decoupling effect can again be observed in the leftmost figure, since the link positions remain constant despite the change of joint stiffness and other links position.