Elastic Structure Preserving Control for a Structurally Elastic Robot

Alexander Kitzinger[1], Hubert Gattringer[1] and Andreas Müller[1]

***Abstract*— Elastic lightweight manipulators offer multiple benefits but come at the cost of increased structural flexibility, making the system more susceptible to vibrations. These circumstances require control concepts with a special focus on vibration suppression. Based on an lumped element model formulation, a control method called elastic structure preserving control is used for additional damping injection, while using standard motor PD control, to ensure low tracking error of the flexible link robot's end effector. As a first proof of concept for the used structural elastic robot the method is only applied for the first degree of freedom. The results obtained are further compared to a flatness-based control approach utilizing exact feed forward linearization and full state feedback control. Both methods are tested using cost-effective IMU measurements for feedback control, in addition to the motor measurements. The outcome demonstrates that, based on the evaluated angular accelerations, both methods achieve comparatively effective vibration damping relative to standard motor PD control.**

Keywords: elastic structure preserving control, flatness-based control, elastic robot, lumped element model

I. INTRODUCTION

Elastic lightweight robots, such as the one shown in Fig. 1, are characterized by an improved payload-to-manipulator weight ratio, resulting in advantages like lower manufacturing costs, reduced energy consumption, and space-efficient usability. Additionally, their advantageous dynamic properties enable high speed manipulations, which are crucial for industrial applications. Nevertheless, high jerk inputs and external disturbances lead to non-desirable TCP oscillations, resulting in intolerable position errors and settling times. To tackle this challenges [1] presents a flatness-based trajectory control method, emphasizing the use of IMU sensors for vibration suppression. The aim of this work is to evaluate the feasibility and performance of elastic structure preserving (ESP) control introduced in [2] and benefit from its advantages, potentially also for structurally elastic robots. In doing so, an easily comprehensible controller parameterization is expected to enhance the damping characteristics of the considered flexible link manipulator. However, due to the limiting factors of the robot setup, a positive result is not guaranteed. Crucial aspects include the distinctive multiple oscillatory modes of the flexible links, bus delay times caused by the centralized ESP control scheme and noise and uncertainties introduced by the low-cost accelerometer and gyroscope measurements.

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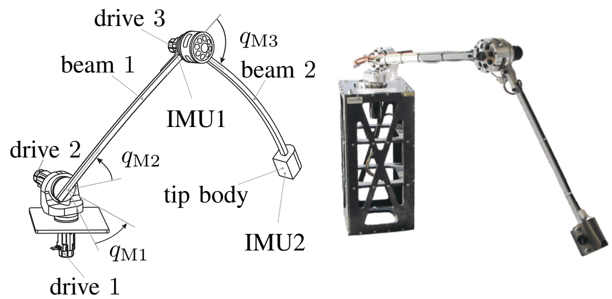

Fig. 1: Sketch and photo of considered elastic robot

II. MODELING

The foundation of the model-based control builds a lumped element model using virtual springs to represent the three elastic harmonic drive gears and two flexible beams. The formulation of the equations of motion (EoM) for the underactuated mechanical system is based on [3] and given by

$$\mathbf{M}_{\mathrm{M}}\ddot{\mathbf{q}}_{\mathrm{M}} + \mathbf{Q}_{\mathrm{R}}(\dot{\mathbf{q}}_{\mathrm{M}}) + \mathbf{K}(\mathbf{q}_{\mathrm{M}} - \mathbf{q}_{\mathrm{A}}) = \mathbf{Q}_{\mathrm{M}} \quad (1)$$

$$\mathbf{M}_{\mathrm{A}}(\mathbf{q}_{\mathrm{A}})\ddot{\mathbf{q}}_{\mathrm{A}} + \mathbf{g}_{\mathrm{A}}(\mathbf{q}_{\mathrm{A}}, \dot{\mathbf{q}}_{\mathrm{A}}) + \mathbf{K}(\mathbf{q}_{\mathrm{A}} - \mathbf{q}_{\mathrm{M}}) = \mathbf{0} \quad (2)$$

using the minimal coordinates of the three motor $\mathbf{q}_{\mathrm{M}}$ and their corresponding arm angles $\mathbf{q}_{\mathrm{A}}$. The positive definite, symmetric mass matrices $\mathbf{M}_{\mathrm{M}}$ and $\mathbf{M}_{\mathrm{A}}$ include the motor and arm inertia, whereas vector $\mathbf{g}_{\mathrm{A}}$ describes the nonlinear gravitational, Coriolis and centrifugal forces of the links. Coupling between the actuated motor and under-actuated arm equation is represented by the diagonal and positive definite linear stiffness matrix $\mathbf{K}$. The vector $\mathbf{Q}_{\mathrm{R}}$ contains considered viscous and Coulomb friction forces, while $\mathbf{Q}_{\mathrm{M}}$ is the vector of the generalized motor driving torques.

III. CONTROL

According to [2] the control goal for the elastic robot is to derive a structure preserving state transformation that transforms the under-actuated system (1)–(2) into the quasi-full actuated closed loop form

$$\mathbf{M}_{\mathrm{M}}\ddot{\tilde{\mathbf{q}}}_{\mathrm{M}} + \mathbf{K}(\tilde{\mathbf{q}}_{\mathrm{M}} - \tilde{\mathbf{q}}_{\mathrm{A}}) = \tilde{\mathbf{Q}}_{\mathrm{M}} \quad (3)$$

$$\mathbf{M}_{\mathrm{A}}(\tilde{\mathbf{q}}_{\mathrm{A}})\ddot{\tilde{\mathbf{q}}}_{\mathrm{A}} + \tilde{\mathbf{g}}_{\mathrm{A}}(\tilde{\mathbf{q}}_{\mathrm{A}}, \dot{\tilde{\mathbf{q}}}_{\mathrm{A}}) + \mathbf{K}(\tilde{\mathbf{q}}_{\mathrm{A}} - \tilde{\mathbf{q}}_{\mathrm{M}}) = -\mathbf{D}\dot{\tilde{\mathbf{q}}}_{\mathrm{A}} \quad (4)$$

where the adjustable positive definite diagonal-matrix $\mathbf{D}$ injects damping according to the new coordinates $\tilde{\mathbf{q}}^T = (\tilde{\mathbf{q}}_{\mathrm{M}}^T, \tilde{\mathbf{q}}_{\mathrm{A}}^T)$ and input $\tilde{\mathbf{Q}}_{\mathrm{M}}$. The new arm coordinates correspond to the motion error of the arm angles $\tilde{\mathbf{q}}_{\mathrm{A}}^T = \mathbf{q}_{\mathrm{A}} - \mathbf{q}_{\mathrm{A,d}}$ and the new motor coordinates $\tilde{\mathbf{q}}_{\mathrm{M}}^T$ reflect the desired damping and tracking behavior. The transformation to the

https://doi.org/10.34749/3061-0710.2025.21

closed loop form (3)–(4) does not cause dynamical shaping of the inertial properties and is preserving the initial stiffness $\mathbf{K}$ of the links. The gravitational and friction terms are compensated, while the Coriolis terms remain.

For a proof of concept, only the first degree of freedom $q_{\mathrm{A}} = q_{\mathrm{A},1}$ will be considered, using stationary angles of $q_{\mathrm{A},2} = q_{\mathrm{A},3} = 0$ for the remaining arm and corresponding motor coordinates. Therefore, the control law simplifies drastically as the gravitation, centrifugal and Coriolis terms vanish. Equating (2) and (4) yields the state transformation for the motor coordinate

$$\tilde{q}_{\mathrm{M}} = q_{\mathrm{M}} - \underbrace{\left(q_{\mathrm{A,d}} - K^{-1} D \dot{\tilde{q}}_{\mathrm{A}} + K^{-1} M_{\mathrm{A}} \ddot{q}_{\mathrm{A,d}}\right)}_{q_{\mathrm{M,d}}}. \qquad (5)$$

The corresponding input transformation, obtained by equating (1) and (3), characterizes the control law without friction compensation for the applied motor torque

$$Q_{\mathrm{M}} = \tilde{Q}_{\mathrm{M}} \underbrace{- D \dot{\tilde{q}}_{\mathrm{A}} - M_{\mathrm{M}} K^{-1} D \tilde{q}_{\mathrm{A}}^{(3)}}_{Q_{\mathrm{da}}} + \qquad (6)$$

$$\underbrace{(M_{\mathrm{M}} + M_{\mathrm{A}}) \ddot{q}_{\mathrm{A,d}} + M_{\mathrm{M}} K^{-1} M_{\mathrm{A}} q_{\mathrm{A,d}}^{(4)}}_{Q_{\mathrm{ff}}}$$

and using cascaded motor PD control (servo drive) in the new coordinates

$$\tilde{Q}_{\mathrm{M}} = -K_{\mathrm{D}} (K_{\mathrm{P}} \tilde{q}_{\mathrm{M}} + \dot{\tilde{q}}_{\mathrm{M}}) \qquad (7)$$

The i-th time derivative is denoted by $\tilde{q}_{\mathrm{A}}^{(i)}$. The adjustable control parameters are K_{P}, K_{D} and the link-side damping factor D. Based on the desired motor position $q_{\mathrm{M,d}}$, the feed forward Q_{ff} and damping torque Q_{da} the control law is implemented on the elastic robot using a cycle time of $400\,\mu\mathrm{s}$ and the setup shown in Fig. 2.

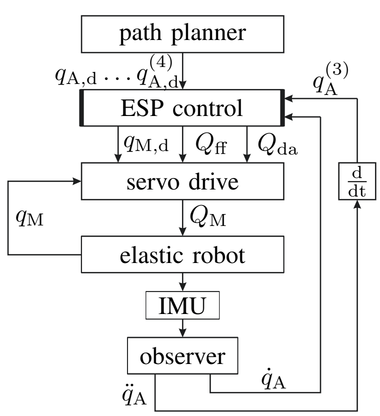

Fig. 2: Control Scheme

IV. Results

The control method is tested using a required fourfold continuously differentiable $\sin^2$ trajectory with angular motion from $-45\,\mathrm{deg}$ to $45\,\mathrm{deg}$. The joint limitations are: maximum velocity $1.25\,\mathrm{rad/s}$, maximum acceleration $15.6\,\mathrm{rad/s^2}$ and maximum jerk $195.3\,\mathrm{rad/s^3}$.

The result in Fig. 3 shows that ESP control achieves significantly better tracking performance than simple PD motor joint control (same servo drive parameters), preventing the robot arm from overshooting oscillations as indicated by the angular accelerations $\ddot{q}_{\mathrm{A}}$. After the trajectory, residual vibrations remain which result from model uncertainties, static friction and coupled in vibrations in other directions of motion that are not actively controlled. The vibration suppression and motor torque Q_{M} is comparable to the results obtained using the flatness-based approach from [1]. However, ESP control has the advantage that TCP damping can be easily varied and adjusted intuitively, making it particularly interesting for further investigations.

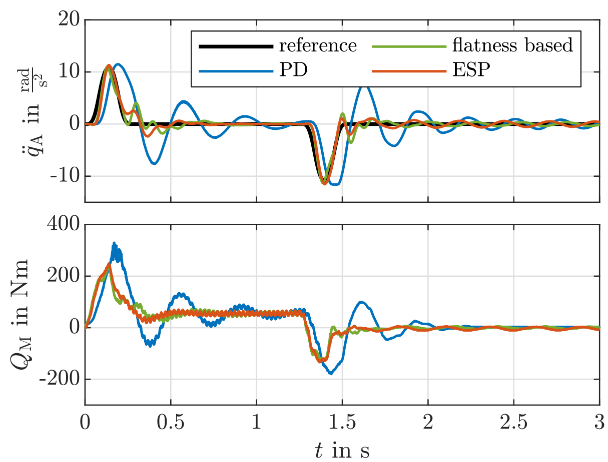

Fig. 3: Comparison of the tested control methods

V. Conclusion

This initial test demonstrates that elastic structure-preserving control can also be beneficial for structural elastic robots using IMU measurements. Nevertheless, the next step should involve extended research implementing the control method in combination with a suitable real-time observer including all three DOF of the elastic robot. Furthermore, a time-optimal application as outlined in [4] is desirable.

ACKNOWLEDGMENT

This work has been supported by the “LCM – K2 Center for Symbiotic Mechatronics” within the framework of the Austrian COMET-K2 program.

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https://doi.org/10.34749/3061-0710.2025.21