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Friction Compensation and Stiffness Evaluation on a Variable Torsion Stiffness

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1 Introduction

With safety aspects due to closer human-robot interaction and increased requirements in energy effiency due to mobile applications, series elastic joint concepts receive high priority in contemporary robotics. Beyond making robots more safe and flexbile, such concepts can store energy and thus optimize the energetic efficiency of the robot's motion. Therefore adjusting the stiffness is advantageous, since the natural frequency of the drive train and the frequency of the desired trajectory can be matched [1, 2].

2 State of the Art

Introduced in the 1990s, the Series Elastic Actuator (SEA) [1] and the Mechanical Impedance Adjuster (MIA) [3] pathed the way for series elastic actuation and variable compliance in robotic joints. The majority of concepts developed since then can be categorized in four groups considering the principle of stiffness variation [4]. Those are equilibrium-controlled, antagonistic-controlled, structure-controlled and mechanically controlled stiffness. As the original SEA changes the equilibrium position of a spring, it belongs to the first group. Antagonistic-controlled approaches utilize actuators working against each other as in AMASC [5]. Although both groups allow for stiffness variation, energy is dissipated during operation in both: The equilibrium-controlled solutions require power to simulate a virtual spring while the actuators work against each other in the antagonistically-controlled ones. Thus, many contemporary variable stiffness designs belong to structure-controlled and mechanically controlled solutions. Strucutre-controlled devices change stiffness by a modification of an elastic element's structure as in MIA. Mechanically controlled ones like MACCEPA [2] adjust the system stiffness by pretension.

3 Concept and Implementation

The authors' approach based on variable torsion stiffness (VTS) aims at biomechanically inspired robotic joints [6]. As described there and shown in Figure 1, actuator 1 applies an input torque τ_i to the torsional elastic element to move the link. For the the adjustment of the torsional stiffness $k_{vts}(x)$, the active length x of an torsional elastic element is varied by changing the position of counter bear-

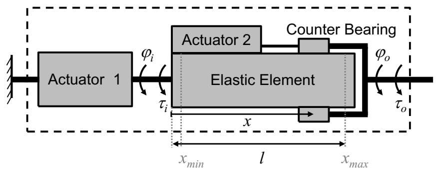

Figure 1: Concept of variable torsion stiffness [6]

ing using actuator 2. Hence, this concept belongs to the structure-controlled group. Since the joint driving and the stiffness control actuator are seperated, the adjustment of the stiffness does not depend on the joint position. For the im-

Figure 2: Implementation of the elastic element

plementation of the elastic element, a hollow cylinder with outer radius $R = 11.0\,\text{mm}$ and inner radiues $r = 8.7\,\text{mm}$ and a length of $l = 0.16\,\text{m}$ is chosen due to [6]. The realized version manufactured from polyamide is presented in Figure 2. A flange on the left connects the element to actuator 1, while six evenly distributed fitting rails are used to transmit the torque from the tube to the output side. Due to the deviations in material and geometry compared to the ideal cylinder proposed in [6], the stiffness characteristics might not fit perfectly the requirements given there. Thus, the influence of those deviations is investigated experimentally in this paper. To realize the experimental evaluation

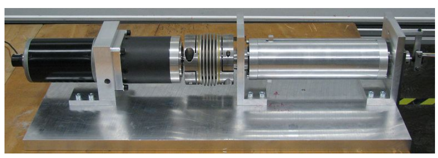

Figure 3: Test rig for experimental investigations

of the stiffness characteristics, a friction compensation is realized. As most of the friction is due to the motor-gear unit, only this is investigated. In the experiment, the motor torque is increased linearly from 0 Nm to ± 10 Nm. Figure 4

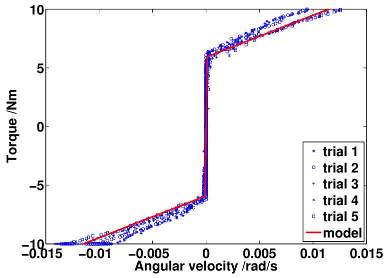

Figure 4: Friction characteristics and model

shows the data measured in 5 trials for each direction and the model fitted with least squares regression. With this, the friction torque is compensated by feedforward control of the model $\tau_f = 5.9\,\mathrm{Nm}\, sign(\dot{\varphi}_i) + 357.1\,\mathrm{Nms/rad}\,\dot{\varphi}_i$.

4 Stiffness Characteristics

The stiffness characteristics of the element are investigated in a static experiment. Therefore, the active length x of the elastic element is set to values between 0.011 m and 0.151 m in steps of 0.02 m and a final step at $x = 0.166$ m. As these settings should refer to different stiffness values, the pendulum is positioned at specific angles statically and the input and output angles are measured. Further, the torque τ_g resulting from gravity is determined. With the models given in [6], the stiffness k_{vts} at a specific length x can be determined by

$$k_{vts} = \frac{\tau_g}{\varphi_i - \varphi_o}, \qquad (1)$$

and is parameterized by a least squares regression. The stiffness characteristics determined in this experiments are shown in Figure 5. It becomes distinct that the stiffness

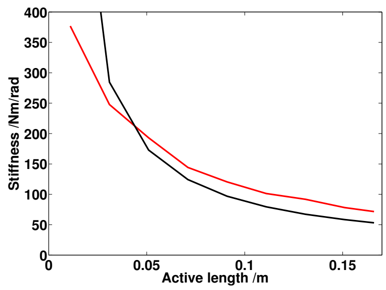

Figure 5: Experimentally determined stiffness characteristics

determined in the experiment on the test rig plotted in red shows higher values than expected from the analytical model plotted in red. Only for an active length below $x = 0.04$ m the analytical solution exceeds the experimentally obtained results. This is due to the reason, that the analytical solution converges to infinity, while the real system is contrained to finite stiffness. The increased stiffness of the experimental measurement is caused by the implementation, as the fitting rails reinforce the elements structure.

5 Discussion and Conclusion

Regarding the friction characteristics, the influence of static friction (5.9 Nm) is higher than the one of gravity (4.1 Nm for $\varphi_o = 10°$) and has to compensated. Further, a confirmation of the friction compesation in the complete test rig should be performed before testing in dynamic scenarios. For the stiffness characteristics, the evaluation shows that the implemented elastic elements has comparable behaviour as the analytical model predicts. Anyhow, the real element geometry should be considered during design to achieve a better consistency - e.g., by finite element simulation.

6 Format

Oral presentation and hardware demo are preferred.

7 Open Questions

One open questions for future research is the investigation of alternative design of the elastic element. Further, the structural integrity of the elastic element is a key issue due to the high loads and stresses that can be expected during dynamic operation. As for the current implementation stiffness control is performed manually, an appropriate actuation is to be determined for a complete realization of the concept.

References

[1] G. A. Pratt and M. M. Williamson, "Series elastic actuators," in *Proceedings of the 1995 IEEE/RSJ International Conference on Intelligent Robots and Systems*, 1995.

[2] B. Vanderborght et al., "Comparison of Mechanical Design and Energy Consumption of Adaptable, Passive-compliant Actuators," *The International Journal of Robotics Research*, vol. 28, pp. 90–103, 2009.

[3] T. Morita and S. Sugano, "Design and development of a new robot joint using a mechanical impedance adjuster," in *1995 IEEE International Conference on Robotics and Automation*, 1995.

[4] R. Van Ham et al., "Compliant Actuator Designs Review of Actuators with Passive Adjustable Compliance/Controllable Stiffness for Robotic Applications," *IEEE Robotics & Automation Magazine*, vol. 16, pp. 81–94, 2009.

[5] J. W. Hurst et al., "An actuator with physically variable stiffness for highly dynamic legged locomotion," in *2004 IEEE International Conference on Robotics and Automation*, 2004.

[6] J. Schuy et al., "Conception and Evaluation of a Novel Variable Torsion Stiffness for Biomechanical Applications," *in IEEE International Conference on Biomedical Robotics and Biomechatronics*, 2012.