# Design, Modeling and Control of a Variable Stiffness Elbow Joint

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## Abstract

New technological advances are changing the way robotics are designed for safe and dependable physical human-robot interaction and human-like prosthesis. Outstanding examples are the adoption of soft covers, compliant transmission elements, and motion control laws that allow compliant behavior in the event of collisions while preserving accuracy and performance during motion in free space. In this scenario, there is growing interest in variable stiffness actuators (VSAs) [1]. Herein, we present a new design of an anthropomorphic elbow VSA based on an architecture we developed previously [2]. A robust dynamic feedback linearization algorithm is used to achieve simultaneous control of the output link position and stiffness. This actuation system makes use of two compliant transmission elements (CTEs), characterized by a nonlinear relation between deflection and applied torque. The main parameter of the CTEs were determined using a Matlab\ANSYS APDL optimization routine, whereby ANSYS was tasked to solve the 1D model of the beam while Matlab managed the optimization procedure in batch. The optimal parameters were then verified using a 3D FEA simulation and confirmed through experimental test. A Static feedback control algorithms have been proposed in literature considering purely elastic transmission [3]; however, viscoelasticity is often observed in practice. This phenomenon may harm the performance of static feedback linearization algorithms, particularly in the case of trajectory tracking. To overcome this limitation, we propose a dynamic feedback linearization algorithm that explicitly considers the viscoelasticity of the transmission elements, and validate it through simulations and experimental studies. The results are compared with the static feedback case to showcase the improvement in trajectory tracking, even in the case of parameter uncertainty. Figure 1 shows all the phases of the work that have been carried out.

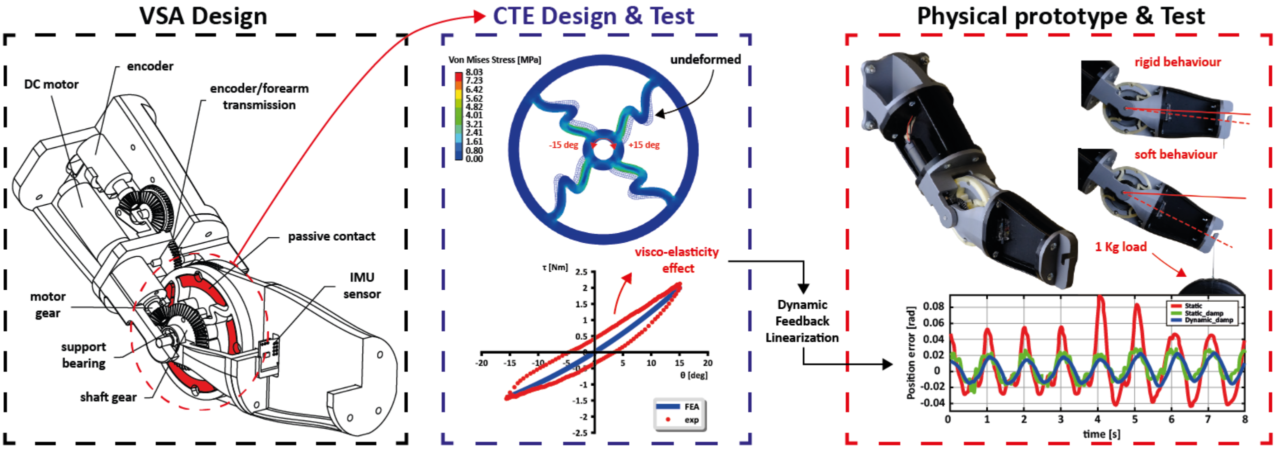

**Fig. 1** Visual Abstract

## References

[1] Vanderborght, Bram, et al. "Variable impedance actuators: A review." Robotics and autonomous systems 61.12 (2013): 1601-1614.
[2] Bilancia, Pietro, Giovanni Berselli, and Gianluca Palli. "Virtual and physical prototyping of a beam-based variable stiffness actuator for safe human-machine interaction." Robotics and Computer-Integrated Manufacturing 65 (2020): 101886.
[3] Palli, Gianluca, et al. "Feedback linearization and simultaneous stiffness-position control of robots with antagonistic actuated joints." Proceedings 2007 IEEE International Conference on Robotics and Automation. IEEE, 2007.

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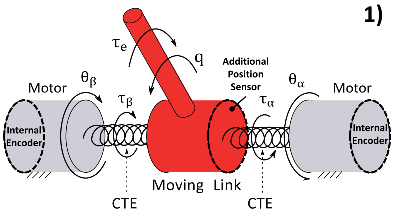
## Introduction

By taking the human limb as a reference to create a prosthesis as natural as possible, the following characteristics must be considered: a) Variable Stiffness (VS) b) Passive Compliance and c) Antagonistic Motor Configuration. In this poster a novel VS elbow joint making use of two Compliant Transmission Elements (CTEs) in an antagonistic configuration is presented, and a robust dynamic feedback linearization algorithm is shown to achieve effective simultaneous control of the position and stiffness of the output link while minimizing the adverse effects of the viscoelasticity of the compliant elements.

## Static Model

1)

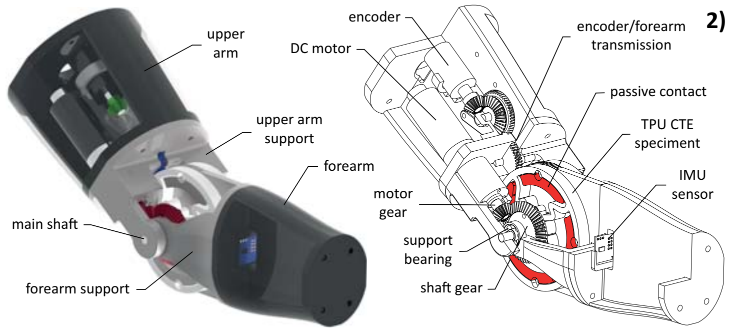


As schematized in Figure 1, each moving joint consists in a coulple of actuators, both of which, by acting on the two CTEs that are connected between the motors and the moving joint, contribute to determine its position *q* and stiffness $k = \delta\tau_e / \delta q$ ,where $\tau_e = \tau_\beta - \tau_\alpha$, $\tau_{(\alpha,\beta)} = a_n \varepsilon^n_{(\alpha,\beta)} + a_{(n-1)} \varepsilon^{(n-1)}_{(\alpha,\beta)} + .. + a_0$, $\varepsilon_{(\alpha,\beta)} = \theta_{(\alpha,\beta)} \pm q$ and $[a_n .. a_0]$ are the CTEs characteristic's coefficients. To variate *q* and *k* independently, the CTEs should have a nonlinear characteristic. By consider a quadratic characteristic, the following torque expression can be obtained: $k = \delta\tau_e / \delta q = 2[a_2 (\vartheta_\alpha + \vartheta_\beta) + a_1] \neq$ *cost.*

## Design Overview

The device shown in Figure 2, to be used as an upper limb prosthesis, must be specially adapted to the shape and size of the missing limb. It has the following dimensions and weights: a) *165x95 mm x 920 g* for the upper arm and b) *156x92 mm x 419 g* for the forearm. In terms of capabilities, a rotation range of *± 100 deg* and a stiffness range of *[2417, 15830] Nmm/rad* were achieved. All non-commercial components were made by additive manufacturing using the following printers and materials: a) Formlabs 3 tough 1500 resin for the encoder and the forearm gears b) Ultimaker S3 TPU for the two CTEs and c) Ultimaker S3 PLA for all other components.

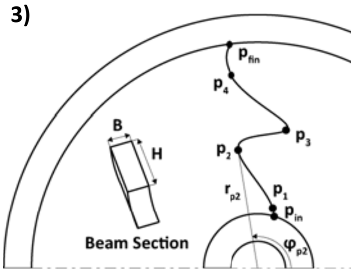
2)



## CTEs Design and Test

The CTE consists of an inner and an outer ring connected by four slender beams. As shown in Figure 3, the shape of the beam was determined using a series of 6 points interpolated over a cubic spline. The position of the parametric points were determined using a Matlab/ANSYS$_{APDL}$ optimization routine to obtain a quadratic behavior as in [1]. The beam section were then optimized to have the maximum torque transmitted at the outer ring, taking into account the material allowable stress as well as the dimensions of the joint. A torque of *2000 Nmm* were achieved over a rotational range of *± 15 degrees*. The experimental tests agree with those of the FEA analysis, but show hysteresis effects due to the internal damping of the material (Figure 4).

3)



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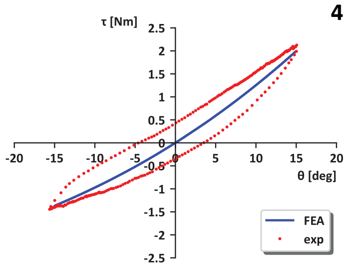
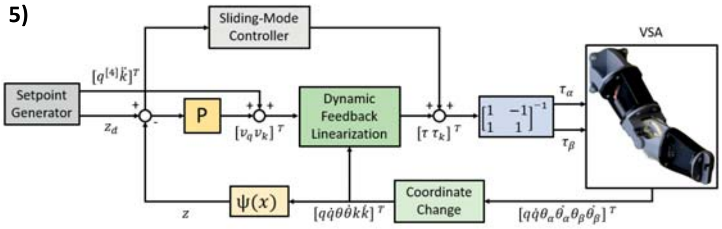


## Modeling and Control

Figure 5 briefly reports the control algorithm used in this work.

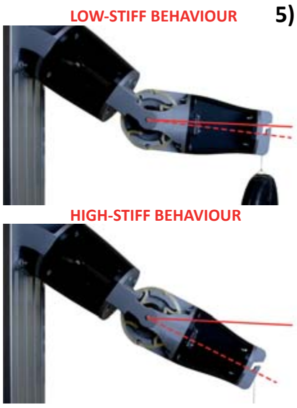
5)



## Results

A physical prototype of the device was finally fabricated and tested. Figure 5 shows the actual change in stiffness of the designed joint using a weight of *1 kg* as a load in the minimum and maximum stiffness configurations of the joint. In addition, Figure 6 shows the errors related to the position and stiffness of the joint in the following cases: a) static feedback control without damping b) static feedback control with damping and c) dynamic feedback control with damping. In all three cases, the joint was given both a sinusoidal and a stepwise position reference with an amplitude of *0.5 rad*.

5)



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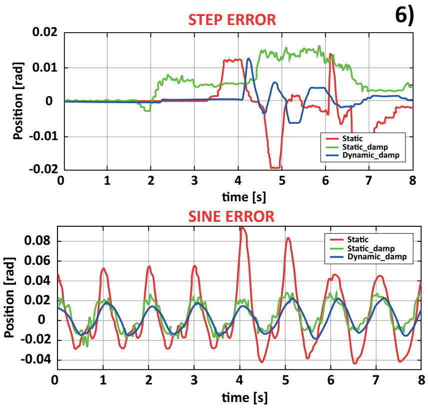

## Conclusions

This poster reports on the design of a variable stiffness elbow joint that uses a pair of motors in an antagonistic configuration and two nonlinear CTEs. The design of the device matches the appearance of a human upper limb, so it can be used as a prosthesis. The CTEs were designed to have nonlinear characteristics but showed a non-negligible hysteresis. To counteract this effect, a robust control strategy was presented and experimentally verified on a physical setup.

## References

[1] Bilancia, Pietro, Giovanni Berselli, and Gianluca Palli. "Virtual and physical prototyping of a beam-based variable stiffness actuator for safe human-machine interaction." Robotics and Computer-Integrated Manufacturing 65 (2020): 101886.